DIAGNOSING CONSTRUCTION PERFOMRANCE

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ABSTRACT

Effective control during the construction phase is very important for the overall success of a project. The ability to diagnose the causes of unsatisfactory performance forms a critical part of the foundation of good construction control practice. Based on an extensive literature review, it is observed that the majority of research efforts to date have focused on developing predictive construction performance models as opposed to explanatory ones, and several important issues relevant to diagnosing construction performance have not been addressed or sufficiently emphasized. Described in this paper is a conceptual construction performance diagnosis schema that is applicable to a broad range of performance measures. Important factors for time as a representative performance measure are identified and discussed along with the issue of mapping these factors onto data typically collected in support of ongoing management functions. Then, issues pertaining to the practical formulation and application of formally structured causal models for diagnosing construction performance are discussed. An overview of the diagnosis schema proposed is provided, followed by its application to an example project.

KEY WORDS

construction performance, diagnosing, causal model, schedule,

INTRODUCTION

It is not uncommon to observe discrepancies or variances between the values of planned and actual construction performance measures such as cost, time, scope, productivity, quality and safety. Further, it is often not clear if a performance variance results from inaccurate planning, poor construction management practice, events beyond the contractor's control, or some combination thereof. The academic community has expended considerable effort to reduce or eliminate completely such discrepancies by developing improved management tools. These efforts can be divided into two lines of inquiry. The first assumes that the discrepancy mainly comes from inaccurate planning, leading to the development of predictive models for performance to improve the accuracy of estimation. By predictive models we mean models that can be used to provide or 'predict' a priori accurate estimates of performance measure achievements, given an estimate of the likely state of a set of factors that are believed to be relevant for the work scope and performance measure of interest. Values used are assumed to represent an average of the conditions forecast to be encountered (e.g. labour skill level).

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Such models are useful in the estimating phase of a project and assist in providing benchmarks for project control. In contrast, the second line of inquiry assumes that the discrepancy mainly results from poor construction management practice and events beyond the contractor's control. Thus, researchers have focused on developing explanatory models to help practitioners identify plausible causes for unsatisfactory achievements. By explanatory models we mean those that can help construction personnel figure out what the most plausible explanation is for a deviation of actual performance from expected performance, given relevant actual project data collected during the construction phase. As compared to predictive models, the body of research on explanatory models is very limited.

Presented in this paper are selected aspects of a conceptual framework for diagnosing reasons for various dimensions of actual construction performance deviating from what was planned. Because of space constraints, time performance at the project level (i.e. project duration) is selected as a representative performance measure for explaining issues associated with diagnosing reasons for performance, and features of the approach being pursued. A list of factors identified in the literature as affecting time performance is presented along with a mapping of these factors onto data items typically collected as part of ongoing management functions. Then, important practical issues pertaining to the formulation and application of formally structured causal models for diagnosing construction performance are discussed. An overview of the diagnosis schema proposed is then provided, followed by its application to an example project.

LITERATURE REVIEW

An extensive literature review was carried out to survey the state-of-the-art of predictive and explanatory construction performance models, as well as critical factors having impact on different construction performance measures (Korde et al. 2005). These papers have been categorized in terms of performance measure treated (e.g. productivity, time, cost, quality, safety), performance level treated (activity level, trade level, project level), method used (e.g. regression, neural networks, fuzzy logic, importance index, decision support system), type of model (predictive, explanatory), and factors that influence performance measures.

Findings from the literature search have provided a useful point of departure for pursuit of our research goal, which is to develop an approach for construction users to define experience-based hypotheses about explanations for performance achieved in terms of formally structured causal models that make use of data already collected as an essential part of day-to-day management functions. Such hypotheses can be used to guide searches of a project's data base in order to find evidence in support of these hypotheses. To develop them, factors having impact on various performance measures or their constituents need to be identified. Based on the literature search, unanimous consensus on the list of critical factors affecting different performance measures was not found. We used a simple frequency test to determine factors for which there was a reasonable level of consensus. The test consisted of identifying those factors which were listed in at least 20 percent (a rather lenient threshold) of the papers relevant to that performance measure.

For time performance or project duration, of the 134 papers identified to date, 41 of them focus on it. For this measure a factor is regarded as being important only if at least 9 of these 41 papers regarded it as important. Using this criterion, 15 factors were identified, as shown in Table 1. The terminology used to express these factors is the authors, as no consistent terminology was employed in the literature. Further, for each factor identified, a number of sub-factors were presented by various authors. These are shown in Table 1 as well, and again we have attempted to capture different ways of saying the same thing in a consistent manner. Important to us is ensuring that these factors/sub-factors are represented in our diagnostic schema, to the extent possible. Besides knowing what factors/sub-factors are important, it is also necessary to know how their states can be expressed. Unfortunately, little discussion of this issue can be found in the papers reviewed.

As noted previously, we have sought to build on the collective wisdom found in the literature. As a first step we have mapped factors and sub-factors found in the literature onto data normally collected in support of ongoing management functions in order to make sure they are represented directly or indirectly through surrogates in the project data base. Corresponding data fields are reflected in a multi-view representation of a project (Russell and Udaipurwala 2004), or can be derived through operations on one or more data fields. The views treated include physical, process, organizational/contractual, environmental, quality, cost, as-built, change and risk. In general, the data used to represent these views (e.g. schedule, weather, labour data, etc.) embrace many of the factors/sub-factors identified in the literature. Examples of such mappings are presented in the bottom of Table 1.

CAUSAL MODELS

We have adopted a causal model approach to assist with the diagnosis of construction performance for three main reasons: (i) we wish to empower management personnel to be able to easily encode their knowledge and experience in a very hands on and transparent manner; (ii) we seek an approach that is applicable to a broad range of performance measures and which provides leverage in terms of allowing reuse of models for lower level measures to generate more extended models for higher level measures; and (iii) we want an approach that does not require the processing of extensive data sets from past projects using analysis techniques unfamiliar to industry personnel. In using causal models to reason about performance, we do not seek answers to the question: how much of the variance in performance measure y can be explained by factor x? Rather, our goal is more modest: we wish to find any evidence that supports the hypotheses embedded in the causal model – i.e. these factors are the determinants of the level of performance.

Cause-effect diagrams have been used by other researchers to study different construction performance measures (e.g. Abu-Hijleh 1991; Diekmann and Al-Tabtabai 1992; Moselhi et al. 2004). Nevertheless, an in-depth discussion of how best to structure such diagrams and issues inherent in their use have not been the focus of these researchers. Figure 1 illustrates the general form we have adopted for expressing a causal model. It is comprised of three main layers: (1) the performance measure of interest; (2) fundamