VISUALIZATION OF CONSTRUCTION DATA

by

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ABSTRACT

Measuring and assessing construction project performance forms an integral part of management's control function. Construction projects are often associated with voluminous and unstructured data sets. Visualization techniques hold significant potential to cope with large datasets by presenting subsets of the data in a number of forms that provide valuable insights for management personnel. A central theme of the thesis is that data visualization can provide a means of associating data from various dimensions of a project to aid decision-making and help explain reasons for performance to date. An important objective of the thesis research is to develop data visualization images that are particularly helpful to management personnel, and which could eventually be incorporated into project management systems.

Underlying visual formats, are different causal or explanatory models that link performances to the properties of one or more project parameters. Thus, to formulate visual formats that can assist in explaining project performance, it is essential to identify the underlying causal model/hypothesis explaining this performance. Hence two detailed literature reviews were carried out (i) studying the current state-of-the-art of research on prediction and explanation of construction project performance (ii) identifying current state-of-the-art visualization techniques.

Visualization strategies were mainly explored in the context of change order management during the construction phase. An initial exploratory study of different visual formats was

carried out for a partial change order dataset from a previous project. This work was then extended on to a more extensive dataset for an on-going project.

One aim of the work is to provide the end-users an ability to assess the impact of collection of items or of their occurrence pattern on project performance as opposed to dealing with individual items. We therefore created images illustrating clustering of data items (extra work orders in this case) by different attributes like location, turnaround times, trades involved etc. Although these images are developed for specific scenarios they can be readily adapted to the exploration of other management functions and project data types. The usefulness of the images was verified through interaction with site and senior management personnel of the cooperating construction firm.

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CO-AUTHORSHIP STATEMENT

The thesis author developed the methodology of the thesis research. She has been the lead author for manuscripts in chapter 2 and 4 and was responsible for substantial contributions to the content and writing of the manuscripts presented in chapters 3.

She played a lead role in carrying out the extensive literature review presented in chapter 2 and chapter 4. The focus of her work was directed at identifying the current state-of-the-art visualization techniques, their working principles and applications. She further explored the use of visualization techniques in context of change order management during the construction phase of a project and presented several images to represent aspects of an actual change order dataset.

The co-authors participated in the development and drafting of the ideas and were equal partners with the thesis author in the review and revision of the manuscripts.

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CHAPTER 1.0

INTRODUCTION

1.1 Motivation

Measuring and assessing project performance is an important part of management's control function for construction projects. Associated with such projects are large data sets, comprised of data collected as part of the full spectrum of functions performed by management personnel (e.g. planning and scheduling, drawing control, document management, quality management and change order management). Project management staff is often confronted with the need to make high quality and timely decisions based on the information content that can be deduced from these large data sets in order to explain the reasons for project performance achieved to date.

Aside from its large volume, a construction project's database is also very peculiar in terms of its form, nature and structure. As mentioned earlier, datasets are generated in support of an array of management functions and hence the collected data may vary in its form from textual as in the case of drawing specifications and contractual clauses to quantitative data like number of change orders, their related properties dealing with value, timing and number or participants, RFIs issued and turn around times, drawing control data, schedule information pertaining to dates and activity durations (planned and actual), weather conditions on site, and cost breakdowns. In addition to this, construction data is generally time and location variant and originates from multiple project participants. It is often unstructured and lacks proper grouping and sub grouping which can lead to missed opportunities to associate related data or facts. This lack of clarity of the linkages amongst different data items or project parameters can lead to an imperfect understanding of causal relationships between different project parameters and project performance metrics leading to an incorrect assessment of the reasons for project performance.

Assessing performance involves either predicting or explaining performance of a project. Predicting performance means trying to forecast the expected performance outcome, given an estimate of the likely state of a number of variables deemed to affect performance. In other words one is trying to determine the outcome of the planned story for a given project. On the other hand, explaining performance means trying to deduce the most plausible explanation for deviations from the expected performance outcomes, based on the examination of relevant data. In this case one is trying to understand the reasons for the as-built story of the project. Hence given the volume and types of data that need to be processed and the existence at best of imperfect cause-effect relationships between project parameters and performance measures, explaining the as-built performance is difficult. This creates a need for developing suitable methods for interpreting the available data and extracting information from it to assess the basis for performance to date.

Classic visual aids like graphs and diagrams are one of the oldest and the most popular methods for representing and interpreting the information content of complex datasets. Representing data in a visual format "makes the human brain use more of its perceptual abilities for the initial processing of any data than relying completely on its cognitive abilities" (Geisler 1998). Over the past decade visualization techniques have evolved tremendously from the traditional graphs and diagrams to an array of computerized interactive visual aids. They have proved to be a promising data interpretation alternative with significant potential for coping with very large data sets and presenting subsets of the data in a number of forms that can provide valuable insights for management personnel. Realizing this potential of visualization to facilitate data interpretation, we decided to explore the use of data visualization techniques on construction datasets such that it would reduce the time required by the project management staff to plumb the depths of these large databases in order to extract insights from the data, thus helping the staff to manage projects more effectively. Use of such visual aids for construction data interpretation can benefit both the process of predicting as well as explaining performance. However the focus of this thesis is mainly to apply data visualization techniques to help the end-users understand the as-built story - i.e. identify problem areas in a project as concentrated in one or more of time, space and project participant on an on-going basis during the execution phase of a project.

1.2 Background Work

Considerable research has been done in the broad area of project performance assessment including the construction domain using the causal model approach as one of the data interpretation methods. A numbers of researchers have made an attempt to identify various factors affecting performance and evaluate their relative importance. For example, Fazio et al. (1984) used a questionnaire survey and relative importance scale (0:least important ~ 10:most important) to calculate the relative importance of various factors impairing productivity and Assaf et al. (1995) employed a four scale measurement and a customized importance index to identify critical factors affecting delay in large building construction projects. Sanvido et al. (1992), Halligan et al. (1994), and Chan et al. (2004) proposed different frameworks for categorizing these factors. A few other researchers formulated and/or developed models to study the interaction between these factors and their impact on the performance outcome using different methods including regression analysis, neural nets, fuzzy logic and other decision support systems. For instance, Mohsini and Davidson (1992) used linear regression to study the impact of conflict-inducing organizational factors upon project cost, time and quality performance. Chua et al. (1997) used the neural network technique to develop a model for predicting construction cost performance, while Perera and Imriya (2003) developed a different predictive model for construction cost control based on fuzzy logic and rule-based inference engine technique. These models work on cause-effect relationships that are defined between different project parameters identified to affect project performance and relevant performance measures such as time, cost, productivity and quality and are either predictive or explanatory in nature. The causal model approach has the potential to be an effective data interpretation method enabling end users to explain performance level achieved on a project or predict estimates for a performance measure.

Another line of inquiry that has evolved tremendously over the past decade is data visualization. Visualization techniques can help plumb the depths of databases and put hard to understand data tables and unstructured texts into graphical, easily understood form. Effective visual representation assists in the efficient scanning of different parts of a project's database, allowing users to instantly "identify the trends, jumps or gaps, outliers, maxima and minima, boundaries, clusters and structures in the data" (Brautigam 1996). These visual images when coupled with user interactive tools like filtering and zooming offer increased scope for the analysis of data thereby allowing end users faster and better assimilation of the messages underlying these data sets. Data visualization has special appeal to the construction industry due to its visual orientation and because visualization techniques can be directly used by construction practitioners without the requirement for expert assistance as distinct from the case of other reasoning schema.

1.3 Specific Research Objectives

A central theme of this thesis is that data visualization can assist with a broad range of management functions and provides a means of associating data from various dimensions of a project to aid decision-making and help explain reasons for performance to date. To test this hypothesis, the main goal of the thesis is to explore various data visualization strategies in the context of a specific management function that is core to the success of a project. The function selected is change order management with emphasis on extra work orders and subsequently generated change orders. The specific research objectives described in this thesis are:

1. To examine the state-of-the-art of reasoning about the construction performance in terms of measures like time, cost, productivity, scope and others.
2. To identify various attributes of the datasets that accompany extra work orders and change orders (e.g., issued date, date of approval, turnaround times, impact costs, trades involved, reasons for the extras issued and their connection with other documents like site instructions and RFIs) with particular reference to those properties that impact on overall project performance.

3. To put together a detailed dataset from an actual project that can be used for developing and exploring the utility of various data visualization formats.
4. To experiment with the use of different visual formats to portray selected properties of the data used to represent a specific management function in order to assist users to determine reasons for performance to date.
5. To obtain feedback from construction practitioners as to the usefulness of the images developed.

1.4 Research Methodology

Underlying any visual formats, at least implicitly, are different causal models/explanatory models which link performance to the properties of one or more project parameters. So in order to use visual formats to assist in explaining performance of a project it is essential to identify the underlying causal model or hypothesis explaining this performance (delays, loss of productivity etc.). In order to understand the concept of causal models a thorough literature review was carried out to study the current state-of-the-art of research on prediction and explanation of construction project performance. The review identified a total of 122 relevant articles published over the last 20 years. Findings from the review include identification of a series of performance models developed or formulated for predicting or explaining performance and various factors affecting performance outcomes at different project level definitions (activity level, trade or work package level and overall project level). However a definitive model for predicting or explaining any performance measure could not be identified. The review also suggested that no consensus has been reached to date to discern the most important factors, their definition or relationship amongst them for individual performance measures. Nevertheless, the literature review provided important insights on the existing performance models and related factors.

Based on the findings of this study and an assessment of the properties that an explanation facility should possess if it is to be acceptable to industry practitioners, basic building blocks of our approach to develop mechanisms through a computer-based architecture for extracting reasons or explanations for performance to date from project data were set. Components of the approach include use of an integrated representation of a project in support of a diverse range of construction management functions, a system architecture which allows construction users to express their knowledge/experience in the form of a series of causal-models, a search mechanism to 'prove' or 'disprove' hypotheses as expressed in user-specified causal models, and data visualization as an alternate means to extract meaning from the data to help validate the defined hypotheses.

As mentioned earlier, the main goal of this thesis is to explain performance by extracting information from visual representations. Hence in order to make use of data visualization to represent and consequently interpret different datasets, it is essential to have a basic idea of existing visualization techniques. Thus a literature review was carried out to identify current state-of-the-art visualization techniques, their working principles and software applications. In carrying out this literature review, we also undertook to identify the extent to which visualization techniques have been applied to the field of construction with our focus being primarily on the visualization of construction management data as opposed to visualizing the physical artifact to be built. It was observed that there is very little literature that addresses visualization of construction data, either using conventional representations or some of the more avant garde techniques developed and advocated by computer scientists.

To this end, we then decided to experiment with the use of different visual formats for an actual dataset. We first examined data from a previous project for which a partial dataset of change order data was available. This led to an exploratory study of different formats. This work was discussed with a contractor, which led to the acquisition of a more extensive dataset for an on-going project, again with the focus being on change order management, a topic of significant interest to the contractor. Although our work is mainly focused on visualization of datasets we first needed to identify the nature of the datasets with which we were dealing. Hence, in addition to discussions with the site superintendent and the project manager we carried out a thorough study of the project records in order to understand the project management procedures employed for the project, documentation procedures adopted, and flow of information between different documents/records with a specific focus on extra work orders issued and subsequent change orders generated, their properties and their connection with other project documents/records. Data records for many of the extras generated on this project were found to have certain missing links in terms of date of approval, trades involved, and amount approved for each of the trades involved. Also, we were unable to trace the time taken for decision-making and when the actual work corresponding to an extra work order was actually completed and/or how it unfolded. Part of the aim of our research is to provide end users with an ability to assess the impact of a collection of items or of their occurrence pattern on project performance as opposed to dealing with individual items. We were therefore particularly interested in the clustering of data items (extra work orders in this case) in terms of different attributes like location, turnaround times, trades involved etc. We undertook the task of tracking these missing links in the datasets from relevant and associated documents including the list of site instructions and RFIs, individual SI and RFI records, drawings and contract registry and through discussions with the on-site and off-site management personnel. We thus tried to complete the missing fields in the records to the best of our ability. We then went on to explore various possibilities for representing these datasets in different visual formats such that the collection of these data items and occurrence patterns in an image could help management staff identify related problem areas more efficiently and accurately and bring them to the notice of the owners. Several images were generated illustrating clusters of extras and COs in time by location, project participants and reasons. With clients as the target audience, management staff could use these images to explain to them reasons for the as built story. These images could also be used to communicate with the consultants, quickly demonstrating the reasons for the generated work orders and hence determine the responsibility for the extra work and also to assess the impact of the concentrations of these on various trades involved and overall project delivery date. With a continuous-data updating ability, the images thus generated could also help site staff track day-to-day progress of a project. In the subsequent chapters these images and the accompanying thought processes are described. Although the images have been developed for specific scenarios, they can be readily adapted to the exploration of other management functions and project data types. In fact, an important objective of the work is to identify the kinds of images that are particularly helpful so that the ability to generate them can be incorporated into full-fledged project management systems.

1.5 Thesis Structure

This thesis is written using the manuscript option wherein the main chapters of the thesis constitute papers published, accepted for publication, submitted or in preparation describing the student's research. In this thesis, chapter 2 is a paper presented at the ASCE Construction Research Congress 2005 and is published in the proceedings of the same. Chapters 3 and 4 are papers presented at the CSCE Construction Specialty Conference 2005 and are a part of their proceedings. Chapter 5 is an exploratory chapter prepared as a regular thesis chapter and as a preliminary draft of a journal paper.

Chapter 2, State-Of-The-Art Review Of Construction Performance Models And Factors is a paper presented at the ASCE conference, co-authored by Tanaya Korde, Mingen Li and Alan D. Russell. This chapter is a detailed literature review of current state-of-the-art of research on prediction and explanation of construction project performance. It lists all 122 relevant articles identified. Each of the authors contributed equally in carrying out this literature study and further collaborated to document the findings in the form of two tables, one identifying factors affecting different performance metrics, and the other listing various performance models developed using different quantitative and qualitative methods. This chapter also documents important insights gained through this literature review in terms of areas of consensus and knowledge gaps.

Chapter 3, Explaining Construction Performance Using Causal Models has also been co authored by Mingen Li, Tanaya Korde and Alan D. Russell. This chapter recaps important features of the literature review and then outlines an approach for explaining performance, including the role of visualization, both to help in identifying causal relations and then given a causal relation, to determine support for it in the context of a specific project's dataset.

Chapter 4, Visualization of Construction Data is co authored by Tanaya Korde, Yugui Wang and Alan D. Russell. The central theme of this chapter is that data visualization can assist with a broad range of management functions and provides a means of associating data from various dimensions of a project to aid decision-making and help explain reasons for performance to date. An extensive literature review was carried out to study current state-of-the-art of visualization techniques. A table documenting various visualization techniques, their working principles and sample applications is presented. The focus of my work for this paper was directed at carrying out the foregoing literature review, identifying and presenting the significance of data visualization and its special appeal to the construction environment. Also explored in this chapter is the use of visualization techniques in the context of environmental risk analysis during a project's procurement mode decision-making phase, and change order management during the construction phase. My work specifically concentrated on applying visualization to change order management. In doing this we first undertook the task of identifying the various properties of a change order including their associations with components or other information entities that were then presented in a tabular format. Further, data visualization strategies were explored creating several images that can provide meaningful insights for the function of change order management from the perspective of a general contractor or construction manager. Due to space constraints in the published paper not all the images generated could be documented in this chapter. Hence some of the figures are presented in the appendix section of this thesis. In presenting these images, use has been made of an actual data set in terms of number of change orders (122), value, timing and location. The focus of this chapter is to demonstrate the value of visualization in helping to determine if clustering of change orders is occurring in one or more of time and space or by project participant, which could in turn explain in whole or in part performance difficulties at different levels of the project (e.g. trade level, overall project level). This focus forms part of a larger ongoing research effort directed at a change order management view of a project and its relationship with other project views. In the conclusion for this chapter, the authors further pooled their efforts in identifying the challenges that need to be addressed when implementing visualization techniques for representing construction data.

Chapter 5 is an extensive follow-up to chapter 4 and is exploratory in nature. While written as a conventional thesis chapter, it represents a preliminary draft of a journal manuscript. This chapter is a detailed study of extra work order and change order data from an on-going renovation project on the University of British Columbia campus. Because we were provided with direct access to the site and the management staff for the project we could develop a good background understanding of the project, its management procedures and documentation process. Staff members were enthusiastic participants in our study. This chapter provides a brief overview of the case study project, its physical scope, the delivery mode, special features and challenges encountered on the project. The chapter then discusses in detail the nature of the datasets available and methodology we adopted to fill in the missing links so that we could use these datasets for generating a range of visual images directed at explaining schedule performance and potential capacity constraints for the participating organizations. The goal of this work is to show how data visualization can provide a 'big picture' of what is happening to a project in the way of changes during the construction phase of this project. Here again we are trying to demonstrate the value of visualization to help the users determine the collective impact of changes and their occurrence patterns on construction performance metrics like time, scope etc. An implicit causal model underlying the images given is that the possible impact of extra work orders or change orders is likely to be highest if they are clustered simultaneously in time, space and by project participant. The thought processes accompanying these images is also discussed in detail in this chapter. We have further tried to validate the potential and usability of these images through feedback from project management staff and senior executives associated with this project.

Chapter 6 of this thesis documents conclusions from the foregoing work and puts forth recommendations for future work in this area.

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CHAPTER 2

STATE-OF-THE-ART REVIEW OF CONSTRUCTION PERFORMANCE MODELS AND FACTORS *

2.1 Introduction

Over the last two decades in particular, a considerable amount of research has been focused on identifying important factors that affect construction performance at one or more of the overall project level, individual organizational participant level, and work package or activity level, as measured in terms of cost, time, productivity, safety, and so forth. To date, however, researchers have not reached a consensus as to the most important or critical factors that influence achievements with respect to each performance measure, and further, for the factors identified, there is little consistency in their definition and use of language. Also, researchers have explored different methods to establish models for explaining or predicting performance using various sets of critical factors, but again no consensus has emerged as to the most promising method to use. Moreover, the validity and ease of use of these models for day-to-day use by practitioners is seldom discussed in the literature and there is little evidence that these models have actually been adopted in practice.

* A version of this chapter has been published as part of the proceedings of 2005 Construction Research Congress April 5-7, 2005. San Diego, California, USA. Title: State-of-the-art review of construction performance models and factors. Authors: Tanaya Korde, MASc student and Graduate Research Assistant, Department of Civil Engineering, University of British Columbia, tpk08@hotmail.com, Mingen Li, PhD student and Graduate Research Assistant, Department of Civil Engineering, University of British Columbia, limingen@civil.ubc.ca, and Alan D. Russell, Professor and Chair, Computer Integrated Design and Construction, Department of Civil Engineering, University of British Columbia, adr@civil.ubc.ca.

The objective of our ongoing research program is to develop a system architecture for construction users to define experience-based hypotheses about explanations for performance levels achieved to date in terms of causal models that make use of project parameter values that are already collected as an essential part of day-to-day management functions (e.g. skill levels, weather conditions, etc.). To the extent that they exist, fundamental relationships that link project or activity variables will be embedded in the causal models (e.g. $T = Q/P{\bullet}R$ in which T is duration, Q is a scope variable, P is productivity and R is resource usage level) that define the hypotheses. The goal is to use one or more of these hypotheses to structure an extensive search of a project's database to prove or disprove that they provide the basis for explaining current performance and identifying relevant corrective actions for a specific aspect of the project.

As a precursor to this work, it is important to build on the legacy of other researchers in terms of factors influencing project performance and performance models. In this paper we present the current state-of-the-art of research directed at explaining performance to date (i.e. given a deviation from expected performance, what is the most plausible explanation based on an examination of relevant project data) or predicting performance (i.e. given an estimate of the likely state of a number of variables, what is the expected performance outcome).

The paper is structured as follows. Because of the large volume of material treated, the main findings of the research are presented in two tables. Construction performance models identified through this search are first tabulated, including the performance measures treated, level of applicability (overall project, work package, individual activity) and methods used for constructing the models (e.g. regression, neural nets, fuzzy logic, belief networks, etc.). Then, various factors affecting different construction performance measures are identified. The paper concludes with a discussion of the findings in terms of areas of consensus, knowledge gaps, and steps to be pursued to develop a robust and practical schema for interpreting project data in order to explain performance to date. The latter should be contrasted with the primary focus of most models presented in the literature, namely checking conditions that should be present at the outset of a project in order to help ensure success, or for post mortem analysis directed at explaining performance of the overall project.

2.2 Literature Review and Methodology

A thorough literature search was carried out resulting in the identification of some 122 articles from various sources (ASCE, CSCE, AACE and other journals and conference proceedings) covering approximately a 20-year time span. A much larger number of papers were examined, but only papers that dealt with construction performance prediction or explanation at different levels of project definition and/or articles identifying factors affecting one or more performance metrics were retained. Papers that dealt with related topics (e.g. the determinants of success on international projects, project risk profile, etc.) were excluded from consideration.

2.3 Construction Performance Models

Researchers have developed a variety of models for evaluating project performance based on different performance metrics as productivity, time, cost and others. Table 2.1 summarizes the findings in terms of these models against the performance metric for which it is developed. In general, individual models have been developed for a specific level of project definition, as follows:

- *Project level:* Models/frameworks at this level adopt a holistic approach towards the project, and are defined at a very aggregated level. Typically, project success constitutes the performance measure of greatest interest.
- *Project participant level (group or trade level):* Models at this level examine a project from an individual organization's perspective (e.g. general contractor, construction manager, trade), and generally treat a collection of activities. Of particular interest are factors and metrics of performance that relate to cost, time, and safety.
- *Activity / work package level*: Models at this level tend to deal with the details associated with carrying out different types of work – e.g. formwork, concrete placement, earthmoving, etc., and are often focused on productivity.

Table 2.1 Construction Performance Models

Performance Metric	Performance Level	Quantitative Models	Qualitative Models
Productivity	Activity Level	**RM**-9,56,96,106,111,115,118;**NN**-3,101,109,112; **DSS**-39; **OT**-116;	**OT**-105,110,114;
	Group level	**RM**-48,50,51,52; **MM**-113;	**OT**-76,117,
	Project Level	**RM**-60,70,88;**NN**-82,122;**MM**-43,97,120; **DSS**-89; **OT**-45,	**OT**-12,16,20,30,46,47,59,66, 74,76,90,95; **II**-41,49,78,103;
Time	Activity Level	**DSS**-4,121,	
	Group level		
	Project Level	**RM**-23,25,26,44,64,72,79,87,100, 119;**NN**-5,71;**DSS**-89;**BN**-84;**GA**-27;**FL**-99;**OT**-21;	**OT**-6,8,12,54,74,90,102; **II**-14,31,37,38,68,73,83,85, 91,92;
Cost	Activity Level	**DSS**-4,	
	Group level		
	Project Level	**RM**-23,42,44,64,79,87,100;**NN**-5,32; **DSS**-53,89;**OT**-7,35;**BN**-84;**GA**-27;**FL**-99;	**OT**-8,54,62,69; **II**-31,36,68,85,94;
Scope	Activity Level		
	Group level		
	Project Level	**RM**-100;	**OT**-8;
Quality	Activity Level		
	Group level		
	Project Level	**RM**-79,87; **OT**-80;	**OT**-8,81; **II**-2,13,31,85;
Safety	Activity Level	**FL**-75;	
	Group level		**OT**-57;
	Project Level		**OT**-58,63,65,108;
Project success	Activity Level		
	Group level		
	Project Level	**RM**-19,23,64,104; **MM**-67; **FL**-99; **OT**-7;	**OT**-1,17,18,24,33,55,61,77,86, 93,98,107; **II**-10;
Other	Activity Level		
	Group level		
	Project Level	**NN**-28; **RM**-22,29,79;	**OT**-20,40,54; **II**-15;

The majority of the models reviewed in the literature correspond to project level models. In the view of the authors, however, many of them are applicable to lower levels of project definition. Having said this, the categorization in Table 2.1 is solely based on the authors' interpretation of the literature reviewed – thus a project level model as defined in the source paper is only classified as such in Table 2.1 (for compactness of presentation, all references have been numbered in addition to normal citation practice). We have further subcategorized the models at each level as being Quantitative or Qualitative depending upon the method used to establish a relationship between the factors identified and performance measure of interest. Papers which identify the factors believed to affect a performance measure through web-based or questionnaire surveys or present a conceptual framework explaining the causal relation between the factors and the measure being considered have been categorized as Qualitative models. Quantitative models encompass a large variety of models including simple mathematical models, regression models, neural nets (ANN and PINN) and belief nets.

Table 2.1 also documents the methods used to establish quantitative models or frameworks presented in the literature for predicting or explaining performance as a function of factors believed to influence performance. In order to present the information in the table in compact form, abbreviations have been used to represent the methods used as follows: NN: Neural Network; RM: Regression Method; FL: Fuzzy Logic; DSS: Decision Support System; MM: Mathematical Model; GA: Genetic Algorithm; BN: Belief Network; II: Importance Index; OT: Others.

Neural nets and regression analysis models have been widely used to establish predictive performance models. Because the manner in which they are derived is generally understood, the mechanics of their derivation are not elaborated upon here. Models based on fuzzy logic and decision support systems appear less frequently, and are less clear-cut in terms of their mechanics. We therefore elaborate briefly on how these models are constituted. A fuzzy logic model typically involves identifying factors thought to be relevant to the performance measure of interest, and then allowing for the description of possible states of these factors in terms of linguistic values such as 'moderate', 'high', 'very high'. The model then consists of a series of rules that reflect various combinations of factor states in order to predict through the use of an inference engine the likely state of the performance variable. Factor states are provided by the intended end-users (e.g. researchers and construction personnel) for processing by the inference engine (e.g. Perera and Imriya 2003). The labeling of decision support system (DSS) as a methodology follows from several of the papers reviewed and in general involves the combination of a number of modules that treat data input/output, data preprocessing and validation, reasoning and suggestion offering. Thus a number of techniques which are integrated into a unified whole can be involved, and no one dominant technique can be singled out for categorizing the approach – hence the use of the label DSS. References of particular note regarding the application of DSS include Abu-Hijleh and Ibbs (1993), El-Rayes and Moselhi (2001), Hastak et al. (1996), Moselhi et al. (2004), Yates (1993).

As a further note regarding the methods used, some of the papers use two or more methods to establish the relations between the factors. In such cases, the method used for establishing the final relationship is regarded as the primary method: i.e. if a paper first uses regression analysis to identify critical factors and then uses a neural network to establish the final model, the paper was placed in the neural network category. Several papers identify the factors and also provide their relative importance in the form of an importance index or rank. These papers have been tabulated under the 'II' category. Importance indices presented were generally derived using statistical techniques like 'Pearson's Correlation Coefficient', 'Factor/cluster analysis' or customized index equations (e.g. Assaf et al. 1995). A substantial number of papers were focused solely on identifying a list of factors affecting various performance metrics using statistical analysis, literature study, case studies or exploratory surveys. These articles have been grouped under the category –'OT'-Others.

As noted earlier, construction performance models can also be classified as being predictive or explanatory – i.e. they offer a framework/mathematical relationship for prospective or retrospective evaluation of project performance, respectively. Because of space constraints, we have not attempted to identify in Table 2.1 this classification dimension for each of the references cited. However, the preponderance of the models described is that of predictive. Further, most models reflect a 'single layer' of factors, with the assumption being that there is no relationship and hence no interaction between factors in the same layer (i.e. the factors are independent). A good example of this is the productivity prediction model proposed by Woodward (2002). In reality, there can be multiple layers of factors with significant interaction between the factors in the various layers. Quantifying the interaction in a practical way can prove to be very difficult, and is a topic seldom addressed in the literature identified.

Almost all of the models studied involve one or more factors for which data is not typically collected during the course of the project. This tends to limit their practicality for day-to-day use by construction personnel unless it can be demonstrated that the incremental value in collecting the extra data needed far exceeds the cost of doing so. There is very little evidence of extended use in practice of the models developed to date. Exceptions include Ameen et al. (2003) who report the one-time use of a customized regression model to help validate a claim, while Portas and AbouRizk (1997) describe the use of neural net model by a major general contractor. Various researchers have attempted to validate their models by comparing performance predicted by the model using actual data sets versus actual performance (Jaselskis and Ashley 1991, Portas and AbouRizk 1997). There can be a conflict between the informal hypotheses about performance that practitioners use in evaluating situations and which have been developed based on years of experience versus those embedded in the various models presented in the literature, lessening the likelihood of their adoption by practitioners. And yet, the need for a facility to allow the end user to customize or extend the models presented is seldom elaborated upon in the papers identified, most likely because they are assumed to be a research as opposed to operational tool.

2.4 Construction Performance Factors

Collectively, researchers have identified an extensive list of some 77 factors thought to influence different performance dimensions (this list is not necessarily all inclusive). Each model proposed in the literature makes use of a subset of the members of this master list. In compiling the list, we have selected only those factors that were identified as 'significant factors' by the authors of the respective articles. For example, if a paper lists 14 factors as influencing performance and carries out a regression analysis to select 7 factors as the most significant ones, then only these 7 short-listed factors have been included in our master list. Then, using frequency analysis, we sought to develop a consensus list of critical factors that are most strongly believed to or have been clearly demonstrated to affect performance measures for schedule, cost, productivity and overall performance. Because of space constraints, only those factors that passed the following frequency test are presented herein: given a performance measure, a factor was only included if it was listed in at least 20 percent of the papers deemed to be relevant to that performance measure. This reduced the list of factors from 77 to the 39 factors presented in Table 2.2.

Table 2.2 Consensus Factors Affecting Construction Performance Measures

ID	Factors	Productivity (24)	Time (33)	Cost (23)	Overall Performance (15)
1	Availability of resources	**16**-11,16,20,30,34,47,49,59,66,74,78,89,90,97,103,120	**18**-6,8,12,14,26,37,38,54,68,74,79,83,84,89,90,91,92,119	**7**-8,36,53,54,69,84,89	**5**-10,18,67,98,107
2	Management	**14**-11,16,20,30,41,46,47,49,59,78,89,90,97,103	**13**-6,12,14,27,31,37,38,68,71,83,89,90,92	**9**-27,32,35,36,42,53,64, 69,89	**10**-10,18,19,24,64,67,93,98,104,107
3	Weather/environment	**11**-41,47,59,66,74,78,89,90,97,103,120	**10**-6,12,14,27,37,38,68,74,89,91,92	**6**-27,36,53,68,69,89	
4	Planning	**10**-16,34,41,47,49,59,66,74,89,97	**17**-6,8,12,14,23,27,31,37,38,54,68,87,89,83,85,92,119	**10**-8,10,27,31,35,36,42,53,54,69	**7**-10,18,19,23,24,67,107
5	Training/Education	**10**-11,16,30,41,46,47,66,89,95,103			**3**-18,67,93
6	Working conditions	**9**-34,47,49,59,66,89,97,103,120	**8**-6,26,27,38,54,68,89,119		
7	Crew ability	**8**-41,47,49,59,78,89,90,120			**3**-24,67,107
8	Labor density	**8**-20,47,59,66,89,90,97,120			
9	Changes	**8**-34,47,59,60,88,89,97,103	**10**-6,12,14,27,37,38,68,85,89,91,92	**8**-10,27,35,36,53,69,85, 89	**4**-10,33,67,107
10	Rework	**7**-20,34,47,59,89,90,97			
11	Technology	**7**-11,16,30,46,	**13**-6,31,37,38,	**7**-7,31,32,53,	**9**-7,10,18,19,24,

	(Method)	47,49,122	54,64,71,72,89, 91,92,102,119	54,79,89	64,67,98,107
12	Motivation	**7**-41,47,49,59,66,97,103			
13	Communication	**6**-16,41,47,49, 78,90	**15**-6,14,23,25, 27,37,68,83,85,89,90, 91,92,100,119	**7**-27,35,36, 69,85,89,100	**8**-10,18,19,23, 24,67,93,98
14	Regulations	**6**-11,16,30,41,47,78	**8**-6,12,27,37,38, 85,91, 92	**7**-27,35,36,53, 68,69,85	
15	Economy	**6**-27,35,36,53,68,69, 85	**8**-6,12,14,38,83, 91,92,119	**5**-7,10,35,36, 79	**8**-7,10,18,23,24, 67,98,104
16	Labor turnover	**6**-11,16,30,47,78,89			
17	Quality control	**6**-11,16,30,47,103,120			
18	Shiftwork (overtime)	**6**-34,49,66,89,97,120			
19	Fatigue	**3**-34,47,97			
20	Scheduling	**5**-16,47,59,103,120			**4**-18,19,67,98
21	Crew size	**5**-34,59,89,97,120			
22	Productivity		**10**-6,8,14,25,38, 68,72,89, 92,102		**3**-1,24,67
23	Contract type		**10**-6,25,27,37, 44,64,83,85,91,92		
24	Experience		**9**-14,27,37,68, 71,74,83,89,91	**9**-7,27,32,35, 53,64,68,79,89	**4**-7,24,93,107
25	Subcontractor integration		**8**-6,37,38,68,83, 91,92,119		**3**-10,24,67
26	Delays		**8**-6,12,14,37,38, 73,89,92		
27	Client characteristics		**7**-12,21,27,38, 91,92,119	**5**-7,27,53,69, 79	**5**-7,23,24,104, 107
28	Project size			**6**-7,27,47,69,79,89	**3**-7,18,24
29	% design completed			**5**-7,32,69,79,89	
30	Construction cost			**5**-10,36,53,68,89	**3**-1,24,104
31	Quality of Management staff				**8**-18,19,23,24, 67,98,93,104
32	Organizational structure				**6**-18,19,24,64,67, 98
33	Errors/Omissions				**4**-1,10,24,67
34	Architect/Designer characteristics				**4**-23,24,104,107
35	Political				**4**-7,18,24,98

	influence				
36	Client satisfaction				4-1,18,19,24
37	Safety				3-1,24,67
38	Complexity				3-7,18,24
39	Procurement method				3-7,24,67

In general, there is a lack of clarity or precision in the definition of the factors identified, which can lead to a misinterpretation of meaning by different users and hence different findings from application of the models put forward. Further, authors tend to use different terminology to describe the same factor, and there can be overlap in what is being measured by different factors. This can pose significant difficulties in terms of properly interpreting findings presented in the literature, and from the practical point of view of trying to apply the models in practice and collect data in the field. We believe that developing clear and consistent factor definitions is an important research topic, along with determining the nature of the interactions amongst factors. In arriving at the list of factors in Table 2.2, we interpreted as best we could the intended meaning of the factors identified in the literature reviewed, and then agreed on a definition for each factor and its scope. This enabled us to group factors that were synonyms for each under a single factor name, thereby avoiding double counting. For instance, 'competence of workers' and 'suitability of the workforce' are represented by 'Crew ability'; 'delay in delivery', 'resource delivery time', and 'resource allocation' all relate to resource availability on site and hence are represented by 'Availability of resources'. Often some of the factors identified in the literature are so vague in scope and definition that it is not clear what tests can be articulated for the purpose of assigning either a numerical or linguistic value to them. Combined with this, very different levels of aggregation are implicit in some factor definitions. For example, some authors consider scheduling as a single entity which is described as poor, satisfactory, good, while for others, more tangible tests are involved such as type of schedule (bar chart model, network model), frequency of updating, and so forth. Also problematic is any consistency in the definition of the states that each factor can take on, and on how best to express the values of these states. Much work remains to be done in this regard. Finally, what needs to be addressed is how the definition of factors and related values can be mapped onto data that is already collected as part of other management functions. This would greatly enhance the potential for use by industry of some of the more promising models presented in the literature, and would help in embedding these models in computer-based management systems.

2.5 Conclusions

Described in the paper are findings from a thorough literature review of work to date directed at developing models for predicting or explaining construction performance in terms of the values taken on by a number of factors deemed to be relevant to one or more dimensions of construction performance and at various levels of project definition. Key amongst the findings are the following: there is no definitive model for either predicting or explaining performance; most of the models described are more research than practice oriented; and, there is no strong consensus at to the most important factors to be used, what their definition should be, how best to express outcomes for them, or what the relationship amongst factors is, if any. Nevertheless, the literature review provided important insights on the current state-of-the-art, and has contributed to the formulation of the approach being pursued by the authors for developing transparent mechanisms for extracting explanations for performance to date from a project's database. We seek an approach that can be embedded in computer systems that support a significant spectrum of construction management functions and which allows construction users to express their experience in the form of causal models or hypotheses that can be used to facilitate extensive data searches to help management reason about construction performance. Transparency is an essential feature of our approach, because we believe that it is end-users that should express their expertise in the form of causal models that exploit data that is already being collected in support of day-to-day management functions (e.g. drawing control). These causal models are then used to automatically generate search queries that can be applied to the project's database in order to find evidence that supports the hypothesis of the causal model. Current work is focused on mapping the most important factors identified in the literature search onto data collected as part of day-to-day management functions, and determining consistent ways of expressing the likely states of these factors. Additional work is directed at determining how parameters that take on different values over time (e.g. weather conditions) should be treated in the causal models.

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CHAPTER 3

EXPLAINING CONSTRUCTION PERFORMANCE USING CAUSAL MODELS*

3.1 Introduction

Over the last two decades a significant amount of research has been carried out on identifying critical factors and formulating predictive and explanatory models for construction performance measures such as productivity, quality, time and cost. By predictive models we mean models that can be used to provide or 'predict' a priori accurate estimates of performance measure achievements on part or all of a project, given an estimate of the likely state of a set of critical variables that are believed to be relevant for the work scope of interest. Values used are assumed to represent an average of the conditions forecast to be encountered (e.g. labour skill level). Such models are useful in the estimating phase of a project and provide the benchmarks required for project control. By explanatory models we mean models that can help construction personnel figure out what the most plausible explanation is for a deviation of actual performance from expected performance, based on an examination of relevant project data. As part of this quest, there is a need to determine the actual status of a critical factor for the work of interest, which may involve 'integrating' over factor values in terms of time, space and organization in order to find a representative value,

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a difficult task. The development and use of explanatory models constitute the primary focus of this paper, with emphasis on the performance measures of productivity and time. We believe that the next generation of construction project management systems should be able to leverage the abilities of management to pinpoint reasons for performance to date, and perhaps offer advice on how best to improve performance. The knowledge required to use such systems should be compatible with that of a well-trained university or technology program graduate, and the techniques embedded in these systems should be understandable by the firm's personnel and not require the use of outside specialists on a day-to-day basis. This is easier said than done, and the reality is that some upgrading of personnel skills is required if industry is to advance in terms of the effectiveness of its management practices and capitalize on the benefits offered by more powerful information technologies.

While a number of methods have been proposed by researchers for predicting or explaining construction performance at the overall project level, individual participant level (e.g. individual trade), or component level (e.g. activity, cost centre, etc.), to date no consensus has emerged either on a preferred method or even on the most critical factors that have the greatest influence for a specific performance measure. Further, while work done to date has provided valuable insights and a good foundation to build on, its impact on practitioners appears to be minimal, and workable mechanisms for incorporating it in practice seemingly not pursued. Possible explanations for this are several. First, most firms do not have the knowledge base and/or resources required to make use of some of the modeling techniques used by researchers, such as neural networks, generalized regression analysis, belief networks, etc., nor the ability to interface such techniques with the firm's information system(s). Second, outcomes obtained by using such techniques and critical factors can be inconsistent with actual outcomes or not coincide with the experience of practitioners. And third, some of the factors identified as important to performance by researchers are not tracked as part of any management function.

In this paper, we first set out an overview of the findings of an extensive literature review directed at determining the state-of-the-art in terms of developing predictive and explanatory construction performance measure models and related critical factors. We offer some observations as to the role(s) previous work can play in terms of assisting with the next generation of management systems for the construction industry. We then set out some properties that we believe should be possessed by an approach for explaining performance, if it is to have an impact on current construction management practices. This is accompanied by a description of the line of inquiry we are following for developing explanatory models. Selected aspects of the approach are then elaborated upon. In essence, our approach has four interrelated components or steps. The first is the use of an integrated representation of a project in the form of a decision support system capable of supporting a significant number of construction management functions. Second is the development of the architecture required to allow construction users to express their knowledge/experience in the form of a series of causal-models which link critical factors and related states that map onto the data collected in support of day-to-day management functions and which build on fundamental relationships (to the extent that they exist) that link project variables. This architecture should form an integral part of the decision support system identified previously. Third is the ability to 'prove' or 'disprove' the hypothesis about reasons for performance embedded in user-specified causal models by conducting comprehensive searches on the project's data base to finding evidence that supports the hypothesis. Lastly, and as an alternative or complement to the third step, is the use of data visualization as a strategy for extracting the information content from the large masses of data that characterize a construction project. This fourth component is described elsewhere (Korde et al. 2005(a)). The ultimate objective of our approach is to demonstrate what is feasible in the next generation of management systems for the construction industry.

3.2 Findings from the Literature

The literature review identified 123 academic papers published in the past 20 years in various sources (ASCE, CJCE, AACE and other journals and conference proceedings) as being directly relevant to our focus. These papers were categorized in terms of performance metric treated (productivity, time, cost, scope, quality, safety, project success, etc.), performance level treated (activity level, group level, and project level), and method used (quantitative methods - including regression models, neural networks, simple mathematical models, and decision support systems; qualitative methods - including importance index, case studies and exploratory surveys). In what follows, we provide a brief overview of performance models and factors identified as influencing performance as presented in the literature. A detailed discussion of the literature review may be found in the paper of Korde et al. (2005(b)).

Academic researchers have tried various methods to identify critical factors and develop better predictive or explanatory models to help practitioners improve base line predictions, explain the basis for project performance to date, or conduct post-mortem analyses of project performance. In the literature reviewed, methods such as importance index (Fazio et al. 1984; Assaf et al. 1985; Kaming et al.1997), statistical regression (Smith 1999; Jaselskis and Ashley 1991; Mohsini and Davidson 1992), neural networks (Chua et al. 1997; Kog et al. 1999; Portas and AbouRizk 1997;), fuzzy logic (Lee and Halpin 2003; Perera and Imriya 2003), and decision support system (Abu-Hijleh and Ibbs 1993; Yates 1993; Moselhi et al. 2004) were used most frequently to develop predictive/explanatory models, using all or a subset of factors identified through a variety of means (e.g. surveys).

From the review it can be seen that there is no consensus on the most promising method to use in terms of establishing predictive or explanatory construction performance models. In the opinion of the authors, however, the decision support system approach is the most promising of all the approaches explored to date in terms of helping the user explain performance variance. Nevertheless, past work of this types has focused only on fundamental relations, the preponderance of the models described is that of predictive, and most models reflect a 'single layer' of factors, with the assumption being that there is no relationship and hence no interaction between any of the factors (i.e. the factors are independent). Particularly interesting examples of this are the productivity prediction models proposed by Woodward (2003) and Neil and Knack (1984) (Woodward's work used many of the same factors identified by Neil and Knack (1984)). Although the productivity prediction relationship adopted by the two sets of authors was different, the models proposed shared a number of important features: (a) they are simple to use and hence of interest to practitioners; (b) factors used are clearly defined as are possible states for each factor; (c) the models allow for judgements on the part of users; (d) the models are readily extendable by users in terms of the factors considered; and (e) the models can be used for both prediction and explanation. These properties are desired in any schema that is targeted for use by industry personnel. However, the use of single layer models ignores the complexity of the interactions that occur amongst project variables (e.g. a combination of poor weather and labour unrest can affect labour motivation). Quantifying such interaction or expressing it in linguistic terms can prove to be very difficult, and is a topic seldom addressed in the literature reviewed. In our view, while the treatment of interaction is important, proper consideration of it results in a potentially very large combinatorial problem. As discussed later, we have opted for a pragmatic solution which can handle multiple layers, but only of a special form. Another observation from the literature reviewed is that almost all of the models studied involve one or more factors for which data is not typically collected during the course of the project. This tends to limit their practicality for day-to-day use by construction personnel unless a surrogate for the factor can be found amongst the variables for which data is typically collected or it can be demonstrated that the incremental value in collecting the extra data needed far exceeds the cost of doing so. And finally, there is little evidence of extended use in practice of the models developed to date. Exceptions include Ameen et al. (2003) who report the use of a customized regression model to help validate a claim, while Portas and AbouRizk (1997) describe the use of neural networks model by a major general contractor.

Based on the literature review, we identified a large number of factors as influencing the construction performance measures of interest. Unfortunately, many of the factors cited lack clarity or precision in their definition, and in some cases researchers use different terminology to describe basically the same factor. Hence there is a fair level of duplication amongst the factors in terms of intent. Further, some of the factors identified are so vague in scope and definition that it is not clear how to articulate tests for the purpose of assigning either a numerical or linguistic value to them. For example, some authors consider scheduling as a single entity which is described in linguistic terms such as poor, satisfactory, good, while for other authors, more tangible tests in the form of sub factors and their values are involved such as type of schedule (bar chart model, network model), frequency of updating, and so forth. Also problematic is the inconsistency in the definition of the states that each factor can take on, and on how best to express the values of these states. Clearly there is a need for greater standardization of vocabulary amongst researchers and industry practitioners. To cope with the problem of duplication, we interpreted as carefully as possible the intended meaning of the complete set of factors identified, and then agreed amongst ourselves on a definition for each factor and its scope. This enabled us to group factors that were synonyms for each under a single factor name, thereby avoiding double counting. For instance, 'competence of workers' and 'suitability of the workforce' are represented by 'Crew ability'; 'delay in delivery', 'resource delivery time', and 'resource allocation' all relate to resource availability on site and hence are represented by 'Availability of resources'. This reduced the factor list to a total of 77 items.

Using this reduced list of factors, we then used frequency analysis to develop a consensus list of the most important factors. The test applied was, given a performance measure, a factor was only included if it showed up in at least 25 percent of the papers deemed to be relevant to that performance measure. Applying this test resulted in a list of 22 critical factors affecting one or more of the performance measures of productivity, schedule, and cost. More detailed information such as frequency of factor occurrence and which researchers cited which factor(s) can be found in the paper by Korde et al. (2005(b)). The 22 consensus factors are presented in Table 3.1, and linked to the performance measures of productivity, schedule (time), and cost by way of the tick marks shown, which were derived from the frequency analysis. The right hand column deals with mapping the factors onto the project views (defined later) that contain data fields that measure directly or indirectly the factor of interest. Because of space constraints, sub factors for the factors listed are not included in the table (e.g. for the factor weather, sub-factors include temperature, precipitation wind speed, and humidity). We note that many authors simply deal with high level factors like management, with the apparent assumption being that one can assess a value at a holistic level as opposed to evaluating a number of sub-factors and then aggregating them into a single value (a process for which fuzzy logic may be of considerable assistance).

Table 3.1 Consensus Factors Affecting Construction Performance Measures

ID	Factor	Productivity	Schedule	Cost	Mapped Data Sets (Views)
1	Resource availability	√	√	√	process, as-built,
2	Management	√	√	√	process, organizational/contractual, as-built,
3	Weather	√	√	√	environmental, as-built,
4	Planning	√	√	√	process,
5	Training/Education	√			process, organizational/contractual, as-built,
6	Working conditions	√			physical, process, environmental, as-built,
7	Crew ability	√			process, organizational/contractual, as-built,
8	Labor density	√			physical, process, as-built,
9	Changes	√	√	√	physical, process, cost, change, as-built,
10	Rework	√			quality, change, as-built,
11	Technology	√	√	√	Physical, process, as-built,
12	Motivation	√			organizational/contractual, as-built,
13	Communication	√	√	√	process, organizational/contractual, as-built,
14	Regulations	√		√	organizational/contractual, environmental, as-built,
15	Economy	√			environmental,
16	Labor turnover	√			process, organizational/contractual, environmental,
17	Quality control	√			physical, quality, as-built,
18	Shiftwork (overtime)	√			process, organizational/contractual, as-built,
19	Productivity		√		physical, process, quality, change, as-built,
20	Contract type		√		organizational/contractual,
21	Experience		√	√	organizational/contractual, as-built,
22	Project size			√	physical,

3.3 Properties to enhance Industry acceptance and our Approach

In this section, we list several properties that we believe should be possessed by an approach for explaining reasons for performance to date in order for it to be acceptable for use by construction management personnel. This is followed by a description of the main basic-building blocks of our approach along with an overview of how it is meant to operate in practice.

Essential properties which are basically self-explanatory include the following:

- Use should be made of data already collected in support of day-to-day management functions, with minimizing the need for additional data solely for use by the explanation approach used;
- The approach should be capable of communicating directly with a firm's project management information system, and preferably be integrated directly into it;
- The techniques embedded in the approach should be readily compatible with the skill set of technically trained/educated construction personnel without the requirement to have specialist assistance on a day-to-day basis;
- Construction users should be able to formulate and update their own causal models of performance based on their experience and beliefs as to its most important determinants;
- Causal models should be based on fundamental relationships where they exist (e.g. computation of duration as a function of scope of work, productivity, and resource levels, computation of cost as a function of inputs and unit prices of inputs);
- A library facility for organizing and storing user-defined causal models for a range of performance variables (productivity, schedule, etc) and physical component or activity types should be included;
- Causal models which reflect previous research findings on factors which are most critical to various performance measures and which map onto data collected as part of existing management functions should be included as default models in the library;
- The ability to validate user-specified causal models using the full array of data processing tools available to researchers should be treated by way of data-export features;

- The user-interface should support the speedy formulation of causal models by providing access to a menu of all data fields in the system, the application of these models to individual system components (e.g. activities), collections of components, or the entire project set, and data filtering capabilities in terms of time, location and project participant windows;
- Comprehensive reporting should be included for outputting all data identified as being relevant to the hypothesis represented by the causal model, along with some index suggesting 'degree of proof' of the hypothesis; and,
- A range of data visualization capabilities should be included to augment the causal model approach and to provide images that help personnel identify potential cause-effect relationships and clustering of data.

As stated earlier, our approach has four main components: (i) use of an integrated representation of a project in support of a diverse range of construction management functions; (ii) a system architecture which allows construction users to express their knowledge/experience in the form of a series of causal-models using data fields from (i); (iii) a search mechanism to 'prove' or 'disprove' hypotheses as expressed in user-specified causal models with data values drawn from the project data base; and, (iv) data visualization. The main pieces of our approach are depicted in figure 3.1.

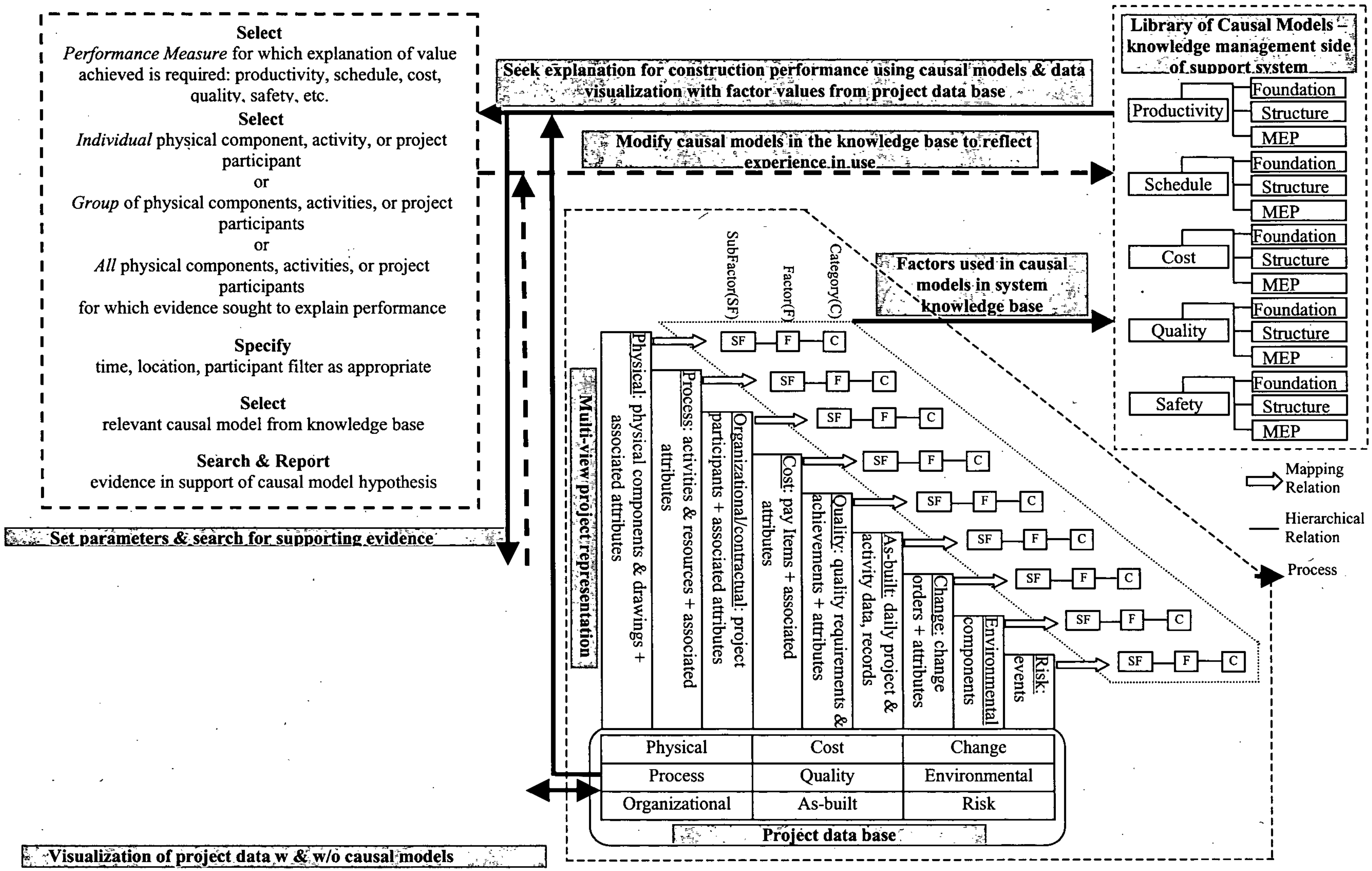

Figure 3.1 Overview of Components of Approach to Explaining Construction Performance

The first component of our approach involves a nine-view representation of a project integrated within a single system. Both user-specified and system generated data values are supported. A view is defined as a data set which describes an abstraction of a significant dimension of a project. The definition and scope of the nine views is as follows: 1. Physical - what is to be built and site context; 2. Process - how, when, where and by whom; 3. Organizational/contractual – project participants, contractual obligations & entitlements, insurance, bonding, warranties, and evaluation of participant performance; 4. Cost - how much and from whose perspective; 5. Quality - compliance requirements and achievements for input and output products; 6. As-built - what happened, why and actions taken; 7. Change - scope changes, why and consequences for other views; 8. Environmental - the project's natural and man-made environments; and, 9. Risk - potential risk events, mitigation measures, risk assignment, and outcomes. An in-depth treatment of the features and benefits of a multi-view representation of a project is presented in Russell and Udaipurwala (2004). The central role of the nine-view project representation for explaining performance is illustrated in figure 3.1 by way of the database foundation, the use of modeling constructs and associated attributes to represent each view, and the mapping of view attributes onto causal model factors. Table 3.2 which is described in more detail later provides an example of the information constructs and supporting attributes used for representing the as-built view of a project.

Table 3.2 Properties of As-Built View

User Defined List of Problem Codes
- ❑ Problem Code Category (Number & Name)
- ❑ Description of problem code (Number & Description)
- ❑ Remark
- ❑ Attributes – links to activity attributes and weight w, 0 ≤w ≤1.0

Daily Data Overall Project Conditions
Site Environment Data
- [3] AM Sky Condition (one of)
- [3] PM Sky Condition (one of)
  - Clear
  - Cloudy
  - Rain
  - Snow
- [3] Temperature (C)
  - AM
  - PM
- [3] Precipitation (mm)
- [3] Wind (kph)
- [6] Ground Condition (one of)
- [6]Storage on Site(one of)
- [6]Access to Site (one of)
  - Good
  - Fair
  - Poor
- [3] & [6]Effects (none, minor, significant)
  - o Comments: (Each field can have an explanatory comment)

Daily Work Force Data (For each active participant)
- Responsibility Code
- [2] Number of Supervisors
- [8] Number of Workers
- [1] Sufficient
- [2] Number of Traffic Controllers
- [7]Skill Level (one of) H/M/L
- [16]Turn Over (one of) H/M/L
- [18] Over Time Hours

Survey Works
- Responsibility Code
- [1] Number of Crews
- Locations
- Activities
  - o Comments

[2] & [1] Inspections
- Location
  - o Comments

Visitors
- Name
  - o Comments

Safety Log & Accidents
- Location
  - o Comments

[2] & [3] Site Instructions
- o Comments

[1] Daily Deliveries (Can have multiple entries)
- Item
- Quantity
- Unit
  - o Comments

Blasting
- Locations
  - o Comments

Visitors
- Name
  - o Comments

[1] Daily Equipment Rentals
- Resource
- Quantity
- Status (Can have multiple entries)
  - Delivered
  - Active
  - Idle
  - Returned
  - No Status
  - o Comments

Miscellaneous Notes
- o Comments

Daily Activity Data:
For each day and each active activity enter:
[4] Actual Status (one of)
- Daily Status
  - Finished
  - Idle
  - On-going
  - Postponed
  - Started
  - Started & Finished
  - No Status
- Start Time
- Comments

[1] – [22] Problem(s)
Enter for each problem encountered,
- Problem Code
- Responsibility Code (if applicable)
- Problem Description
- Estimate of time lost in
  - man hours FE (field estimate)
  - ADJ (adjustment)
  - days FE
  - ADJ
- Actions Pursued (Item plus remarks)
  - Telephone
  - Letter/Memo To
  - Letter/Memo From
  - Back charge
  - Extra Work Order
  - Oral Instruction
  - Photo
  - Video

(Optional information for each activity each day)

Work Force
- [2]Number of Supervisors
- [8]Number of Workers
- [1]Sufficient
- [2] Number of Traffic Controllers
- [7]Skill Level (H/M/L)
- [16]Turn Over (H/M/L/
- [18]Over Time Hours

[1] Equipment
- Resource (from resource list)
- Quantity
- Status
  - Delivered
  - Active
  - Idle
  - Returned
  - No Status
- Comments

[1] – [22] Records
- Photos
- Video clips
- Letters/memos to
- Letters/memos from
- Permits/certificates
- Consultant meeting minutes
- Site coordination meeting minutes
- Trade meeting minutes
- Occupational Health/Safety meeting minutes
- Miscellaneous meeting minutes
- Construction Drawing/Details
- Shop Drawings
- Schedule/work plans
- Requests for information
- Site instructions
- Inspection Reports
- Extra Work Orders
- Backcharges
- Change notices
- Change orders
- Claims

Record abstractions consist of a common set of attributes, and in selected cases, unique properties.

Common Properties for all Records Include:
- Type
- Code
- Date
- Associations with
  - Activity
  - PCBS
  - Quality
  - Problem Code
  - Pay Item
  - Other Records
  - Keywords
- File: (where document is stored, if electronically stored
- Remarks

Unique Properties (not included here)

The second major component involves development of a library of causal models for explaining performance. This library, which resides on the knowledge management side of the decision support system, is shown in the upper right hand corner of figure 3.1. The factors used in formulating these models are drawn from a user-editable classification of the attributes contained in each project view, as shown in the middle of figure 3.1. The causal model library is organized by performance measure of interest (e.g. productivity, schedule, etc.), and within this classification, by type of work (e.g. equipment intensive, unprotected environment) or physical component type (e.g. structural system vs. mechanical system). This aspect of the system is being structured to provide maximum flexibility to the user - they can define as few or as many models as they see fit and continuously refine them as experience is gained from their application. This latter aspect is shown as the dotted feedback arrow in figure 3.1. Default models based on findings in the literature are included in the library for convenience and to provide examples to assist with the formulation of new models – the ability to duplicate existing models and then edit the copies to forge variations of a theme is being included as a user-interface feature. The use of a graphical interface to define causal models which draws on a palette of system attributes/factors is also being explored. In a subsequent section, we discuss the formulation of causal models and some of the attendant challenges.

The third component of our approach occurs at the project level, and brings together the data values for the project at hand and causal models drawn from the causal model library. This component is shown in the upper left hand corner of figure 3.1. In response to what appears to be inadequate performance and a sense of what is causing it (it is possible that one wishes to examine reasons for superlative performance as well), management seeks confirmation of their belief prior to initiating corrective action. As shown in figure 3.1, the following multi-step process is then pursued: (a) *select* the performance measure of interest – e.g. productivity; (b) *select* the aspect of the project to be explored – e.g. formwork activities for verticals; (c) *specify* filters to limit the data search – e.g. January and February and superstructure locations only; (d) select the relevant causal model from the knowledge management library – e.g. vertical formwork productivity; and, (e) *search* the data base by generating a search profile from the causal model, apply the filters from (c), identify supporting data in the form of data states for the causal model factors that act as drivers for reduced productivity, and *report* all factors contributing to reduced productivity. For our example of concrete formwork, and assuming that the causal model employed captures the most important factors that influence productivity, the findings from the search should provide management with the information needed to initiate corrective action. It is recognized that getting the causal model 'right' might involve a number of iterations. This is where the academic community could be of assistance to industry, provided the latter is prepared to make their data sets available for research purposes.

The fourth and last component of our approach involves the visualization of construction data, as shown in the lower left hand corner of figure 3.1. While data visualization is not the primary focus of this paper, we observe that it can facilitate the speedy inspection of masses of data which helps management pinpoint potential causes for variances in performance. For example, the image in figure 3.1 shows a concentration of change orders in the latter stages of a project, which could affect both productivity and schedule. As shown by the arrows into and out of the visualization component in figure 3.1, data visualization can be applied directly to the project data base, it can be used to examine support for part or all of a causal model depending on its complexity, and it can provide valuable feedback to modifying existing causal models or creating new ones in the causal model library.

3.4 Mapping & Organizing Factors

Important to the usability of our approach is the ability to access and navigate easily the complete set of data items in the system when formulating causal models. (One challenge not addressed herein because of space constraints is handling user-defined attributes which are unique to a specific project. We treat this by allowing causal models to be defined that are project specific and which are not retained in the causal model library). How best to organize the very large number of data elements used in our nine-view representation of a project for easy access is not clear. Sanvido et al. (1992), Halligan et al. (1994), and Chan et al. (2004) proposed different frameworks for categorizing factors, but researchers still have not reached consensus on the most suitable framework. Shown in figure 3.1 is a category, factor and sub-factor hierarchy. A possible classification of categories we are pursuing is management factors, product design features, work/force equipment spread features, site conditions, technology/process features and exogenous variables, although these will be soft coded to allow users to substitute their own classification system (as we explore various classification systems, thought is being given to add a sub-category level as well). Users will then be provided with access to a master list of system data fields organized by view, system factor definition and corresponding sub-factors. Using this master list and the factor classification scheme adopted, a palette of factors can be organized using either the factor classification scheme provided as a default or defined by the user. For example, under the category *site conditions*, the *as-built view* factor of *site environment data* would be listed, along with the sub-factors of *sky conditions, temperature, precipitation, wind speed* (see Table 3.2). Once developed, the palette is used in turn to formulate causal models of interest.

In keeping with the properties identified in section 3 for acceptance by industry of an approach for explaining reasons for construction performance, it is important to be able to demonstrate that critical factors identified by researchers as influencing construction performance can be mapped onto the data elements collected by management personnel as part of their day-to-day duties. This was done in general terms in table 3.1, and is further elaborated upon by mapping the critical factors listed in table 3.1 onto the data fields used to represent the as-built view (Table 3.2). The bold numbers to the left of the factors/sub-factors in this table correspond to the critical factors listed in table 3.1. This mapping helps to demonstrate the coarse or aggregated nature of many of the critical factors identified by other researchers.

3.5 Formulating Causal Models

We illustrate here the formulation and use of causal models by way of an example, with the intent of providing some insights into the properties desired of causal models, some of the compromises or pragmatic decisions that have to be made to help ensure usability, and some of the challenges involved in applying them to project data sets. Our focus will be activity duration and productivity as performance measures for substructure excavation. Figure 3.2 has been developed to assist with the discussion. In what follows, we demonstrate that there can be a hierarchy of factors, and rather than refer to them as factors and related sub-factors, we choose to label all of them as factors to simplify the discussion.

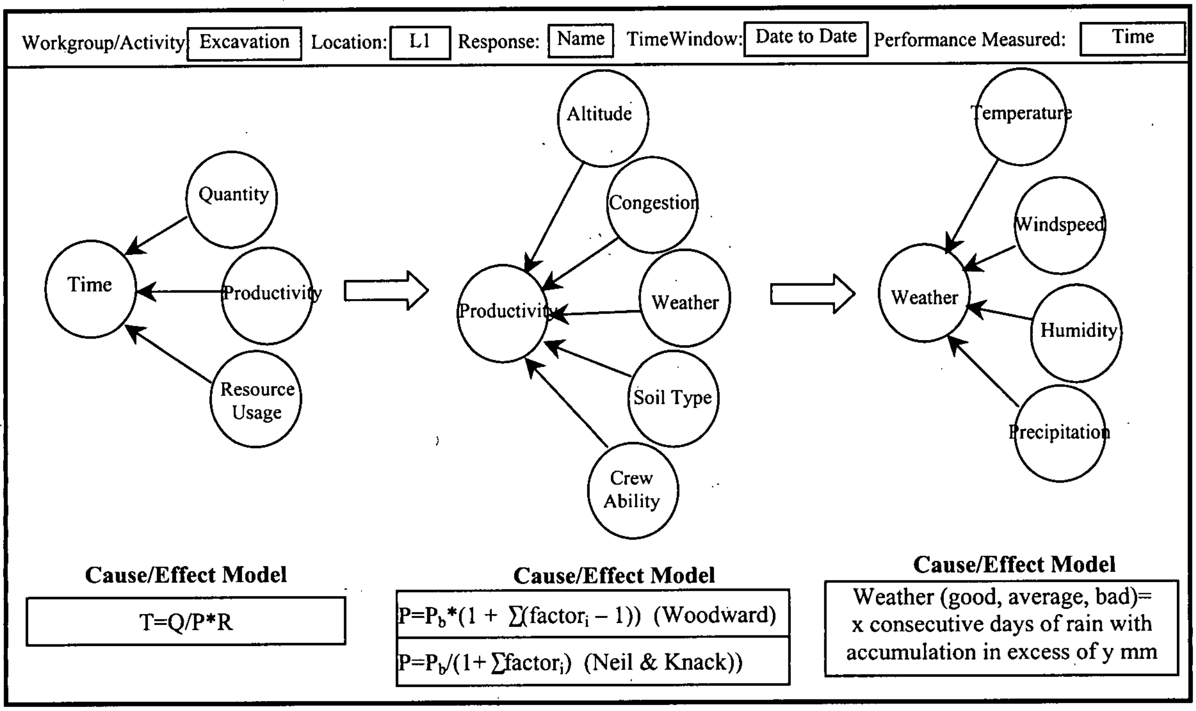

Figure 3.2 Sequence of Causal Models for Explaining Activity Duration

We have selected activity duration as our primary example, because it conforms to the ideal of having causal models that are founded on a fundamental relationship of performance and which can be expressed in quantitative form. For example, consider the relationship for estimating activity duration, $T = Q/(P \cdot R)$ in which T = activity duration, Q = scope of work, P = productivity, and R = resource usage level – e.g. days = $m^3/(m^3/mhr \cdot mhrs/day)$. This relationship is depicted in the left hand side of figure 3.2. Direct use can be made of this model to determine the variance between planned and actual for duration, and the corresponding variances for each of the factors Q, P and R. This kind of analysis is readily available from most information systems, and does not involve any causal reasoning.

However, the use of such a basic relationship fails to adequately explain the reasons for the variances observed, and must be augmented by consideration of a number of related factors. Consider for example the task of explaining the basis for the variance between actual vs. planned activity duration. Q, the scope of work is simply a surrogate for a more complex relationship amongst factors such as quantity of work, quality required, design complexity, clarity of drawings, and so on. Whether such factors should be used to modify the value of Q to achieve some equivalent standard measure or more properly be assigned to P is an issue that needs to be addressed in defining the causal model structure. P, productivity, is influenced by a myriad of factors (weather, site access, ground conditions, design complexity (also a sub-factor for Q), etc.). R is also influenced by a number of factors, such as equipment breakdown, maintenance policy, absenteeism, etc. Thus, for the model shown in figure 3.2 to be truly helpful, each of the primary factors needs to be elaborated upon. This is done for the productivity factor shown in the middle of figure 3.2.

The semantic network shown in the middle of figure 3.2 shows a causal model for explaining productivity in terms of 5 factors, which map in part onto data values within the as-built view of the project, while others have to be derived from processing other data values (e.g. congestion, measured in terms of available work area divided by the footprint of the equipment spread used). The apparent challenge now becomes to deal with factor values that involve subjective judgments on the part of construction personnel and combine them into some overall estimate of the likely value for productivity. This value can then be compared with both the actual value achieved as well as the planned value. To assist in this process, factor models like the ones proposed by Woodward (2003) and Neil and Knack (1984) can be very useful, and it is suggested that models like these be incorporated within the causal model library. These models, while simple in form, have significant appeal to construction users because they involve no complex interaction amongst factors (they are a one layer model similar to what is shown in the middle of figure 3.2), and are accompanied by a definition of possible states for each factor and an estimate of the upper and lower bound of the adjustment that should be made to overall productivity as a function of the factor state achieved. Implicit in this range of outcomes is a relative weighting of the importance of each contributing factor to overall productivity. In determining the factor state value, Woodward (2003) and Neil and Knack (1984) suggest that each factor state experienced be weighted by the percentage of time it was present, for the time window of interest to achieve some composite state value.

In the foregoing discussion, we used the phrase apparent challenge. This is because while it is desirable to produce an estimate of the magnitude of the change in the dependent factor as a function of the states encountered for the independent factors, it is not necessary to do so for our approach. We simply seek to identify those factors whose actual states would result in unsatisfactory performance, and highlight them to users as the likely reasons for that performance. As part of this process, however, it could be discovered that the factor values that explain performance were not properly accounted for when setting performance levels at the outset of the project, and the problem therefore exists with the threshold of performance expected, not with what has been achieved.

The right hand side of figure 3.2 is included to show that an independent factor which contributes to performance, but which is not a performance measure itself, can in fact represent the combined effect of a number of basic factors. Here, we focus on weather as a critical factor (see table 3.1). But the question is – how can one define weather in the aggregate? Clearly, the definition of what constitutes good, satisfactory or poor weather is a function of the context – i.e. work in unprotected areas vs. work in protected areas. Similar to the second layer of our model, one could attempt to define some kind of index to express weather as a composite factor (a possible role for fuzzy logic). But again, our approach allows us to avoid the need for this. All that is required is to identify the relevant weather factors (e.g. temperature and precipitation), and define states which result in lower productivity (e.g. excavation is precipitation sensitive if there is more than x days of consecutive precipitation and the cumulative precipitation is in excess of y mm). Then the query process generated by the causal model simply seeks out corresponding factor states, and if present, includes them as part of the 'proof' of the causal model hypothesis.

A number of observations from the foregoing are in order. First, it is desirable to have a causal model that can be built around a fundamental, quantitative relationship. Although not sufficient in itself for explaining the basis for performance, it assists greatly in structuring the model and identifying additional layers of factors. Second, it should be possible to construct factor models from other factor models (refer back to figure 3.2). Third, given a factor at any level in a semantic network, the simplest and most desirable model for that factor is a single layer one, similar to the models proposed by Woodward (2003) and Neil and Knack (1984), with none of the sub-factors connecting to other nodes in the network (i.e. each node in the network should have only one arrow leaving it). As soon as there is a high level of interconnectivity in the factor semantic network, one encounters a combinatorial problem which will not only overtax the capabilities of industry personnel, but one which is fraught with difficulty as it is not clear how to combine a 'good' state value for one factor with say a 'bad' state value with another. The reality is that we have to be prepared to work with imperfect models in order to achieve workability. Fourth, great care should be taken in defining factors that are basically redundant. For example, if our productivity factor model in the middle of figure 3.2 had included both attitude and motivation as sub-factors, we would be considering basically the same factor twice. Fifth, it is possible that a causal model can be incomplete or just plain wrong. For example, our causal model for excavation productivity is missing factors such as access, ground conditions, and equipment downtime, which means that it is unlikely to be effective in explaining reasons for poor performance. Also, as mentioned previously and again in this example, care must be taken in assigning sub-factors to the most appropriate factors and getting the definition of performance measures right. To elaborate, activity duration can be expressed as the sum of working time plus scheduled idle time plus unscheduled idle time. If this definition is used, then equipment downtime should be a factor associated with the resource factor, and not with productivity. On the other hand, if activity duration is simply defined as elapsed time, then equipment downtime should be a factor influencing productivity. Lastly, it is important to understand the nature of the output sought from the data search process. It is not to express in quantitative terms how much of the variance in the performance measure can be accounted for, by what factors, and how much of the variance can be attributed to each factor. Rather, it is simply to provide supporting evidence for factor states that would result in lower or unsatisfactory performance.

3.6 Conclusions

Findings from a thorough literature review of work to date directed at identifying factors viewed as critical to one or more construction performance measures and developing models as a function of these factors for predicting or explaining performance are described in this paper as a prelude to describing a comprehensive approach to explaining reasons for construction performance. Key amongst the findings is the following: there is no definitive model for either predicting or explaining performance; most of the models described are more research than practice oriented; and, there is no strong consensus as to the most important factors to use, what their definition should be, how best to express outcomes for them, or what the relationship amongst factors is, if any. Nevertheless, the literature review provided important insights on the current state-of-the-art, and helped to identify how best to proceed on developing mechanisms for extracting from project data reasons or explanations for performance to date. Based on previous work and an assessment of the properties that an explanation facility should possess if it is to be acceptable to industry practitioners, the authors presented a comprehensive approach to developing a computer-based architecture within which construction practitioners can define causal models which capture their experience about reasons for construction performance and which are expressed in terms of data already collected as part of day-to-day management functions. A number of issues surrounding the formulation of meaningful causal models are also described. To date, significant progress has been made on the multi-view representation and data visualization components of the approach. Current work is focused on defining causal models and expressing them in terms of generalized queries for searching the project data base for data in support of the causal model hypothesis.

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CHAPTER 4

VISUALIZATION OF CONSTRUCTION DATA*

4.1 Introduction

Construction project participants are confronted with the need to make high quality and timely decisions based on the information content that can be deduced from the very large data sets required to represent the various facets of a project through its development life cycle. How best to extract information from large data sets is a question that fascinates researchers and practitioners alike across a number of disciplines, including construction. One line of inquiry deals with data visualization, which the authors believe has special appeal to the construction industry because of its visual orientation, and because data visualization tools are directly usable by construction practitioners without the requirement for expert assistance, a potential impediment to the adoption of other reasoning schema being examined by the research community. Described in this paper is work directed at exploring how data visualization strategies, in concert with a multi-view representation of construction projects can aid decision making and provide valuable insights into reasons for construction performance. Data visualization has applicability to a broad range of management functions, and, supported by a holistic representation of a project, important learning can take place on cause-effect relations that might otherwise go undetected and/or hypotheses on reasons for

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performance to date proved or disproved. The representation of a project adopted herein involves nine project views integrated within a single system. These views are: physical, process, organizational/contractual, cost, quality, as-built, change management, environmental, and risk (Russell and Udaipurwala 2004). Examples of data visualization as they relate to the environmental and change management views are provided in the paper.

In general, visualization can be defined as the art of representing data using suitable visual formats and/or graphical images such that it simplifies and facilitates its interpretation by the intended target audience. In the construction world, there can be multiple target audiences, and the type of visual image used may vary from one audience to another depending on their comfort with 2-D, 3-D, and more complex images. For example, while construction personnel tend to be very visually oriented, often their clients are not.

Studies have revealed that the visual perceptive system of humans is much faster than the human cognitive system. Hence humans can derive information from data better and faster if it is presented in a suitable visual format. Data and information can be distinguished from one another, with information corresponding to the message(s) extracted from data. Interestingly, in the visualization literature, often the term information visualization is used, although the emphasis is in fact on the visualization of data. Representing data in a visual format "makes the human brain use more of its perceptual system for the initial processing of any data than relying completely on its cognitive abilities" (Geisler 1998). As stated by Brautigam (1996), visualization techniques "exploit the human perceptual system" as opposed to the human cognition system. Various attributes of the data of interest are mapped against certain features like color, size, shape, location or position thereby reducing the need for explicit selection, sorting and scanning operations within the data (Tufte 1990, Shneiderman 1994). These techniques thus tailor the data to be retrieved, such that the eye can quickly distinguish salient features of the data before the brain begins to process it (Brautigam 1996). This helps the target audience achieve insights faster and better as to the information content of a data set that may otherwise be concealed or not easy to comprehend from its representation in tabular or text form. For the current state-of–the-art of computerized visualization techniques, data representation is often coupled with real time interactive tools like zooming and filtering, details-on-demand windows and setting dynamic query fields, which allow users to browse through and study the represented data. Emphasis is placed on the rapid filtering of data to reduce the result sets (Ahlberg and Shneiderman 1993). This is called visual data exploration. Thus, visualization can be described as a two-fold process of data presentation and data exploration.

4.2 Significance of Application of Visualization to Construction Environment

Construction projects involve voluminous data sets. A project's database may contain data varying from textual form such as drawing specifications and contractual clauses, to quantitative data like number of change orders and related properties dealing with value, timing, number or participants, etc., RFIs issued and turn around times, drawing control data, schedule information pertaining to dates and activity durations (planned and actual), weather conditions on site, and cost breakdowns. The data is generally time and location variant and originates from multiple project participants. The sheer volume and nature of the data pose significant management challenges. Further complicating these challenges is the observation that construction data is often poorly organized because it lacks proper grouping and sub grouping which can lead to missed opportunities to associate related data or facts. For effective management of a project, efficient handling, monitoring and control of all project data is essential. Buried within this data are important messages which relate to the reasons for performance to date, but extracting this information from any database, especially a poorly organized one can be very difficult (even if a database is well organized, linkages amongst different data items may not be obvious – data visualization may in fact help one forge relevant links). As a consequence, explaining different aspects of construction project performance often qualifies as a classic case of "data rich - information poor" problems (Songer and Hays 2003). Thus, the massive amount of data available to management personnel results in information overload (Songer and Hays 2003) unless it is accompanied by a high level of organization and accompanying reporting mechanisms.

Effective visual representation schema assist the efficient scanning of different parts of a project's database, allowing users to instantly "identify the trends, jumps or gaps, outliers, maxima and minima, boundaries, clusters and structures in the data" (Brautigam 1996). Exploration tools allow continuous interaction between users and the graphic displays by offering scope for "constant reformulation" of search goals and parameters as new insights into the data are gained (Ahlberg and Shneiderman 1993). It provides a continuously updated information platform to users, thereby aiding the decision making process from project conception to completion of construction, the timeline of interest in this paper.

4.3 Visualization Technologies

Based on a literature review, it is observed that the field of visualization has evolved tremendously from classical graphs and diagrams to the current array of computerized interactive visual aids. Over the past decade, a number of visualization techniques have been developed and enhanced to achieve a range of objectives and increased scope of application. In this section the authors provide a brief overview of the current state-of-the-art of these techniques, their working principles and sample software applications, although this treatment is not exhaustive. Several authors have tried to classify visualization techniques using various schema. Earliest amongst these was classification by the data type(s) that they can represent, proposed by Shneiderman (1996), who further proposed another classification framework on the basis of the type of user interactive tools offered by a given technique like overview, zoom and filter, details-on-demand, etc. The intent of proposing this latter classification was to identify techniques that could fulfill a specific analytical task desired by the user. Different interactive tools offer different analytic capabilities like clustering, comparing, and identifying patterns within the data, thereby assisting users to gain deeper insights into the data. In selecting a visualization technique for a certain application, users need to resolve two predominant issues: the data type(s) the technique can represent; and, the kind of user interaction it offers for analytic purposes. In order to satisfy both of these fundamental user concerns, Qin et al. (2003) combined the two classification frameworks proposed by Shneiderman to put forth a matrix framework (Table 4.1) where visualization techniques are situated in a cell depending upon which data type they are applicable to and what analytical tasks they offer to users for interaction.

Table 4.1 Visualization Techniques, Working Principles and Sample Software Applications (Qin et al. 2003)

Analytical Task Data Type	Overview-query	Comparison	Cluster-classification	Distribution pattern	Dependency-correlation analysis
1D					
	Animation; LifeLine; Line graph; Color map; Curve density plot	Pie plot; Line graph	Color map; Curve density plot	Value bar; Curve density plot; Histogram	
2D					AViz
	Geographic map; Scatter plot; Color map	Geographic map; Scatter plot	Color map	Isogramplot	
3D	Visible Human				
	Volume rendering; Scatter plot	Scatter plot	Color map		
Multi-dimensional	GrandTour		WinViz; HD-Eye	GrandTour; Project pursuit, FastMap	
	Table Lens; n-Vision; Scatterplot Matrix; Star glyphs	Andrews Curve; Star glyphs	Parallel Coordinates; InfoCrystal	Circle Segments; InfoCrystal	Scatterplot Matrix; Dimension Stacking
Hierarchical					
	Hyperbolic view; Magic Eye View; Cone Tree; Disk Tree			Treemap; Information Cube	
Graph	WebBook WebForager			NetMap	WebView
	DA-Tu; Fisheye view				
Text/hypertext					NetMap
	Perspective Wall; Document Lens	TileBars	InfoCrystal	TileBars; InfoCrystal	

The two-dimensional classification framework shown in Table 4.1 has data type (1D, 2D, 3D, Multi-dimensional, Hierarchical, Graph and Text/hypertext) as one dimension and analytical tasks (overview-query, comparison, cluster-classification, distribution pattern and dependency-correlation analysis) as the other. 'Outlier analysis i.e. identifying outliers in a data set forms a part of cluster classification as clusters and outliers are cross problems' (Qin et al. 2003). Visualization techniques and/or software applications are grouped in cells depending upon which data type they can represent and the corresponding analytical task they offer to users. Some visualization techniques like 'Perspective wall' or 'Cone trees' are suitable for only a specific data type and a specific analytic task and hence occur only in a single cell in the table, while other techniques like 'Colormaps', 'Scatter plots' are applicable to several data types or analytic tasks and hence appear in several cells. For clarity, each cell is divided into two sections: the top section lists names of specific software applications where appropriate, while the lower section contains the names of visualization techniques. An interesting observation made by Qin et al. (2003) is that techniques for deeper analysis are much fewer than those for overview-query and comparison.

4.4 Applications of Visualization in Construction

In carrying out the literature review on visualization techniques, the authors also undertook to identify the extent to which they have been applied to the field of construction, with the focus being primarily on the visualization of contruction management data as opposed to visualizing the physical artifact to be built for purposes of constructability reasoning or workability of the methods selected for its construction (e.g. Staub and Fischer 1998). Somewhat surprisingly, there is very little literature that addresses visualization of construction data, either using conventional representations or some of the more avant-garde techniques developed and advocated by computer scientists.

Songer and Hays (2003) addressed the issue of managing project control data using Treemaps and other visual aids like scatterplots and histograms. They described an iterative process of structure-filter-communicate while considering level of detail, density, and efficiency of data representation. Russell and Udaipurwala (2000a) (2000b), (2002) used linear planning charts to help with assessing schedule quality and schedule updating strategies, 2-D and 3-D graphs to represent the distribution of resources in time and space, stacked 2-D graphs to assist with explaining activity performance to date as a function of site conditions encountered, and 3-D graphs to portray problems encountered in time and space and their consequences.

For the remainder of this paper, the authors treat two different phases of a project and participant viewpoints to illustrate the types of insights that can be achieved through data visualization. The thought processes described and accompanying images for these scenarios can be readily adapted to the exploration of other mangement functions and project data types. For the first combination, the authors examine the client's perspective on decision making as to the most suitable procurement mode and formulation of contractual terms. For the second, the authors examine the contractor's perspective on change order management during project execution, and possible impacts on project performance. The two examples given are illustrative of the kinds of situations often encountered on capital projects, and which can be missed because of a preoccupation with individual items as opposed to the collection of many items and related patterns of occurrence – i.e. there can be a failure to see the big picture. This in turn can lead to several undesirable situations, including an underestimation of consequences, failure to initiate corrective action in a timely way, delays, management burnout, loss of entitlement, and loss of reputation, to name a few.

4.5 Using Images to Model Environmental Risk Drivers

The identification and management of risks arising from a project's environmental context is vital to project success. Failure to manage such risks can lead to adverse impacts on performance measures such as cost, duration, revenue, scope, safety and quality. In extreme circumstances, it can even lead to the termination of a project. One or more attributes of an environmental component (environmental view of a project) separately or in combination with the attributes a physical component (physical view of a project) and/or those of an activity or a group of activities (process view of a project) can act as risk drivers for a risk event, and the likelihood of its occurrence and quantum of consequences can be dependent on whether or not they share the same site location and/or participant responsibility at the same time, as shown in Figure 4.1. The challenge becomes how to detect the confluence of these attributes.

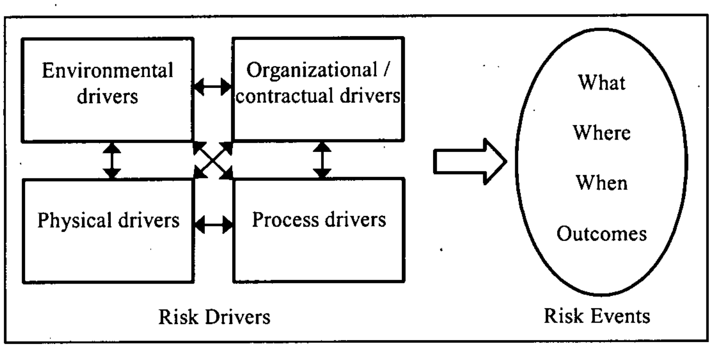

Figure 4.1 Risk Drivers and Events

A projects' environmental context is comprised of the natural and man-made environments. Here the focus is on the natural environment. In most jurisdictions, the requirement exists to carry out an Environmental Impact Assessment (EIA) prior to undertaking a construction project, and a wide array of environmental components must be examined, as illustrated in the hierarchical environmental breakdown structure (EBS) depicted in figure 4.2(a). Each component of this structure can be described in terms of a number of attributes, and depending on the presence of these attributes and their value at a specific location, the potential for one or more risk events may result (figures 4.2(b) and 4.2(c)).

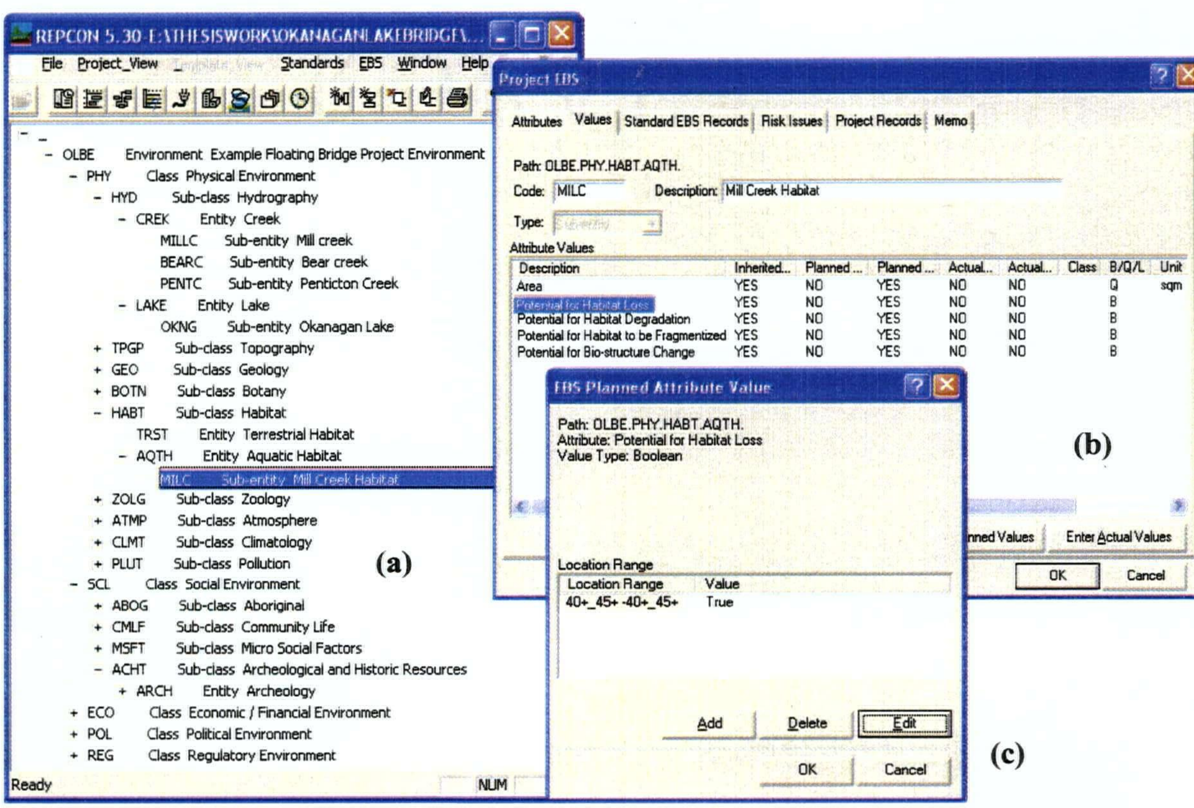

Figure 4.2 (a) Environmental Breakdown Structure (EBS); (b) Environmental Component Attribute Definitions; (c) Attribute Value.

Visualization techniques can be very helpful for comprehending the distribution of environmental risk drivers in time and space and assignment of responsibility for their management. The resulting images can be augmented by superimposing additional data in terms of the timing and placement of physical components and related construction activities, thereby assisting in the identification, quantification, mitigation and assignment of risks. Overviewed here is current work by the authors directed at developing a detailed specification as to how best to represent various aspects of the environmental view of a project in visual form. Shown in figure 4.3 is an innovative 3-D histogram that depicts the number of environmental risk drivers in time and space and by assigned responsibility.

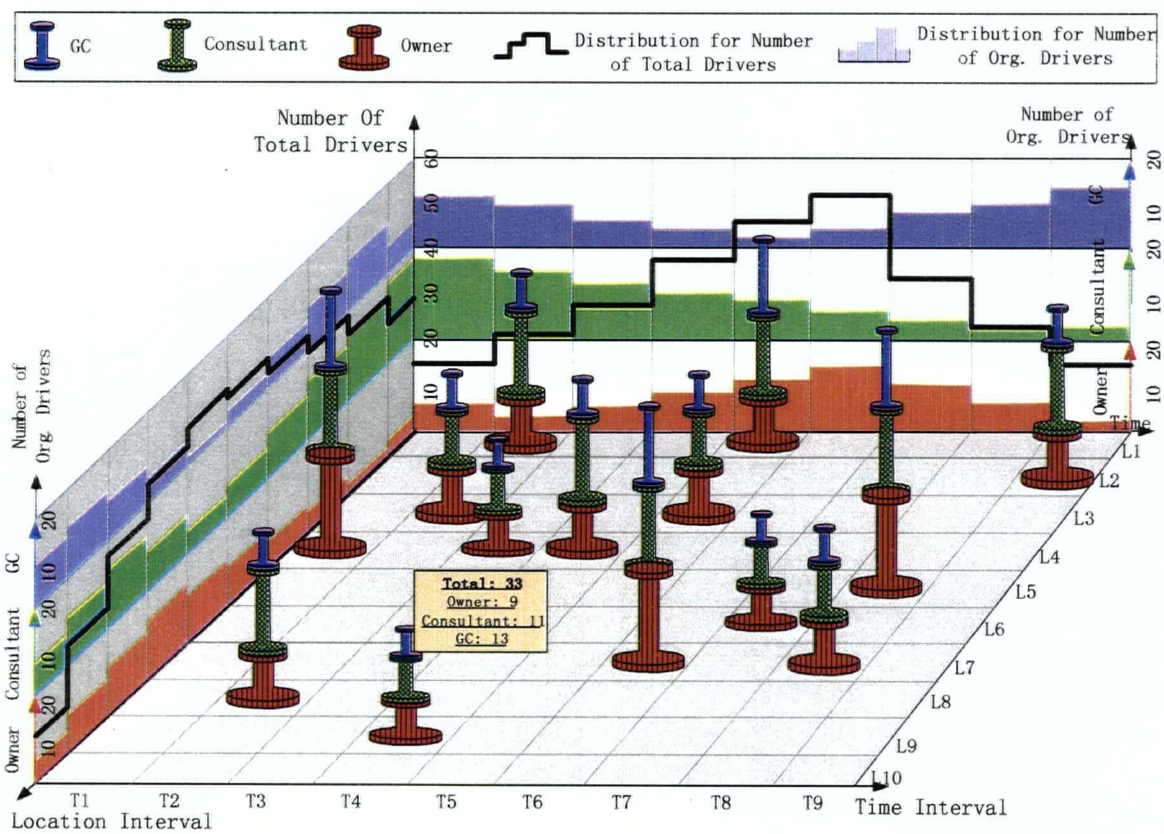

Figure 4.3 Distribution in Time and Space and by Responsibility of Environmental Risk Drivers

Each of its two horizontal axes represents respectively, the project location and time, both of which are treated as intervals instead of specific instances. The interval of these location and time could be reduced or increased as necessary. The vertical axis from the origin point of the three axes represents the number of total drivers while the other two vertical axes at the end of their respective horizontal axes represent the number of drivers by responsibility (e.g. owner, consultant, general contractor) integrated across time and space, respectively.

One common issue in risk identification is the need to know how many risk drivers exist within a specific time interval and at a specific location. This information is readily available by examining each tower shaped column in a time/location cell. The number of organizational drivers for different project participants is represented using different colors, thereby capturing an additional dimension within the 3-D graphs. For example, focusing on the intersection of time T4 and location L9, reveals a tower shaped column with three colors: red for drivers managed by the owner, green for drivers managed by the consultant and blue for drivers managed by the general contractor (in fact for this example, a combination of color and different shaped/sized icons is used). If precise information about these numbers is needed, they can be made to appear in a small information box as shown on the graph by briefly suspending the mouse on the column of interest. A second issue of interest to users is the distribution of the total number of drivers according to time and location, with a further breakdown by project participant. This information is given on the two "side walls" of the graph. Distributions for the number of organizational drivers are shown in different colors while the distribution for total number of drivers is shown by the heavy black lines. For the case when many columns exist making it difficult to scrutinize the distribution information put to the side walls, a 3-D view control box is provided so that the graph can be rotated and the required information made completely visible.

Users are interested in not only how many drivers exist in a specific time and location cell, but also the identity of these drivers and their attributes. To get this information, users should be able to click the hyperlinked text in the small information box being shown in figure 4.3. This will result in a separate window popping up with a hierarchical structure for drivers visualized as shown in figure 4.4(a) using the Magic Eye View technique (Kreuseler and Schumann 2002), a method by which all of the hierarchical nodes are distributed on the surface of a hemisphere. For example, if you click "Total: 33" in the box in figure 4.3, a hierarchical structure with total of 33 drivers will pop up while if you click "Owner: 9" a hierarchical structure with a total of 9 drivers for which the owner is responsible will pop up. If the responsibility for a driver is shared amongst two or more project participants, the driver will be included in the count for each organization but it will only be counted once in terms of the total number of drivers for its corresponding time and locations interval. This hemispherical hierarchy could also be rotated so that nodes of special interest are focused on, as shown in figures 4.4(a) and 4.4(b). By suspending the mouse on one of these nodes for a second, the attributes for that specific driver would pop up in a small information box giving attribute name, value, and location (e.g. archeological site area within a section of a highway corridor or potential = 'TRUE' for habitat degradation within a stream bed).

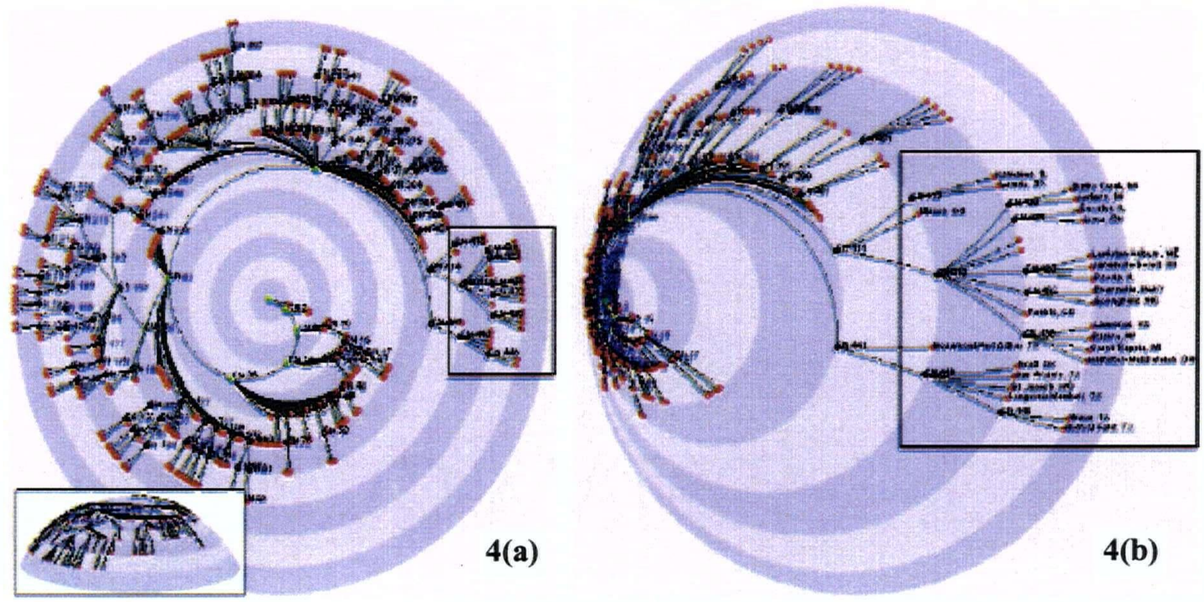

Figure 4.4 (a) Hemispherical Hierarchy; (b) Focused Hemispherical Hierarchy (From Kreuseler and Schumann 2002)

4.6 Applying Visualization Techniques for Change Order Management

In this section, an example is provided of the kind of insights that data visualization can offer for the function of change-order management from the perspective of the general contractor or construction manager. Changes and change orders are an inevitable part of any construction project. They can have a significant effect on a project and its participants in terms of productivity, and overall project performance. Further, they can give rise to contentious disputes because of their cumulative impact on the efficient execution of other work, and the additional load placed on management staff. Various researchers (e.g. Hanna et al. 2004, Ibbs 1997, Thomas and Napolitan 1995) in the past have tried to quantify these impacts as well as the properties of change orders that have the most adverse consequences for performance. Interestingly, however, the subject of change order management is seldom discussed in the literature. The focus in this paper is on demonstrating the value of visualization in helping to determine if clustering of change orders is occurring in one or more of time and space or by project participant, which could in turn explain in whole or in part performance difficulties at different levels of the project (e.g. trade level, overall project level). This focus forms part of a larger ongoing research effort directed at a change order management view of a project and its relationship with other project views.

A change order may be regarded as a separate information entity that can be tracked in an information system. It has a number of properties, including associations with components or information entities that define other project views. Some of these properties are specified by system users, others are derived by the system based on information provided (e.g. durations). A partial list of change order properties is provided in Table 4.2.

Table 4.2 Selected Properties of a Change Order

Change order (CO) property	View	Data type	Source
CO ID (identity)	CO Mgmt	alphanumeric	User
Date CO process initiated	CO Mgmt	date	User
Date CO approved (cancelled)	CO Mgmt	date	User
Duration of CO initiation/approval process	CO Mgmt	number	Derived
Reason for CO (client initiated, design error/omission, …)	CO Mgmt	alphanumeric	User
Date CO work started	As-built	date	User
Date CO work completed	As-built	date	User
Duration of executing CO work	As-built	number	Derived
Number of consultants involved with CO	CO Mgmt	number	Derived
Identity of consultants involved (e.g. Architect, structural engineer, …)	CO Mgmt	alphanumeric	User
Number of trades involved with CO	CO Mgmt	number	Derived
Identity of trades involved (e.g. GC, mechanical, electrical, …)	CO Mgmt	alphanumeric	User
Basis for payment (lump sum, unit price, time & materials, …)	CO Mgmt	alphanumeric	User
Base cost of CO and cost breakdown, exclusive of impact costs	CO Mgmt	numbers	User
Estimate of impact costs of CO if applicable	CO Mgmt	number	User
Physical component(s) of project affected by CO and locations	Physical	alphanumeric	User
Long lead time procurement items associated with CO	Physical	alphanumeric	User
Procurement item procurement sequence	Process	alphanumeric	User
Association with existing schedule activities	Process	alphanumeric	User
Number of existing activities affected	Process	number	Derived
Association with new activities as a consequence of CO	Process	alphanumeric	User
Number of new activities as a consequence of CO	Process	number	Derived
As-built problems associated with CO	As-built	alphanumeric	User
Identity of existing drawings revised due to CO	Physical	alphanumeric	User
Identity of new drawings due to CO	Physical	alphanumeric	User
Number of RFI's associated with CO	As-built	number	Derived
Identity of RFI's associated with CO	As-built	alphanumeric	User

As indicated previously, rather than focus on the properties of an individual change order, here the authors show how data visualization can provide a 'big picture' of what is happening to a project in the way of changes during its construction phase. An implicit causal model underlying the images given is that the possible impact of change orders is likely to be highest if they are clustered simultaneously in time, space and by project participant. In presenting these images, use has been made of an actual data set in terms of number of change orders (122), value, timing and location. Further, to ensure clarity of the image, coarse definitions of time and space have been used. Time is measured in months. In terms of monthly count of active COs, a CO is counted for as many months as it is active. In terms of its value, it is distributed uniformly over its duration. Locations have been aggregated into three: on site, off site, and both on and off site, with the reasoning being that offsite CO's would not contribute to productivity loss or congestion on site. From the viewpoint of developing visualization schema, it is observed that it is important to allow for different granularities in the definition of time (e.g. day, week, month), location (individual, group of locations, class of locations), project participants (individual, by group, by class – e.g. consultants, trades, suppliers), and so on.

Figure 4.5 provides a visual representation of the change order history of a project in terms of CO identity (a simple number in this case), the months in which it was executed, and the monthly expenditure in terms of base costs (no impact costs included). All the change orders executed during a month are mapped against one color to add clarity to the image. The resulting image demonstrates that most of the change orders are clustered in the latter stages of the project, although a significant share of the total value of CO work was performed earlier and was associated with just a few COs.

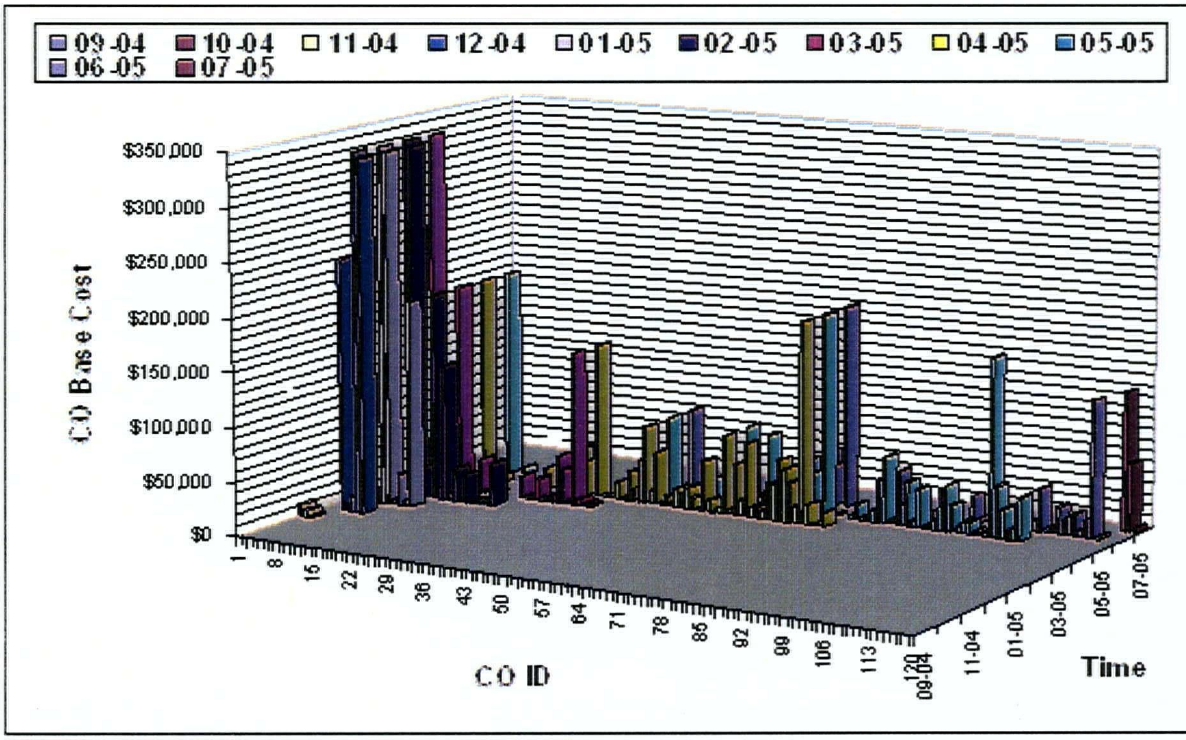

Figure 4.5 CO History in terms of CO ID, Timing and Value of the Work

Figure 4.6 provides a deeper insight into the project's set of COs and perhaps tells a more compelling story than figure 4.5. In this image, each project participant is mapped onto its own colour. The participants are stacked over one another in a predefined order. In this case we have dealt with five participants in total, three on-site trades, Trade A, Trade B and Trade C, and two fabricators, namely Fab X and Fab Y. The vertical axis represents the number of COs active for a specific participant in a given month (a dollar value axis could also have been used). The COs have also been sorted according to their location along X-axis. This makes the available information easier to assimilate. A single cell in the horizontal plane of the graph yields the project participants involved, the number of COs active per participant, the active month and the location of the COs. For instance, the arrow in the figure indicates that in the month May-05, Trade B had 7 active 'On-site' COs.

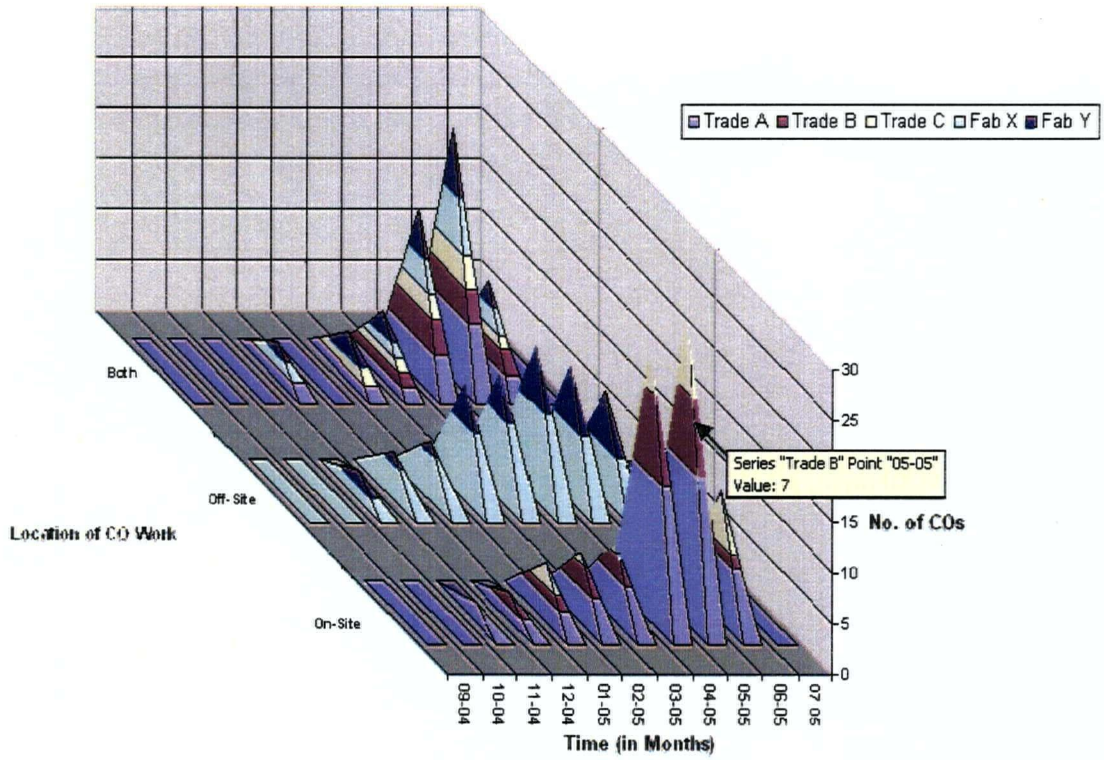

Figure 4.6 History of COs by Location, Time, Responsibility and Number

Figure 4.6 highlights one of the challenges involved in formulating visual images which maximize the clarity and visibility of the data represented. For larger datasets such as this, if vertical columns had been used, the taller columns in the front of the image would obstruct the view of the bars in behind, thereby hiding much of the content of the image. To avoid this problem, we experimented with the use of cones and pyramids, and found the latter provided the most pleasing and useful image.

For the visual images in figures 4.5 and 4.6 various CO attributes were mapped against colour and location in 3D space, thereby allowing significant insights to be derived form the CO data. However coupling the current images with interactive tools like 'zooming and filtering', 'details-on-demand windows' or setting 'dynamic query fields' would increase the scope for data analysis and provide deeper insights into the data. For example, clicking on a particular CO in figure 4.5 would pop up a 'detail-on-demand window' with CO properties selected from the list in table 4.2 and contained in a user defined content profile. Figure 4.6 illustrates a very basic example of such a pop-up window displaying the trade name (Trade B), the month of interest and the Number of COs associated with the trade. Further, by introducing filtering techniques, users would have the flexibility to view only data of current interest: e.g a time window of September-04, 'Off-site' COs only, and work by Fab X only. Such selection and filtering capabilities help management pinpoint specific issues and help with decision making directed at resolving existing or emerging problems.

4.7 Discussion and Conclusions

A number of challenges exist when implementing visualization techniques to represent construction data. Two of them are described here. First, it is important to provide a number of visualization techniques for the same data. Different users have different preferences and capabilities for the visual format that yields the greatest insights or most information content. For example, 2-D drawings are still preferred by most people working in industry, with growing interest in 3-D model being shown in a few organizations – thus both formats should be treated. These formats should also be supplemented by being able to view simultaneously more traditional formats, such as data tables. Additionally, impediments to using visual images such as color-blindness need to be considered, and compensated for by using different shapes to represent data components instead of just relying on colour coding. A second challenge is the loss of interaction when moving from the screen to hard copy form.

As stated previously, interaction is a vital tool for exploring efficiently large data sets on screen using different formats, viewing angles, and so on. Effectively, the screen interactive mode should be used to explore the data in order to determine its information content and then determine which format (2-D, 3-D, colour, scaling, rotation, etc) portrays the information context most clearly. It is this image that should then be produced in hard copy format. Unfortunately, some of the benefits of data visualization are lost when moving from interactive to hard copy mode.

In conclusion, a brief overview of the current state-of-the-art of data visualization techniques and several of the advantages of data visualization that relate to the perceptive as opposed to cognitive processes of humans is provided. Two distinctly different decision/reasoning contexts illustrated the value that data visualization techniques offer in terms of extracting information from the large data sets that characterize construction projects. By combining such techniques with a holistic representation of a project and related data, the potential exists to develop a potent tool for assisting construction management personnel and other project participants improve their decision making and their understanding of the reasons for project performance to date. In the near term, the authors will be focusing on developing a number of causal models or hypotheses for explaining construction performance (e.g. productivity, delays) and how aspects of these models can be represented in one or more visual images to assist in determining the validity of the hypothesis put forward about performance levels achieved. Further images relevant to other management functions as they relate to quality and risk management will also be explored. The most promising of these will be fully implemented and field-tested on actual projects.

4.8 Acknowledgement

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CHAPTER 5.0

EXPLORATORY IMAGES FOR EWO'S/CO'S

5.1 Motivation

Through a thorough literature review of different visualization techniques as described in the previous chapter, we gained significant insights on the current state-of-the-art of visualization techniques. Having experimented with different visual formats to represent aspects of an actual change order dataset from a previous project, we decided to take this a step further and explore a broader range of images for a more comprehensive dataset of an on-going project.

We discussed our previous work with Scott Construction Group, a successful mid-sized general contracting and construction management firm located in Vancouver, B.C., whose annual volume is in the range of $50 – $100 million per year. Their interest in our work led to the acquisition of a more extensive change order dataset for a complex rehabilitation project (the Iona Building), one of the two major projects Scott is currently involved with (2004-2005) on the University of British Columbia campus.

5.2 Project Description and Challenges

The Iona Building is an existing 7 storey heritage building occupied by faculty and students of the Vancouver School of Theology. It is located on Iona Drive off of Westbrook Mall and south of Chancellor Boulevard on the UBC campus. The project involves renovation of the existing structure including structural upgrading and interior reconfiguration. The overall building program includes demolition and replacement of most of the interior, including building services such as mechanical, plumbing and electrical systems, and replacement of the windows (CFT Engineering Inc. Report 2004). The initial estimate for the work was approximately $7.5 - $8 million, and the final cost is likely to be close to double this amount because of the number of changes. The Scott Construction Group was engaged as the construction manager for the project, with trade contracts being signed between the client and each trade.

Being a renovation project, it faces several challenges in terms of inadequate as-built drawings, and non-compliance with current seismic standards, fire-rating requirements, handicapped access, and so on. Work on this project commenced in January 2004 and as of June 2005 it is currently past its targeted completion date by over 10 months. The project has experienced a continuous flow of extras and corresponding changes over its entire period of execution. Though project characteristics like type and size of project and project delivery mode have a significant impact in terms of the schedule and budget, changes and extra work are amongst one of the major factors affecting a project's outcome in terms of cost and schedule. Other factors such as temperature, precipitation and site conditions, which may or may not trigger extra work or changes, also affect project performance. Our focus for this case study was to identify the distribution of extras and changes in time by number and dollar amount, their concentration in terms of trades affected, and reasons for initiating these changes, using visual formats to help enable construction management personnel, design consultants and the client to identify probable causal relationships that exist between the distribution/concentration of extra work orders/change orders and performance outcomes in terms of delay in the project completion time and cost over-run (actual completion date and cost versus original targeted completion date and project budget). The visual formats thus developed can also be used to help validate user-defined hypotheses about reasons for performance outcomes, in the context of the project's dataset.

5.3 Methodology

As a starting point, we examined various datasheets and records to try and understand the nature of the datasets we were dealing with, project management procedures employed for the project, documentation procedures adopted, and flow of information between different documents/records and project participants. While our original intent was to look at the RFIs and SIs, we migrated to the treatment of extra work orders and resultant change orders, a topic of significant interest to the Scott Construction Group. The sheer volume of the extra work orders generated (402 as of June-05) and their occurrence frequency has made change order management on this project a challenging task, including communication with the client. Our work focused specifically on extra work orders issued and subsequent change orders generated, their properties and their connection with other project documents/records. As part of our work, we have to deal with the realities of actual practice, including the observation that data sets are invariably incomplete. Since the primary intention of project management staff is to maintain momentum on the job, keeping and updating records in a comprehensive manner often takes a backseat. Thus, data records for many of the extras generated on this project were found to have certain missing properties in terms of trades affected, issue date and/or date of approval, when was the work actually completed, dollar consequences for each of the affected trades, etc. Our work is focused mainly on visualization of datasets. However, the usefulness of visualization is dependent on the completeness of the data set. Hence as a starting point for our work, we had to search out missing data to the extent possible for the spreadsheets used for project control. As part of our research work, we seek to provide end users with an ability to assess the impact of a collection of items or of their occurrence pattern on project performance as opposed to dealing with individual items. To do so, we made use of relevant and associated documents like the contract register, site instruction and RFI record lists, we reviewed individual SIs and RFIs, and through discussions with on and off-site management personnel, we tried to track the missing links in the data to the best of our ability. This allowed us to cluster data items using different attributes such as location of the work, physical system affected, trades involved, turnaround times, etc., thereby yielding more insightful visual formats. We were able to accomplish this because of the direct access provided to the site, site records and management staff. Moreover, the staff members were enthusiastic in offering their comments and providing us with prompt additional information as and when required.

Another practical issue deals with the form of the datasheets used by the firms and the linkages that exist between them, if any. In terms of Scott's current practice, spreadsheets seem to be the computer software tool of choice because of their flexibility and the seeming difficulty of imposing a single system in the firm. Control documents like the extra work order registry, contract registry, SI and RFI master lists were kept in independent spreadsheet formats, and lacked direct linkages between them. For the Iona project, different management personnel maintain different control documents. Since the project is a construction management project, individual trades have separate contracts with the owner and hence each of them keeps separate records to track individual changes/extras affecting them. Additionally, all of the SIs, though initiated by different consultants, have to be finally signed off by the architect. Hence the architect maintains the entire list of SIs. Scott management personnel generate the RFIs and hence keeps the master list of RFIs. Scott's construction manager (there was a separate project manager retained by the client) is responsible for maintaining the records and updating the master list for the extras issued, a copy of which is kept by the site superintendent as well for quick reference. Seemingly there is no central hub for the documents, and hence no coherent paper or electronic representation of the project is available.

5.4 Role of Visualization

As for most projects, the construction manager (or contractor) faces a challenge on an ongoing basis in trying to explain to the client reasons for increases in the budget of the project and its projected time of completion based on the available datasets. Effective visual representation of available data can assist end users to instantly "identify trends, jumps, or gaps, outliers, maxima and minima, boundaries, clusters and structures in the data" (Brautigam 1996). Visual images therefore have an immense potential to not only serve as a data interpretation method but also as an efficient communication tool. We therefore sought to demonstrate to management staff the potential benefits of being able to visualize available project data to assist in identifying probable cause-effect relationships that exist between extra work orders as they cluster in time, space or by project participant and performance outcome (budget and time), and explain to the owners and other project participants likely reasons for project delay and/or increases in the budget.

5.5 Developing Images

As discussed earlier, considerable understanding of the current-state-of-the art of visualization techniques was gained through a thorough literature review. However the literature search revealed that that no standard procedures exist to determine how best to represent a given data set to maximize the insights that can be extracted from it. Thus making a choice of a visual representation for a given dataset is basically experimental in nature, and what might appeal to one project participant might not appeal to another.

The extra work order data set available for this project is in the form of a change order registry, a copy of which is provided in Appendix B. We note that very considerable effort was expended to provide as complete a data set as possible. While allowance had been made by the construction manager for a number of data fields in the spreadsheets set up for the project, in many cases values were not recorded by the construction manager. Emphasis was placed by management staff on what was essential for processing individual items, as opposed to examining the properties of the entire collection of changes. At the time of writing of this thesis, the Iona project was still in progress and continued to experience an ongoing flow of extras. For the purpose of our work, we chose the time frame from the commencement of the project in January 2004 to the end of December 2004. This choice was made because of the significant amount of work involved in searching through project records in order to generate as complete a data set as possible (i.e. find as many values as possible for the various properties identified for a change order). In accordance with our chosen time frame, the CO registry in Appendix B documents extra work orders up to the end of December-04 only. In examining the available data in terms of extra work order properties and their potential for impacting project performance, we have generated a series of visual images based on several underlying implicit causal models of time performance (e.g. slow decision making results in increased project duration). For all of these images time is defined in terms of months. From the viewpoint of developing visualization schema, it is important to allow for different granularities in the definition of time (e.g. day, week, month), locations (individual, group of locations, class of locations), project participants (individual, by group, by class – e.g. consultants, trades, suppliers), and so on.

The images in the following sections were developed using Microsoft Excel as the basic software tool to generate graphs. For the 3D graphs, individual images generated through Excel were pasted together in Microsoft Paint in order to get the desired third dimension. For the case of 2D graphs (figures 5.4, 5.5 and 5.7), Paint was used to either superimpose different images generated and/or stack the graphs thereby adding more content to the visual format in order to maximize the insights that can be extracted from the image. There are numerous other ways to represent the information presented here using more avant garde visualization techniques. However, such representations often need trained personnel to generate the images and also to interpret the information represented. Part of our research goal is to introduce visualization techniques/strategies to construction management personnel as an easy data interpretation tool requiring no expert assistance. The choice of visual formats (3D graphs, 2D graphs, stacked graphs, scatter plots etc.) in the following images is completely exploratory, and as noted previously, underlying the choice of each image is an implicit causal model of time performance. The scale and orientation of the images and the size, shape, colour and location of the data items is solely driven by the need to achieve maximum visibility of the data and optimum readability of the graphs.

5.6 Images

Figure 5.1 deals with turnaround times in regards to the issuance and follow-up approval of extra work. Only extras issued up to December 2004 are included, with their formal approval dates extending to May 2005. In this case, the Y-axis indicates the time by month when the extra work order was first issued while the X-axis indicates time when it was actually approved. The Z-axis corresponds to the number of extra work orders affecting different trades. This figure helps us understand the time lag between the issuance of an extra and its final approval. In the figure, the diagonal on the graph floor has been highlighted in red. Specifically, items that fall on the diagonal indicate approval of a change issued in the same month, the optimum in terms of efficiency. The further that changes fall off of the diagonal, the longer the lag time, and the greater cause for concern for delays in project completion. However, care must be taken in interpreting the figure, because of other considerations. For example, for the Iona project, often approval of a change order was given verbally, with written approval being received through a batch processing of a group of extras. Another important issue in this case is that a fair number of changes have no issue date and/or date of approval associated with them. It is therefore difficult to determine their turnaround times and hence the 'diagonal-rule' does not apply to them. Since extras corresponding to zero dollar value need no approval (except if a time delay is involved), they are not accounted for in this image. For this particular image, the initial idea was to have time of issuance on the X-axis, which also is indicative of the project progress timeline, and the time of approval on the Y-axis. However, we observed that the foregoing axes definition would result in taller pyramids in the front of the image that would obstruct the view of the data items in behind, thereby hiding much of the content of the image. We therefore decided to have time of approval on the X-axis and the time of issuance on the Y-axis. This kind of experimentation was involved for most of the images explored to date.

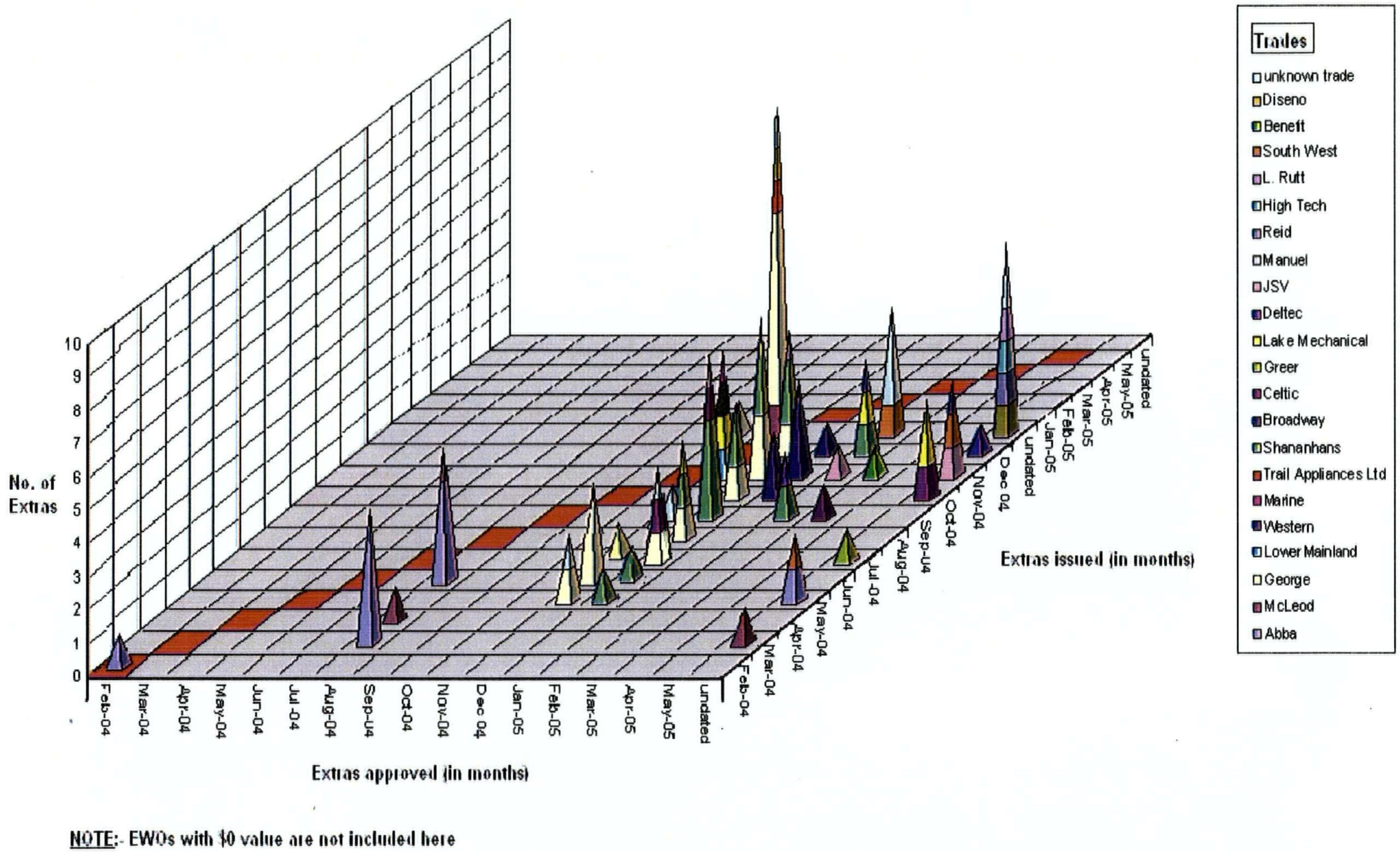

Figure 5.1 Turnaround Time for Extra Work

Figure 5.2 represents the distribution and reasons for the extra work. This figure can help the user determine the distribution of changes over time; trades affected and also assign responsibility for these changes based on the reasons initiating these changes. For instance, the responsibility for the two 'Owner initiated' changes in the month of November 2004 affecting two different trades can be directly assigned to the owner/client. Figure 5.2 is developed based on a refined dataset. In the original dataset, the construction manager had used a suite of six reasons and allowed for a many to one relationship – i.e. many reasons to one extra. Some of these reasons overlapped to a certain extent, creating some ambiguity in interpreting the data. Upon seeing a first draft of the figure, management personnel realized they needed to adopt a less ambiguous set of reasons which led to the use of 4 instead of 6 reasons, provide better definitions of the scope of each, and allow only a one-to-one relationship. The CM revised the dataset, which provided the basis for figure 5.2. The foregoing observations speak to the challenges of having data accurately, unambiguously and completely collected while it is current, a non-trivial task given the preoccupation of management to maintain momentum on the job. On figure 5.2, the X-axis represents time in months when an extra was issued. The right most section on this axis flags time as 'undated'. The extras included in this section are the ones for which the issue date could not be identified. The Y-axis divides the entire graph into 4 separate zones depending upon the reasons for the issued extras. It is observed that every extra work order in the datasheet has now been allocated a single reason for issuance. The vertical axis (Z-axis) represents the total number of extras affecting different trades issued in that particular month as in the case of the previous image. Trades have been colour coded. Most often an extra work order corresponds to a single trade. However, in some other cases it corresponds to multiple trades. In such cases the extra gets 'double counted' for that month. Therefore the peaks of the pyramids in the figure do not necessarily correspond to the total number of extras issued in a month. For instance, in the month of July-04 there were a total of 14 EWOs generated as a result of 'Design Change', ten of which were zero dollar changes, one change affected the trade Greer, another affected the trade George, and one affected an unknown trade. Thus, thirteen out of a total of fourteen EWOs have a one to one relationship with the trades affected. However one out of the fourteen EWOs (EWO ID: 17043) affected two trades, namely 'George' and 'Celtic'. Thus in figure 5.2 this EWO is double counted, once for 'George' and once again for 'Celtic'. Thus, though a total of 14 EWOs were generated due to the reason Design Change in July-04, the corresponding pyramid in figure 5.2 shows a total of 15 EWOs. We observe that if the facility to generate an image like that shown in figure 5.2 was to be incorporated into project management software, then the option to include a breakdown by trade should be included, and a footnote automatically included in regard to the double counting issue. On the other hand, if the breakdown by trade was not chosen as an option, then the correct count of change orders would be shown on the figure.

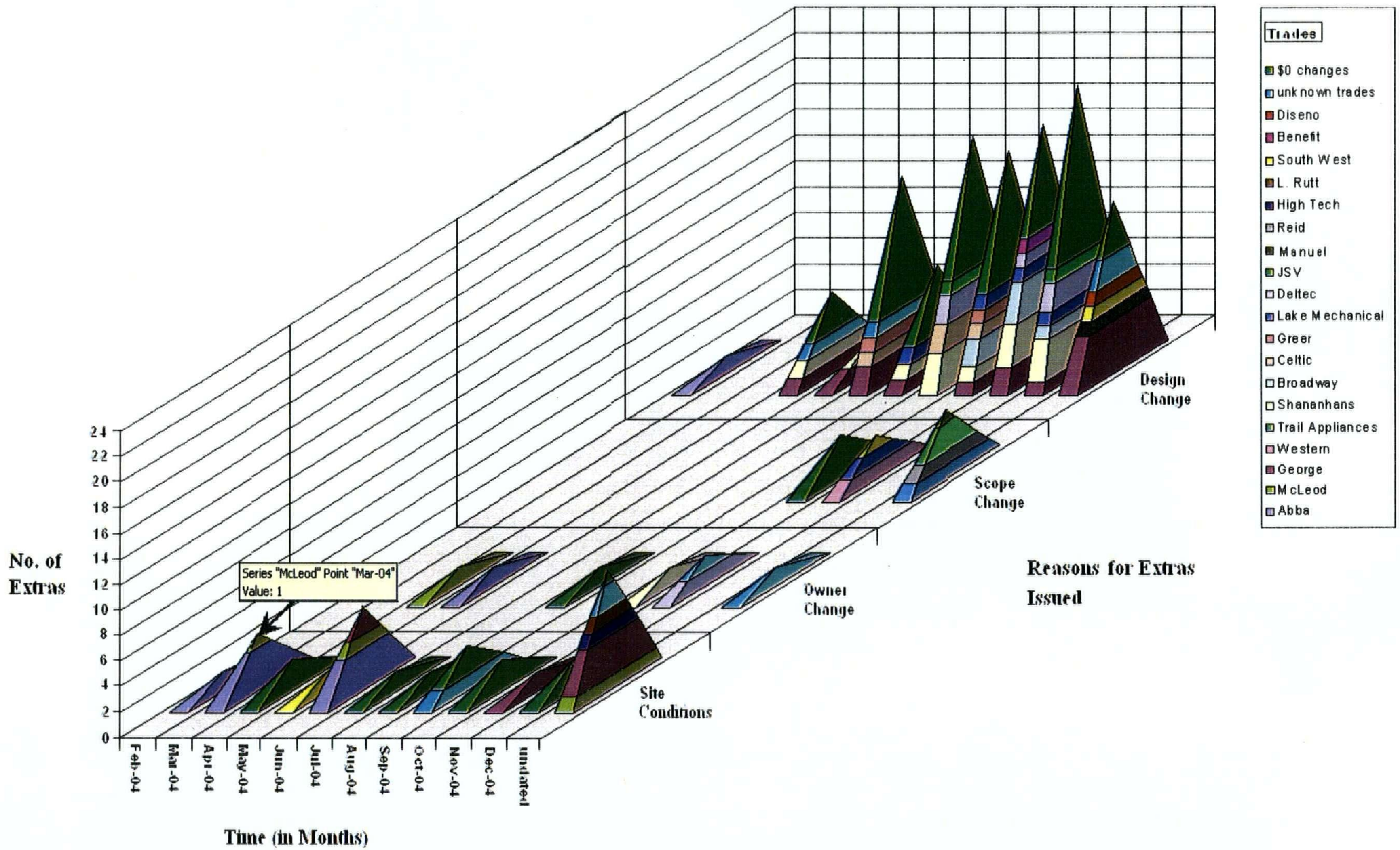

Figure 5.2 Distribution and Reasons for Extra work

Figure 5.3 represents the distribution of the value of extra work. This image is very similar to figure 5.2, the only difference being that the Z-axis now corresponds to dollar amount instead of number of extras. It is observed that number of extras need not be necessarily proportionate to the dollar consequences of these extra work orders. There can be situations where a large number of EWOs generated in a month totals to an insignificant amount whereas in other cases a single EWO may cost a very significant amount. The project management staff therefore faces a two fold challenge of managing the flow of extras (corresponding to the number of extras generated over time) and also observe the cost of extra work orders as they affect the overall project cost. Thus figure 5.2 helps management assess the effect of distribution of changes by number as they affect the targeted project completion time while figure 5.3 helps assess the effect of distribution or collection of extras by value of work on the overall budget. Since in this case we are dealing with the dollar consequences of EWOs on different trades, the issue of double counting of EWOs does not exist. An important observation is that some of the extra work orders actually generate credits. In order to identify these credits with greater ease they have been allotted a separate zone at the forefront in the image.

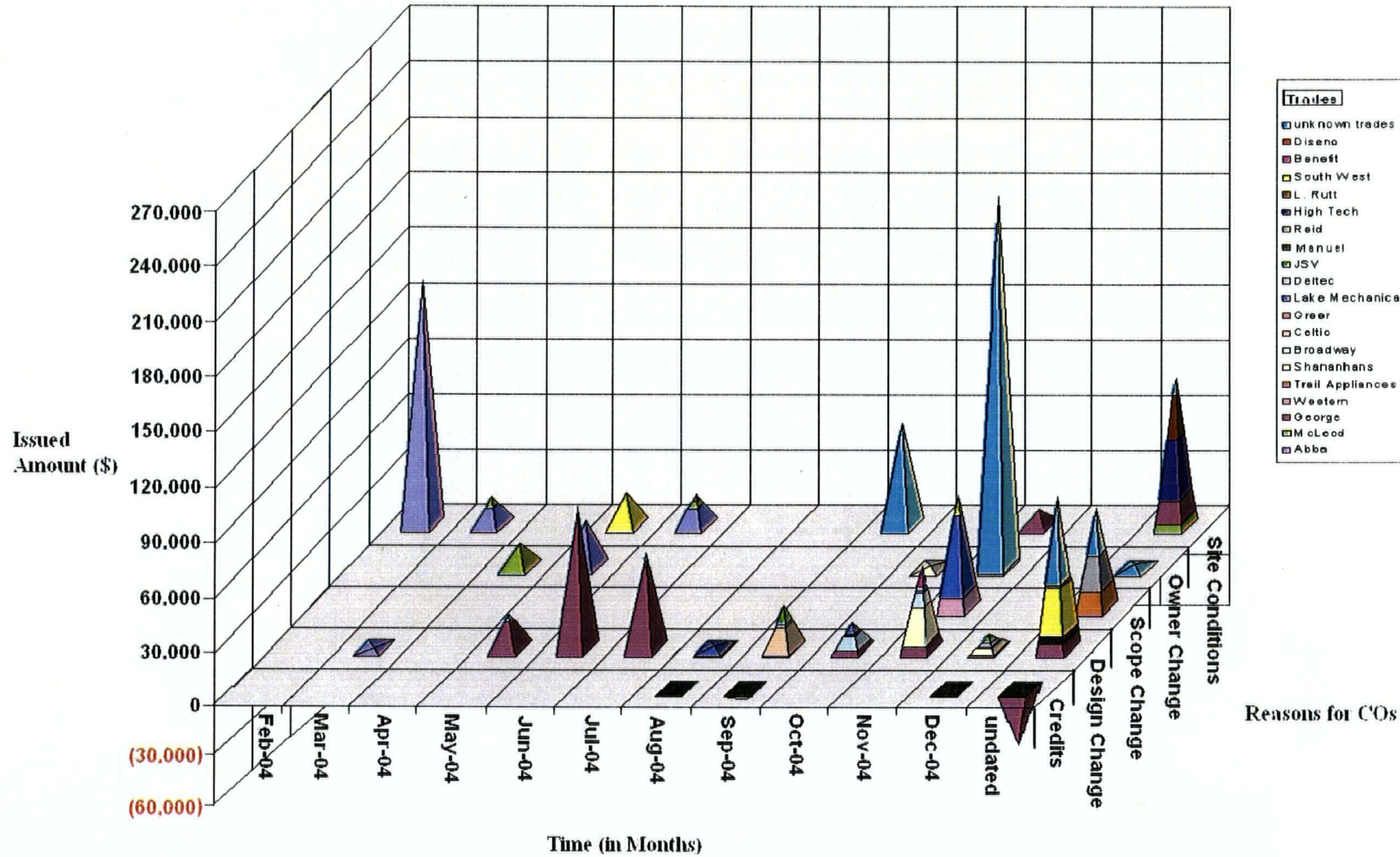

Figure 5.3 Distribution and Reasons for Extra Work by Dollar Amount

Figure 5.4 is a 2D stacked graph presenting information similar to the content of figures 5.1, 5.2 and 5.3. As noted earlier, different users have different preferences and capabilities for visualizing data. Hence it becomes necessary to develop alternate formats for the same data. Figure 5.4 represents all of the information from the previous images in a single graph. This figure can be read in two parts. The top part of the graph is a scatter plot representing the total number of extras issued each month over the project execution phase. The pie charts in the graph are comprised of an inner circle that reflects the fraction of the number of extras affecting individual trades while the outer ring corresponds to the reasons for initiating these extras. For this figure, the X-axis indicates the time when extras were issued and the vertical Y-axis indicates the total number of extras issued. For instance, a total of 10 extra work orders were issued in the month of August-04. 70% of these (i.e. 7 extras) were zero dollar change orders. 1 work order (i.e. 10% of the number of work orders) affected each of George, Shanahan and Lake Mechanical trades, respectively. In terms of the reasons for initiating extras, 80% (i.e. 8) were due to 'Design change' and 10% were due to each of 'Owner change' and 'Site condition' respectively. One important advantage of this graph is that in this case, extras associated with multiple trades are not double counted, as is the case in figure 5.2. In the bottom half of figure 5.4, the total dollar amount of the extras issued each month is shown. For example, in the month of August-04, extras worth \$917 were issued. Also shown on this graph is the cumulative dollar amount of extras issued to date. Figure 5.4 thus enables us to determine the number of extras generated, corresponding trades affected and the subsequent dollar amount in one go. However this graph does not show the split up of dollar amount by trades as per figure 5.3. This could be achieved, however, in the bottom half of figure 5.4.

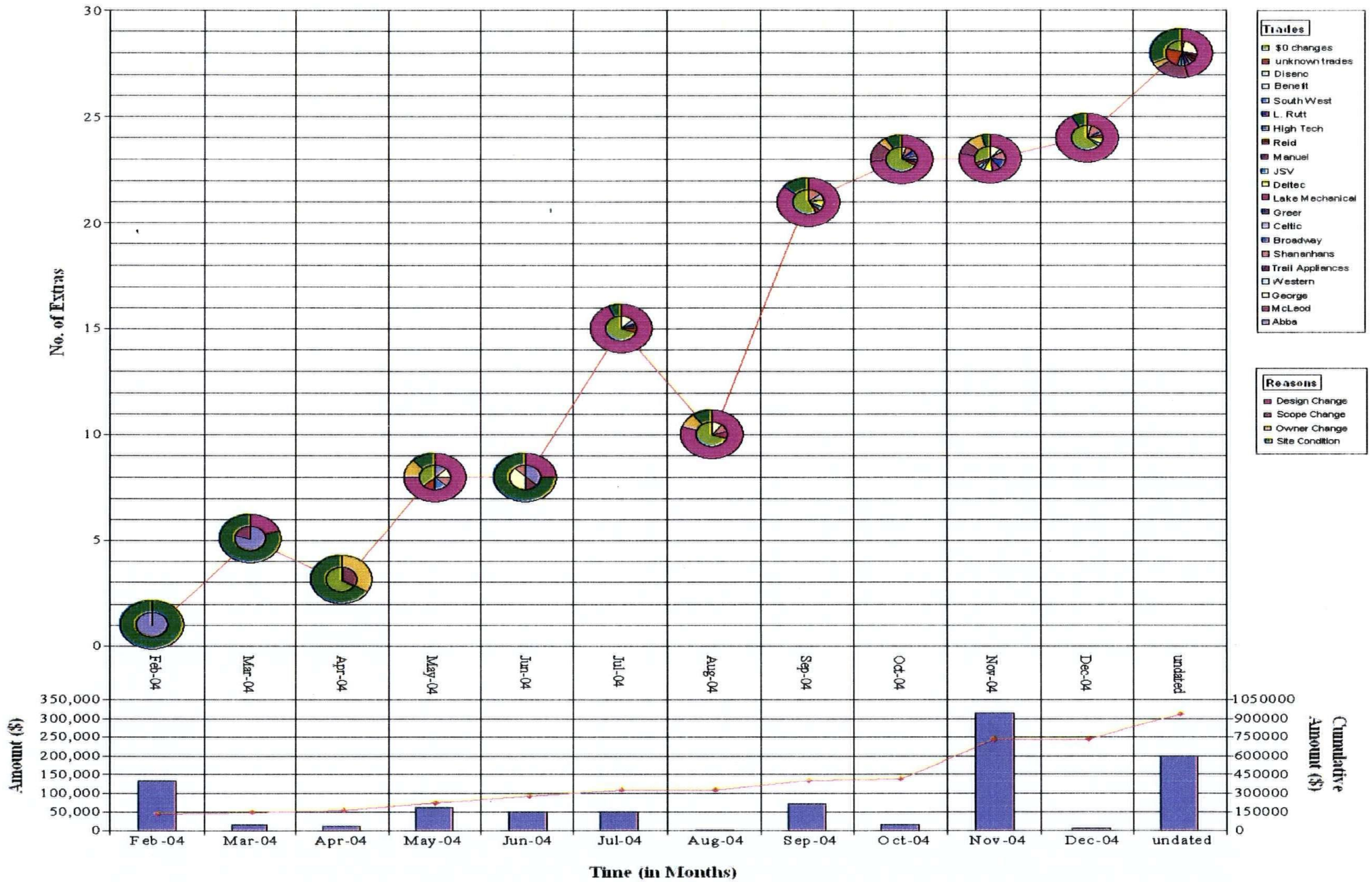

Figure 5.4 Stacked Graph showing Distribution of Extras by Number, Trade, Reasons and Dollar Amount

If coupled with interactive abilities to zoom, filter and add or suppress features, images 5.1 through 5.4 would increase the scope for data analysis and would provide deeper and faster insights into the data. For example, if a user prefers to obtain the distribution of extras only by number and trade, with the use of appropriate filter options one should be able to generate an image as shown in figure 5.5, which represents a subset of the content in figure 5.4. With interactive abilities users can read the images faster and better, and adjust their content to reflect their own cognitive style. Further, a simple click on the pie chart of any month would create a pop up window listing all the required details of the specific data item.

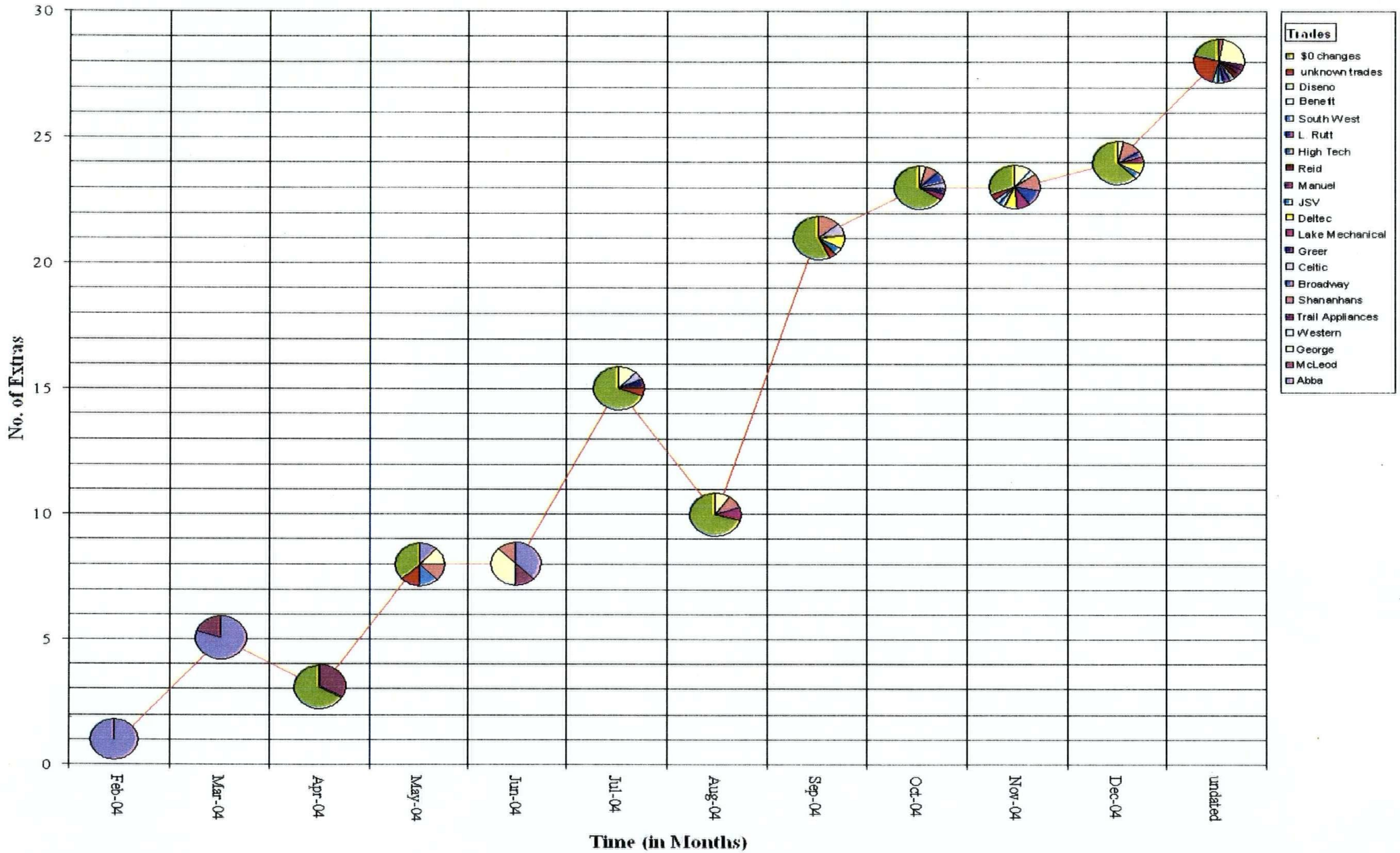

Figure 5.5 Distribution of Extras by Number and Trade in 2D: A Subset of Figure 5.4

Figure 5.6 is a 3D graph which deals with the trajectory of forecast project completion time versus the ever increasing number of changes (with the underlying casual model being that the greater the number of changes, the more the potential for an extended project duration. Note that number of changes is used as the surrogate measure here, not value.) For generating this particular graph we made use of the project schedules. A table with date of schedule update and the corresponding projected completion date was prepared, as shown in table 5.1. For this graph alone, changes or extras issued up until the start of June 2005 have been taken into consideration. For all the other images, we have limited our time line of interest to the end of December-04.

Table 5.1 Schedule Update Dates and Corresponding Projected Completion Dates

Sch No.	Dates of Schedule update	Projected completion date
1.	30 January-04	13 December-04
2.	10 June-04	Late February-05
3.	26 July-04	Late February-05
4.	14 September-04	Late March –05
5.	16 October-04	Mid May-05
6.	3 November-04	Mid May-05
7.	7 December-04	Mid May-05
8.	4 January-05	Late May-05
9.	16 January-05	20 April-05
10.	5 February-05	8 August-05
11.	13 February-05	28 July-05
12.	9 March-05	28 July-05
13.	4 April-05	28 July-05
14.	7 April-05	2 Agust-05
15.	7 June-05	28 October-05

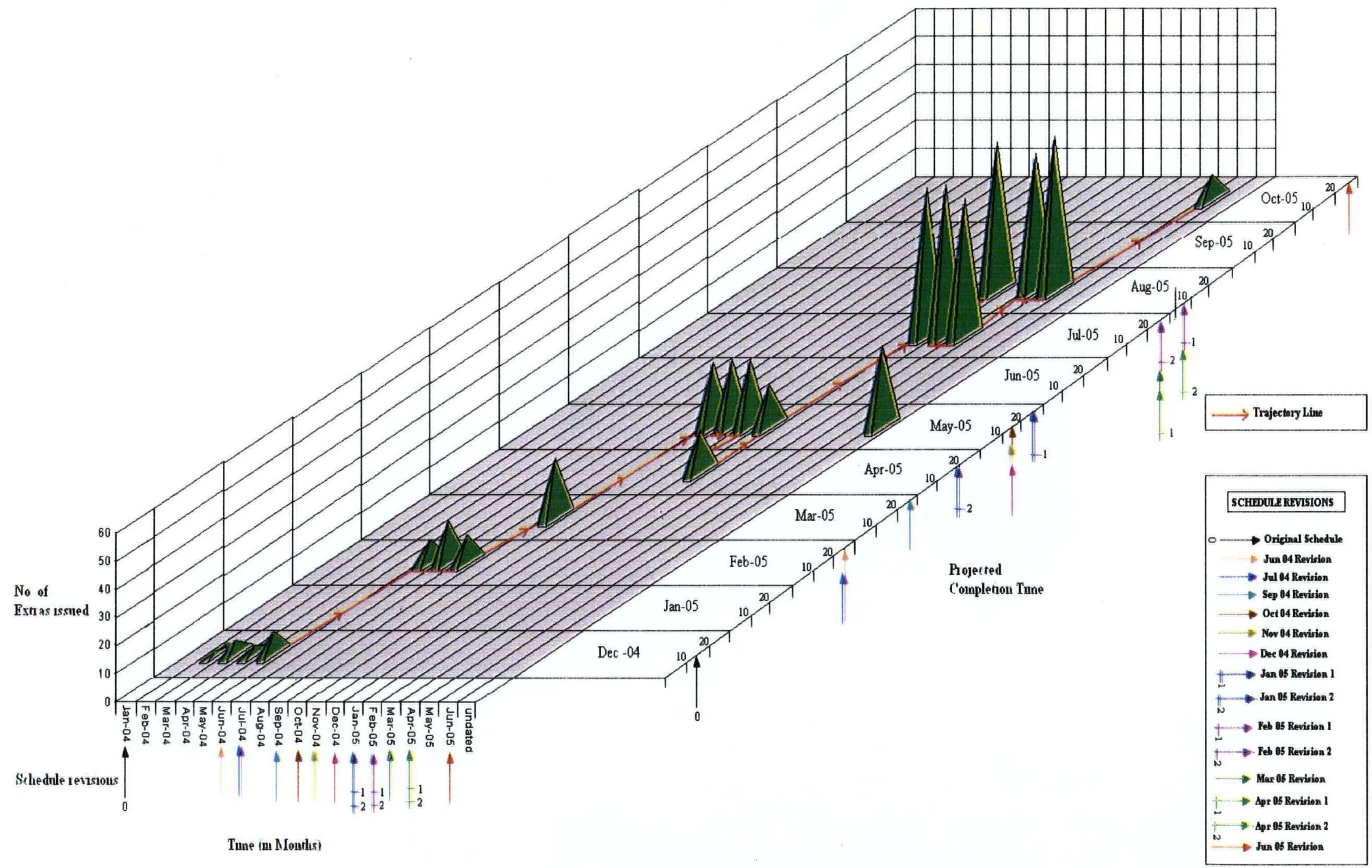

Figure 5.6 Number of Extras and Corresponding Schedule Update Dates and Projected Completion Dates

Across the horizontal axis (X-axis) is time, which serves two purposes: (i) to indicate the months when change or extra work was identified; and, (ii) to represent the dates of schedule update, starting with the original schedule before work started all the way to the current time and the most recent update. On the other horizontal axis (Y-axis) are listed the months when the project was forecast to be completed, with the dates of project completion reflecting the update version on the X-axis. The extra work is stretched out over these months of completion, to indicate how many more changes have occurred since the last update and projected completion date. The red line reflects the trajectory of movement of the forecast completion date. This graph portrays that a relation seems to exist between the number of changes occurring over time and the change in the projected completion date. However it is not fair to state that all the movement in the projected completion date is solely due to number of changes since there might be several other factors impacting the completion date. We have, however, limited our scope to assessing the impact of changes on the project performance outcome.

Most of the extras or change orders issued on this project have been initiated through site instructions. It is observed that every site instruction issued eventually transforms into an extra work order that may then convert into a subsequent change order. Thus in most cases, site instructions are the parent documents for the extras. Figure 5.7 is a simple graph representing the total number of site instructions issued in each month. In this case, the X-axis indicates time in months while the Y-axis represents the total number of SIs issued. The redline in the graph represents the cumulative number of SIs. This project has experienced a total of 129 SIs by the end of December-04. A third dimension could be added to figure 5.7, with this dimension corresponding to the physical system or subsystem to which the SI applies (e.g. mechanical, electrical, enclosure, etc.)

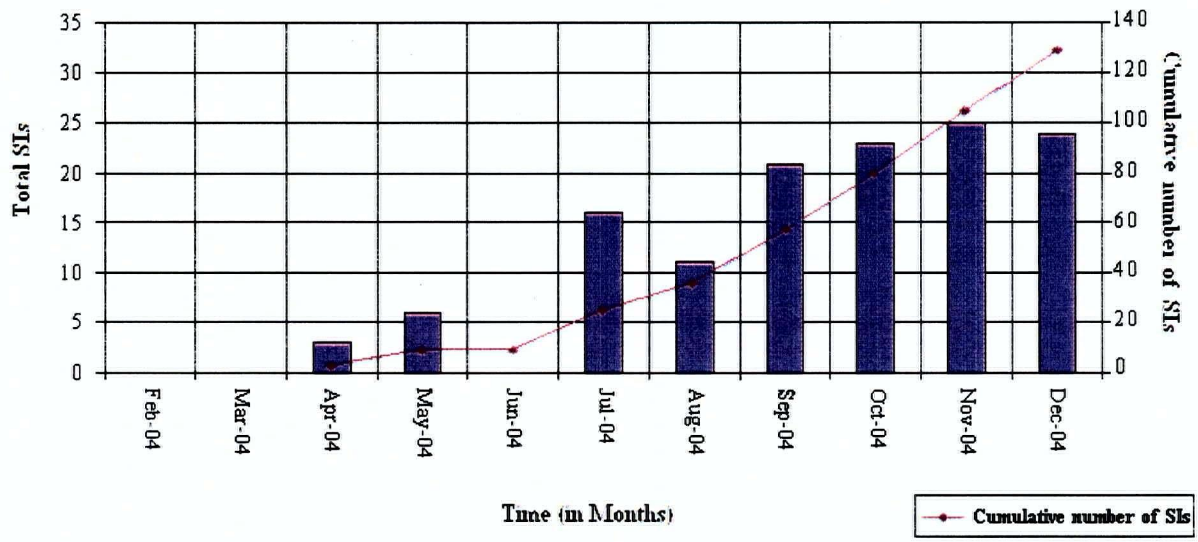

Figure 5.7 Total Number of SIs

5.7 Validation

In order to validate the usefulness of the images generated we showcased our work to Scott Management staff at two different meetings. The first audience included the CEO of the firm, project managers working on different projects, and the site superintendent for the Iona project. Many of the management personnel found the images compelling in terms of ease in understanding the underlying messages of the datasets. One noteworthy comment was that visual images served as a much more efficient tool for communication with various project participants as few individuals are prepared to take the time necessary to understand sheets of large data tables. The Scott management staff took keen interest in trying to understand each of the images and what messages could be extracted from them. They also planned to use these images (especially figures 5.2 and 5.6) in an upcoming meeting with the client to explain to him reasons for project delay. And, as discussed earlier, other important feedback related to our work was that management staff took a much closer look at their own data and tried for a more consistent assignment of reasons for the extras issued and one primary reason, as opposed to a many to one relationship. In a separate meeting with the Vice President of the firm who is responsible selecting, implementing and enforcing the use of scheduling and document control tools, he remarked that he found figures 5.2, 5.3 and 5.6 particularly compelling. Figures 5.2 and 5.3 provided a quick understanding of the reasons for the extras generated and the trades affected, in terms of their number and dollar consequences, respectively. Figure 5.6 was particularly important as it would help him communicate with the client better in trying to explain the flow of extras and the way it affected the targeted project completion date. He also welcomed our idea of adding further content to this image by color-coding the pyramids (indicating the number of extras) by trades affected or other project participants. During this meeting, the Vice-president also brought to our attention an important issue regarding the approval procedures of EWOs. For the Iona project, the owner approved the extras in batches, and the work was started prior to the final approval through a verbal approval. He thus commented that figure 5.1, though insightful in terms of understanding the impact of turnaround times on project delay, might not convey the true story in this case, since this particular image is generated using the dates of extras issued and final approval, since dates of verbal approval were not available in the EWO records. For all the other figures he suggested that a tabular display of numerical values associated with the pyramid peaks and/or pie charts along side the images would serve as a quick reference to end users, which could assist in interpreting the messages underlying these images. However in trying to incorporate the facility to generate images like the ones shown in this chapter into project management software, we seek to couple these images with interactive abilities such that the users can read the numeric values associated with the data items with a simple click on the desired data item in the image. The ability to select, unselect, zoom, filter, add or suppress features will ease the data mining process, which in turn will eliminate the need for a separate tabular display of the associated data values within the image.

5.8 Challenges

As mentioned earlier, the usefulness of visualization is dependent on the completeness of the dataset. We note that industry practices are not standard and hence datasets for the same management function can take different forms from one project to another. Hence one of our main challenges in generating these images was to study the datasets and the documentation procedures thoroughly and try to get the datasets as complete in content as possible. In developing the images we realize that different users have different preferences and capabilities to visualize data. Hence there is a need to develop alternate visual formats and customization capabilities for the same data.

As stated earlier, visualization is the art of representing data using suitable visual formats and or graphical images. We note from our literature review that no standard procedures exist to determine how best to represent a given dataset to maximize the insights that can be extracted from it. Thus the choice of an effective visual representation for a given dataset is based on experimentation and user preferences, as what might appeal to one user might not appeal to another. Some of the challenges encountered in developing the images were in regards of the choice of appropriate scale and viewing angle that could deliver better clarity and visibility to the images. We also realized that though color-coding is an effective way of providing an additional dimension to the visual format in cases of large datasets, colour palette is limited in terms of availability of easily distinguishable colours. Thus a great deal of experimentation was involved in formulating the images generated here in terms of their dimensionality (two-dimensional or three-dimensional), scale, viewing angles and colour-coding in order to maximize the insights that can be extracted from these images.

Having created these images our main concern was the acceptability of these visualization strategies by the industry practitioners. Industry personnel are often used to examining 2D drawings and examining the actual project in 3D form. Extensive use of data visualization in construction is basically a new domain. Over the past decade there has been significant use of 3D computer models to visualize physical artefacts of a project. However data visualization seems to be somewhat different. Construction personnel find it easier to visualize physical components in 3D but have a great deal of difficulty in trying to visualize data in 3D formats. We observed that though there is increasing interest in applying data visualization strategies there still exists an apprehension amongst the practitioners for a need of expert assistance for data interpretation. However through our meeting with CEO and the Vice-president of Scott Management, we were able to get a better perspective of how practitioners would read these images, how effectively they could use them for their day-to-day working, the kinds of images they prefer, and what extra features they desire to have in order to maximize the readability and usability of the images.

5.9 Bibliography

Brautigam, M. (1996). "Applying information visualization techniques to web navigation." *Thesis proposal, UC Santa Cruz, USA.*

CHAPTER 6.0

CONCLUSIONS AND FUTURE WORK

The main goal of this thesis was to explore the use of visualization to provide explanations and insights on reasons for construction performance. We note that underlying any visual format are different causal models that link project performance with the properties of different project parameters. Therefore in order to maximize the use of different visual formats to assist in explaining performance of a project, we needed to understand the concept of causal modeling and also identify the current state-of-the-art of visualization techniques. Consequently, two separate literature reviews were carried out: (i) one on research on prediction and explanation of construction project performance, and, (ii) one on various visualization techniques, their working principles and applications. Further different visual formats were explored for actual datasets. We first examined data from a previous project for which a partial dataset of change order data was available and then extended this experimentation to explore a wider range of visual formats for a more extensive change order dataset for an on-going construction project.

As mentioned earlier we are pursuing the use of data visualization as a data interpretation tool in the context of an integrated representation of a project in terms of multiple views (e.g. product, process, organizational, environmental, risk, etc.). By combining visualization techniques with a holistic representation of a project and related data, the potential exists to develop a powerful tool for assisting construction management personnel and other project participants improve their decision making, their understanding of the reasons for project performance to date, and the communication amongst different project participants. Data visualization can help in identifying the causal relations that exist between different project parameters and various performance measures, and thus assist in formulating causal models. In turn, these causal models can be used to generate images for a given project context in order to help explain the performance level achieved.

As future work, more effort needs to be put in exploring the most appropriate visualization formats for different types of data, with emphasis on front end decision making and messages contained within project documents and as-built data. When consensus is reached on the value of different visual formats, they can be then encoded into the prototype system for extensive field-testing as part of the management of real projects. Rich content profile, filtering, and data aggregation features are crucial to the development of useful images and hence it is essential to incorporate such features in the prototype system.

APPENDIX A

ADDITIONAL IMAGES

In Chapter 4, data visualization strategies were explored creating several images that can provide meaningful insights for the function of change order management using an actual data set of a previous project. A version of chapter 4 appears as a part of the proceedings of the 2005 Construction Specialty Conference. Due to space constraints of this publication not all the images generated could be documented in this chapter. Hence the remaining two figures and the accompanying thought processes are presented in this appendix section.

Figure 1 addresses the issue of identifying the location (on-site, off-site or both) of CO work. The vertical axis corresponds to the base cost of COs and COs executed during a particular month are mapped against a single colour. Individual COs are not serially ordered according to their IDs but are sorted by their location along the X-axis. Thus as is evident from the figure, the bars grouped at the left end are 'off-site' COs, the ones in the central area are 'on-site' COs and COs classified in the 'both' category are found at the right end. By joining two properties together, i.e. CO ID and location, we effectively create a 4th dimension.

As mentioned earlier, users may have preferences in adopting different visual presentations of basically the same format. For example, instead of concatenating CO ID and location together as was done in figure 1, one could concatentate time and location together, as shown in figure 2. Here the COs are ordered by CO ID along the X-axis. It is left to the reader to determine which of figures 1 and 2 provide the most valuable insights.

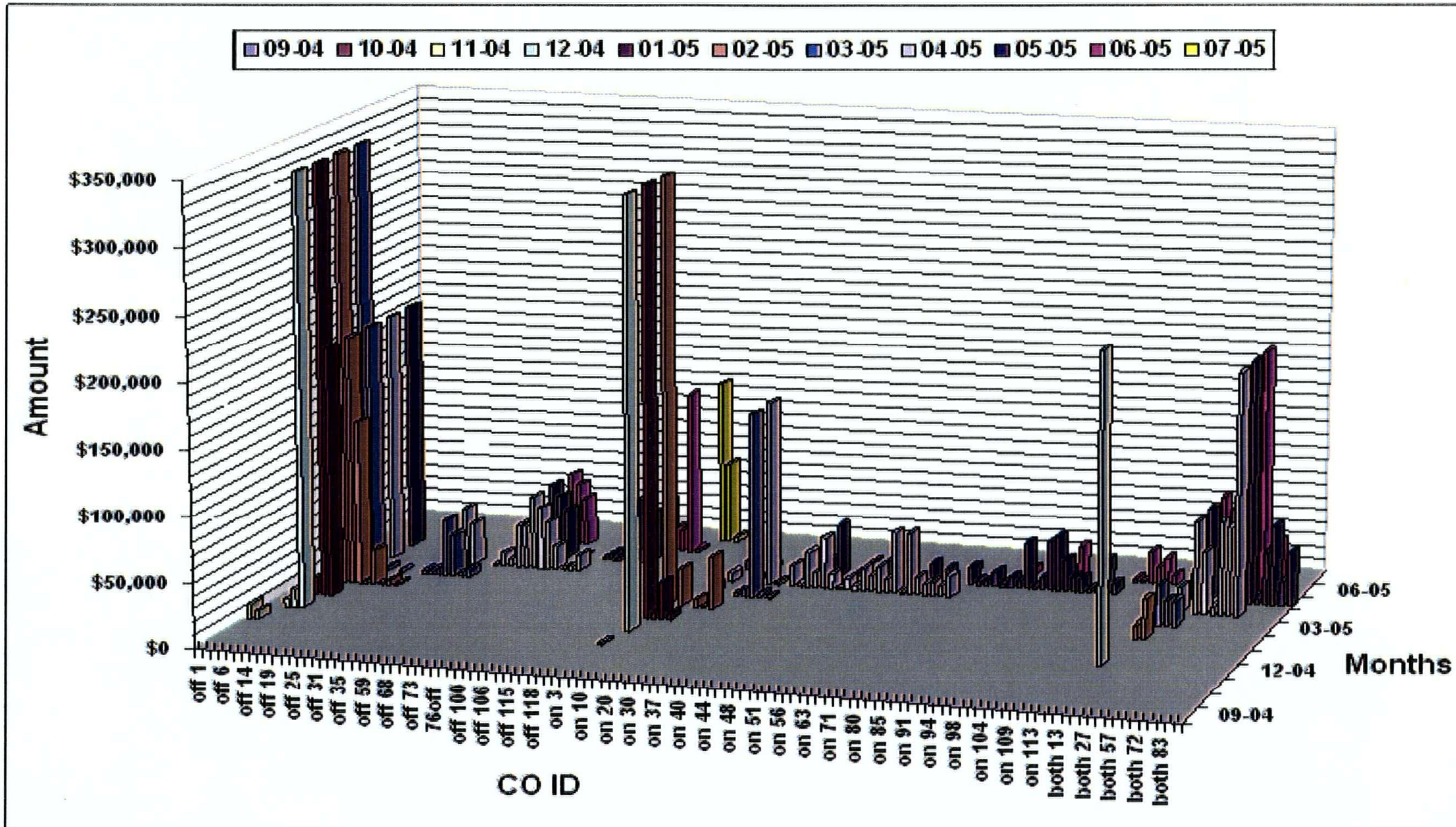

Figure 1 CO History in terms of ID&Location, timing and value of work

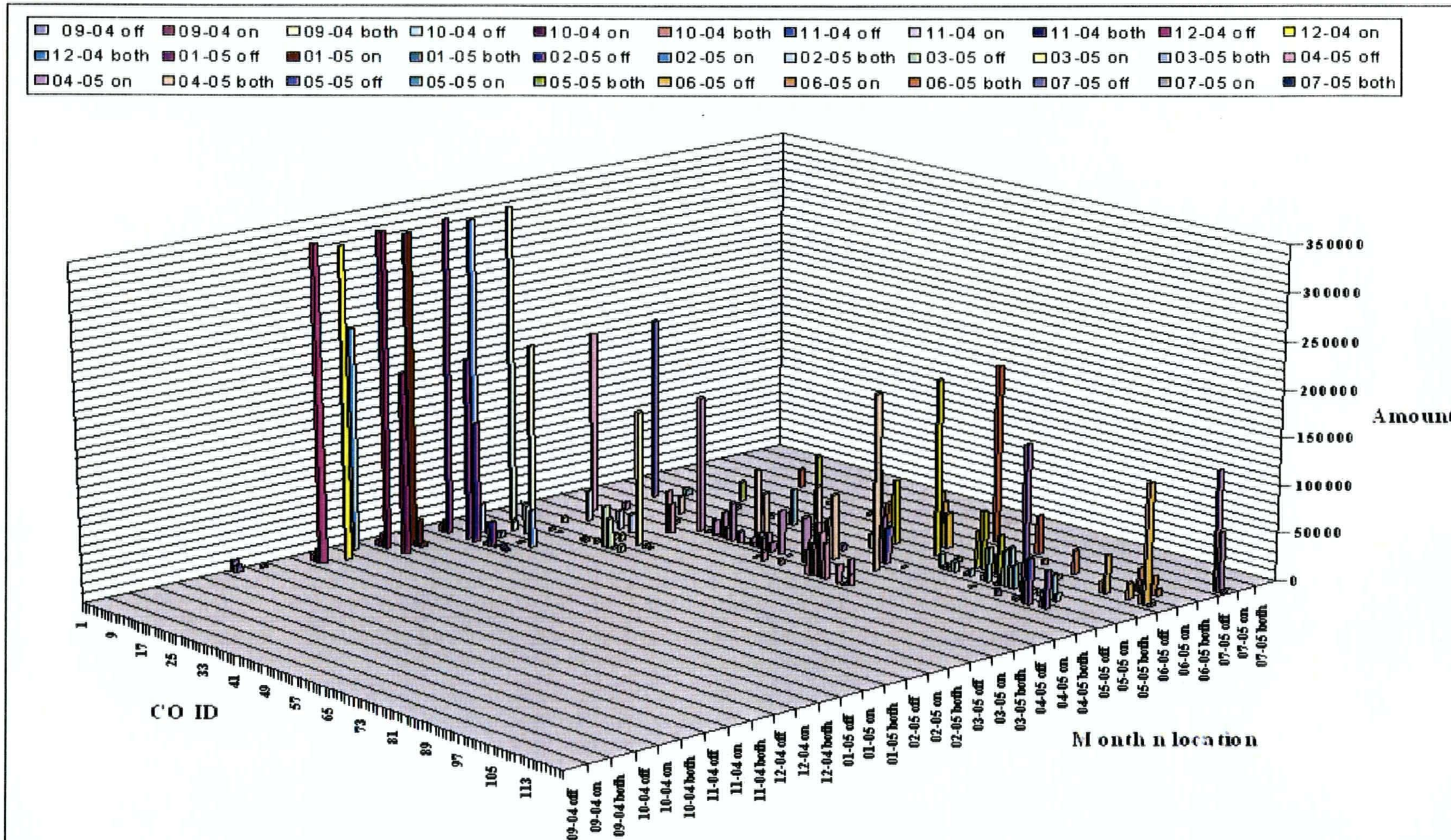

Figure 2 CO History in terms of ID, timing & location, and value of work

APPENDIX B

CHANGE ORDER REGISTRY FOR IONA PROJECT

In creating the images in chapter 5 we have made use of the actual change order registry of the Iona project. The adjoining table is a part of the complete registry. In accordance with our chosen time frame this table documents extra work orders up to the end of December 2004 only. Also the original table contains several extra columns, data fields for most of which are blank. Hence only those columns that are of particular significance to us have been maintained in this table.

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17001	-	Extra asbestos abatement in west wing and tower not identified in PHH's report	11-Feb-04				X	Feb 5/04	132,890.00	Abba, Rev01, $129,140.00
17002	ASI #2	Pin coping stones	29-Mar-04				X	undated	4,900.00	McLeod, Rev02, $ 4,900.00
17003	-	Sawcut & remove concrete window sills	7-May-04				X	undated	17.400.00	South West, Rev02, $17,400.00
17004	-	Removal of level 3 mezzanine - east wing	31-May-04			X		undated	24,800.00	Abba, Rev01, $24,800.00
17005	-	Remove additional concrete walls and granite block - 5th floor	25-Mar-04				X	Aug 13/04	7,700.00	Abba, Rev02, $7,700.00
17006	-	Remove & dispose of 2 chimney stacks - west wall	25-Mar-04				X	Aug 13/04	1,800.00	Abba, Rev03, $1,800.00
17007	-	Remove & dispose of concrete stairs in basement - not on drawings	25-Mar-04	X				Aug 13/04	250.00	Abba, Rev04, $250.00
17008	-	Remove & dispose of chimney stack on main, 2nd, 3rd & 4th floors - GL's Q & R	25-Mar-04				X	Aug 13/04	750.00	Abba, Rev05, $750.00
17009		Remove & dispose of additional materials	15-Jun-04				X	Aug 13/04	5,941.00	Abba, Rev02, $5,941.00
17010		Additional demolition work - Back charge McLeod Masonry	15-Jun-04				X	Aug 13/04	3,810.00	Abba, Rev03, $3,810.00

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17011		Extra shoring on main, 2nd & 3rd floors - JKK fix	15-Jun-04				X	Aug 13/04	360.00	Abba, Rev04, $360.00
17012	ASI # 2	Lower 2 window sills at belfry	13-Apr-04			X		Aug 13/04	13,000.00	McLeod, Rev09, $13,000.00
17012a	ASI # 2		13-Apr-04				X	undated	0.00	
17013		Remove & catalogue stone entrance at new link	21-Jun-04				X	Aug 13/04	3,890.00	McLeod, Rev10, $3,890.00
17014		Revised Structural Steel from " Post Tender Addenda " drawings, dated January 16, 2004, to " IFC ", dated March 12, 2004	21-Jun-04	X				Dec 7/04	32,396.00	George, Rev02, $32,396.00
17015	SSK-1	Remedial steel channels for cut joist on 2nd floor west wing	21-Jun-04				X	Dec 7/04	1,740.00	George, Rev03, $1,740.00
17016	SSK-10, RFI # 26	Change direction of stair # 5 and re-detail - West wing	21-Jun-04				X	Dec 7/04	871.00	George, Rev04, $871.00
17017	SI # 84R	West Roof Replacement & SSI # 8 & MSI # 26	19-Nov-04			X		Dec 7/04	200,000.00	unknown trade
17018		Storm Connection	undated	X				Dec 7/04	33,392.35	unknown trade
17019		Sanitary Connection	undated	X				Dec 7/04	23,913.00	unknown trade

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17020		New embeds. Revisions for seismic tubes for Tower windows	undated				X	Dec 7/04	1,948.00	George, Rev06, $1,948.00
17021		Remedial steel plates & anchors West wing	undated				X	Dec 7/04	3,024.00	George, Rev07, $3,024.00
17022	ASI #8	Stair 10 struct revision	31-May-04	X				Dec 7/04	15,385.00	George, Rev08, $15,385.00
17023	ASI #13	Struct SI #2	6-Jul-04	X				Dec 7/04	43,282.00	George, Rev09, $43,282.00
17024	RFI#45	Additional threaded rods	undated	X				Dec 7/04	367.00	George, Rev10, $367.00
17025	RFI #47R	Supply plates for rebar connections	undated	X				Dec 7/04	934.00	George, Rev13, $934.00
17026	ASI #1	Leveling existing window sills	13-Apr-04				X	undated	0.00	unknown trade
17027		Appliances	undated		X			Dec 7/04	12,119.00	Trail appliances, $12,119.00
17028	ASI #3	Window details extg stone faced walls	13-May-04	X				undated	0.00	
17029	ASI #4	Conc elevator shaft height adjusment	18-May-04	X				Dec 7/04	3,000.00	unknown trade
17029a	ASI #5	Mech room no elevator access	18-May-04	X				undated	0.00	
17030	ASI #6	Add new closet door 20a	26-May-04	X				Jan 6/05	98.00	Shanahan's, Rev01, $98.00
17031	ASI #7	Plumbing walls in residential bathrooms	26-May-04	X				undated	0.00	

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17032	ASI # 8	Stair # 10 Structural Revision	undated	X				undated	0.00	See CN #17022
17033	ASI #9	Add doors & hdware 3-219/44-L144/21B-stair 5	10-Jun-04	X				Jan 6/05	1,616.00	Shanahan's, Rev02, $1,616.00
17033a		Elect Outlet, HO Device, Door alarm	undated	X				undated	0.00	
17033b		Landscape	undated	X				undated	0.00	
17034	ASI #10R	MSI # 1 REV-01	12-Jul-04	X				undated	0.00	Broadway, Rev01, $0.00
17035	ASI #11	Add HM doors 40 & 45 in L 158	6-Jul-04	X				undated	0.00	Cancelled - See CN # 17039
17036	ASI #12 also code 17015	Add new doors to 3rd floor stair 2	6-Jul-04	X				Jan 6/05	4,418.00	unknown trade
17037	ASI # 13	Revised wall type W21	undated	X				undated	0.00	
17038	ASI #14	Wall cut out not required	12-Jul-04	X				undated	0.00	See CN #17041
17039	ASI #15	Clarification revised library layout	13-Jul-04	X				undated	0.00	Cancelled - See CN # 17304
17040	ASI #16	MSI # 3 Proceed at own risk with storm & san connections	13-Jul-04	X				undated	0.00	
17041	ASI #17	MSI #4 Clarification - wall cut-out still required	13-Jul-04	X				undated	0.00	Broadway, Rev02, $0.00
17042	ASI #18	West wing residential stair # 2 exits	16-Jul-04	X				undated	0.00	

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17043	ASI #19	Struct revisions to Stair #8 & #9	16-Jul-04	X				Jan 6/05	2,626.00	George, Rev18, $1,684.00/Celtic, Rev04, $978.00
17044	ASI #20	East wing RWL	20-Jul-04	X				undated	1,250.00	Greer, Rev01, $1250.00
17045	ASI #21	Millwork revisions	22-Jul-04	X				undated	0.00	
17046	ASI #22	MSI #5,6,7 Plumb storm & san revisions	22-Jul-04				X	undated	0.00	
17047	ASI #23	MSI # 8 Clarification re elevator machine room sprinkler heads	23-Jul-04	X				undated	0.00	
17048	ASI #24	MSI #9 Roof drains & piping revision	23-Jul-04	X				undated	0.00	
17049	ASI #25	MSI # 10 & # 11 Mech fans & variable speed drive revisions	3-Aug-04	X				Feb 2/05	0.00	Broadway, Rev03, $0.00
17050	ASI #26	Int Des SI # 1, & # 2 Interior glazing & millwork revisions	3-Aug-04	X				undated	0.00	
17051	ASI #27	Floor leveling & conc topping	4-Aug-04				X	undated	0.00	
17052	ASI #28	Chalmers office layout revisions	4-Aug-04	X				undated	0.00	
17053	ASI #29	Stair #3 & #8 (Lower Portion) revised Layout	23-Aug-04	X				undated	0.00	See CN # 17100

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17054	ASI #30	Stair # 8 Continuity of floor assembly FRR between floor levels	24-Aug-04	X				Jan 6/05	109.00	George, Rev15, $109.00
17055	ASI #31	Rev. to Floor Type F3 & Add Wall Type W1a	26-Aug-04	X				undated	0.00	See CN # 17062
17056	ASI #32	Millwork revision in Reception Area 106	24-Aug-04			X		undated	0.00	
17057	ASI #33	Delete door & hdwe 23-160	24-Aug-04	X				Jan 6/05	(1,314.00)	Shanahan's, Rev03, ($1,314.00)
17058	ASI #34	MSI # 12 Revise east wing storm sewer	26-Aug-04	X				Jan 6/05	2,122.00	Lake, Rev03, $2,122.00
17059	ASI #35	3rd floor tower layout revision	2-Sep-04	X				Jan 6/05	1,809.88	Celtic, Rev 01, $1,809.88 - For George Third Amount of $1,871.00 see CN # 17143
17060	ASI #36	ESI#1 Revised Location Primary Elect. Service	2-Sep-04	X				Mar 21/05	(1,477.00)	Deltec, Rev04, ($1,477.00)
17061	ASI #37	Revised wall type W21	2-Sep-04	X				undated	0.00	
17062	ASI #38	Revision to SI # 30 & SI # 31	2-Sep-04	X				Apr 25/05	9,630.00	Celtic, Rev17, $9,630.00
17063	ASI #39	Addition of roof drains ti 4th & 5th level roofs	15-Sep-04	X				undated	0.00	
17064	ASI #40	Revise washroom Rm 258 level 2	21-Sep-04	X				undated	0.00	Shanahan's, No Charge
17065	ASI #41	1 2/2 hr rating to doors	21-Sep-04	X				Jan 6/05	1,160.00	Shanahan's, Rev#8, $980.00

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17066	ASI #42	Clarification of footing @ stair #1	22-Sep-04				X	undated	0.00	
17067	ASI #43	Clarification of detail reference Dwg A5.0	22-Sep-04	X				undated	0.00	
17068	ASI #44	Hold open devices for exit doors for stair # 2	22-Sep-04	X				Jan 6/05	1,447.00	Shanahan's, Rev04, $220.00/Deltec, Rev05, $1,227.00
17069	ASI #45	Delete Folding doors in Rooms 320 & 332	24-Sep-04	X				Mar 21/05	(4,528.00)	Shanahan's, Rev14, ($4,528.00)
17070	ASI #46	Add Storm Drainage to Centre and West Wing	28-Sep-04				X	Dec 7/04	55,946.00	unknown trade
17071	ASI #47	MSI # 17 Hvac changes to Chalmers Offices & removal of baseboard heaters	28-Sep-04	X				undated	0.00	Broadway, Rev09, $0.00
17072	ASI #48	Int Des SI # 5 Added sinks & cabinets	28-Sep-04	X				undated	0.00	
17073	ASI #49	IDSI#6 update glazing to 3rd floor Multipurpose	28-Sep-04	X				undated	0.00	
17074	ASI #50	Int Des SI #4 Additional millwork	28-Sep-04	X				Jan 6/04	8,850.00	JSV, Rev01, $8,850.00
17075	ASI #51	Change swing of type 9 between 332 & 328	28-Sep-04	X				undated	0.00	Shanahan's No Price Change
17076	ASI #52	Revision to furring in Rm 297	28-Sep-04	X				undated	0.00	
17077	ASI #53	Deletion of room L154 & Storage Room	29-Sep-04	X				Jan 6/04	(250.00)	Shanahan's, Rev15, ($250.00) - See correction on CN # 17304

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17078	ASI #54	Int Des SI #7 Finishes	29-Sep-04	X				undated	0.00	
17079	ASI #55R	Levelling compound 4th Floor east wing	6-Oct-04				X	undated	0.00	
17080	ASI #56	Wall furring to accommodate RWL	1-Oct-04	X				undated	594.00	Celtic, Rev05, $594.00
17081	ASI #57	MSI # 18 Addition of fire protection water curtains	5-Oct-04	X				undated	492.00	Lake, Rev04, $492.00
17082	ASI #58	MSI#19 Roto-rooted footing drains	5-Oct-04				X	undated	0.00	
17083	ASI #59	MSI#20 Relocation of Fixtures in Room 258	5-Oct-04	X				undated	0.00	
17084	ASI # 60	MSI#21 Fire Doors on 5th Level and Belfry	6-Oct-04	X				Feb 2/05	3,912.00	Broadway, Rev04, $3,912.00
17085	ASI # 61	Int Des SI # 8 diffuser co-ordination	6-Oct-04	X				undated	0.00	
17086	ASI # 62	Revision to floor elev of mezz	7-Oct-04	X				Jan 6/05	2,605.00	George, Rev17, $2,605.00
17087	ASI # 63	Revision to library elevator	7-Oct-04	X				undated	0.00	
17088	ASI # 64	MSI # 22 Updated to reflect ceiling plan	15-Oct-04	X				Feb 2/05	2,142.00	Broadway, Rev05, $2,142.00
17089	ASI # 65	Revised access to roof terrace level 4	15-Oct-04			X		Jan 6/05	1,355.00	Shanahan's, Rev05, $1,355.00
17090	ASI # 66	Revised entrance doors - Hall 126	15-Oct-04	X				Jan 6/05	70.00	Shanahan's, Rev06, $70.00
17091	ASI # 67	Revised doors from Rm 104 to Rm 106	15-Oct-04	X				undated	0.00	Shanahan's included in #17090

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17092		Security	undated			X		undated	2,387.50	unknown trade
17093		Video Inspec. Reports and Vacuum Services	undated				X	Mar 21/05	7,525.00	unknown trade
17094		Re-drill holes to accommodate rebar	undated				X	Dec 7/04	5,130.20	Mcleod Masonry Rev 13 $5,130.2
17095		Additional Type 12 light fixture Diff btwn SSDG dwgs dated Sept 13 & Nemetz dwgs Oct 15	undated	X				Dec 7/04	958.72	Diseno, Rev01, $958.72
17096		Extra Shotcrete in Cols & Beams to Sept 30/04	undated	X				Mar 21/05	25,252.00	Southwest, Rev15, $25,252.00
17097		Cutting & coring for duct penetrations West Coast Inv 11371, PO 35473	undated				X	undated	0.00	
17098		Reverse extra 17014 as incl. in GTS Contract	undated	X				Nov 15/04	(32,396.00)	George, Rev05, ($32,396.00)
17099		Rev. to Dwgs & Steel to suit fl.level & Topping	undated				X	Dec 24/04	7,000.00	George, Rev11, $7,000.00
17100		Steel revisions for redesign of Stair # 3	undated	X				Dec 24/04	6,000.00	George, Rev12, $6,000.00
17101		Water connection	undated		X			undated	12,813.74	unknown trade

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17102		Remove chimney west end and stone @new roof east end of west wing Levelton Nov 1/04 report	undated	X				undated	3,520.00	Manuel, Rev01, $3,520.00
17103		All parapets extra to contract	undated		X			undated	18,440.34	Reid, Rev03, $11,789.00/Reid, Rev05, $16,3793.45
17104		FL Toppings excl. West Wing 4th Fl. & ceiling	undated				X	undated	31,043.41	High Tech, Rev01, $17,858.77/High Tech, Rev02, $12,756.64
17105		Radios to Co-ordinate Crane with Intracorp	13-Sep-04				X	undated	0.00	
17106		Access road	undated				X	Mar 21/05	1,050.00	unknown trade
17107		Window prep	undated				X	undated	23,633.00	L. Rutt, Rev01, $23,633.00/L. Rutt, Rev02, $35,876.50/L. Rutt, Rev03, $54,767.00/L. Rutt, Rev04, $53,845.50/L.Rutt, Rev05, $51,815.00/L. Rutt, Rev06, $48,049.50/Manuel, Rev07, ($3,318.00)
17108		Bonding Trades	undated		X			undated	0.00	

Scott C.O. No.	Ref. No.	Description	Date Issued	Design Change	Scope Change	Owner Change	Site Condition	Date Approved	Approved Amount	Trade Change Orders Issued
17109		Supply & Install Fire hydrant	undated		X			Mar 21/05	10,898.69	unknown trade
17110	ASI # 68	IDSI #10	19-Oct-04	X				undated	0.00	
17111	ASI # 69	IDSI #9	20-Oct-04	X				undated	0.00	
17112	ASI # 70	Wall, Dean's Residence	20-Oct-04		X			undated	0.00	
17113	ASI # 71	Wall ratings	22-Oct-04	X				undated	0.00	
17114	ASI # 72R	Building Permit Revisions	29-Oct-04		X			undated	0.00	
17115	ASI # 73	MSI #23	26-Oct-04		X			undated	0.00	
17116	ASI # 74	MSI #24	29-Oct-04	X				undated	5,100.00	Lake, Rev14, $1,888.00/Lake, Rev15, $3,212.00
17117	ASI # 75R	MSI #25	29-Oct-04	X				undated	0.00	
17118	ASI # 76	Revisions to Door Schedule	2-Nov-04	X				Jan 6/04	18,925.00	Shanahan's, Rev#7, $18,925.00
17119	ASI # 77	Wall Schedule changes	29-Oct-04	X				undated	0.00	
17120	ASI # 78	IDSI # 11	29-Oct-04	X				undated	0.00	
17121	ASI # 79	Reposition handicap lift.	2-Nov-04	X				undated	0.00	Shanahan's No Price Change

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17122	ASI # 80	SSI # 5 - Upgrade and Renovation to Dean's Residence.	2-Nov-04		X			undated	18,982.38	Southwest, Rev18, $9,881.75/Western, Rev01, $9,100.63/Western, Rev04, $18,614.86/Western, Rev05, $3,933.50
17123	ASI # 81	Revisions to Door Schedule	3-Nov-04	X				undated	0.00	
17124	ASI # 82	ESI # 2 - Library security alarm.	4-Nov-04	X				undated	0.00	
17125	ASI # 83	SSI # 3 - SSK # 25 to # 34	4-Nov-04	X				undated	0.00	
17126		Cancelled	undated					undated	0.00	
17127	ASI # 85	SSI # 6 - SSK# 51 & # 52 West Wing	8-Nov-04				X	Jan 6/04	8,828.00	George, Rev19, $8,828.00
17128	ASI # 86	ESI # 3 - Units 278 & 282	8-Nov-04			X		undated	1,150.00	Deltec, Rev23, $1,150.00
17129	ASI # 87R	Revision to folding door stacking	24-Nov-04	X				undated	0.00	
17130	ASI # 88	MSI #25R3 - Units 278 & 282	9-Nov-04	X				Feb 2/05	3,650.00	Broadway, Rev12, $2,125.00/Lake, Rev06, $1,525.00
17131	ASI # 89 Re-issue	MSI # 27 - Additional Fire dampers	16-Nov-04	X				Feb 2/05	1,860.00	Broadway, Rev06, $1,860.00
17132	ASI # 90	MSI#26 Revised routing for ductwork from HRV	16-Nov-04	X				Feb 2/05	3,580.00	Broadway, Rev11, $3,580.00

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17133	ASI # 91	ESI # 4 - Lighting Revisions	16-Nov-04	X				Mar 21/05	1,708.00	Deltec, Rev06, $1,708.00
17134	ASI # 92	Vault Room #136	16-Nov-04	X				Jan 6/05	45.00	Shanahan's, Rev09, $45.00
17135	ASI # 93	Mech Rm #136 Revisions	17-Nov-04	X				Jan 6/05	120.00	Shanahan's, Rev 10, $120.00
17136	ASI # 94	Bulkhead at Operable Wall	18-Nov-04	X				undated	0.00	
17137	ASI # 95	IDSI # 12 - Proposed Flooring Changes	19-Nov-04	X				Apr 25/05	9,945.00	Benefit, Rev03, $9,945.00
17138	ASI # 96	MSI # 28 - Additional roof and floor drains, and roof drain schedule changes	19-Nov-04					undated	0.00	Cancelled
17139	ASI # 97	MSI#16R1 Add Storm drain in Centre & West	23-Nov-04		X			Dec 7/04	41,686.00	Lake, Rev02, $41,686.00
17140	ASI # 98	SSI#7 Operable Wall Support SSK 53 & 54	23-Nov-04	X				Jan 6/05	3,316.00	George, Rev20, $3,316.00
17141	ASI # 99	Revision to position of bathroom Level 4	23-Nov-04	X				undated	0.00	
17142	ASI # 100	Revision to position of Insul. On Typ. Flat roof	23-Nov-04	X				undated	0.00	
17143	ASI # 101	Bridge over light well & SSI # 9	26-Nov-04	X				undated	1,871.00	George, Rev21, $1,871.00
17144	ASI # 102	Revision to position of upper lift of Stair # 4	1-Dec-04	X				undated	0.00	
17145	ASI # 103	MSI # 29 - Sink revisions	1-Dec-04	X				undated	0.00	

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17146	ASI # 104	IDSI # 13 - Millwork Revisions	1-Dec-04	X				Jan 6/05	2,700.00	JSV, Rev02, $2,700.00
17147	ASI # 105	MSI # 30 - Additional Fire Dampers	1-Dec-04	X				Feb 2/05	744.00	Broadway, Rev07, $744.00
17148	ASI # 106	MSI # 29R - Sink Revisions	3-Dec-04	X				Mar 21/05	(168.00)	Lake, Rev07, ($168.00)
17149	ASI # 107	ESI # 5 - Additional Outlets	2-Dec-04	X				Mar 21/05	378.00	Deltec, Rev07, $378.00
17150	ASI # 108	MSI # 31 - Relocate transfer grille	3-Dec-04	X				undated	0.00	Broadway, Rev10, $0.00
17151	ASI # 109	SSI#10 Additional stone ties at South Exit	3-Dec-04				X	undated	0.00	Reid, Rev08, $3,883.78/Reid, Rev09, $3,289.06/Reid, Rev11, ($3,289.06)
17152	ASI # 110	IDSI # 14 - Core hole location	3-Dec-04				X	undated	0.00	
17153	ASI # 111	Revision to Kitchen # 604	9-Dec-04	X				undated	0.00	
17154	ASI # 112	Revised Entry using extisting stone	9-Dec-04	X				undated	0.00	
17155	ASI # 113	Revised wall types	9-Dec-04	X				Jan 6/05	1,118.00	Shanahan's, Rev11, $1,118.00
17156	ASI # 114	IDSI # 15 - Revised Kitchen # 604 layout	13-Dec-04	X				undated	0.00	
17157	ASI # 115	Addition of wall under Stair # 9	13-Dec-04	X				Jan 6/05	615.00	Shanahan's, Rev12, $615.00
17158	ASI # 116	SSI#11 Added topping to Landing Level 5	14-Dec-04	X				undated	0.00	

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17159	ASI # 117	SSI#12 Additional angle reinf. At ducts Level 6	14-Dec-04	X				Jan 6/05	675.00	George, Rev16, $675.00
17160	ASI # 118	MSI # 32 - Revised Kitchen # 604	14-Dec-04	X				undated	0.00	Lake no cost involved
17161	ASI # 119	Revised window details	20-Dec-04	X				undated	0.00	
17162	ASI # 120	West entry Tower Window & reveal dimen.	21-Dec-04	X				undated	0.00	
17163	ASI # 121	IDSI #16 Add coat hook to all office doors	21-Dec-04	X				Mar 21/05	750.60	Shanahan's, Rev16, $750.60
17164	ASI # 122	Obscure glazing to windows in washrooms	21-Dec-04	X				undated	0.00	
17165	ASI # 123	Mechanical room in attic of West Roof	21-Dec-04	X				undated	896.00	Deltec, Rev08, $896.00
17166	ASI # 124	Relocate wall in Library	21-Dec-04	X				undated	0.00	
17167	ASI # 125	IDSI # 17 - Bulkheads over cabinets	22-Dec-04	X				undated	0.00	

Note: (###) indicates credited amount.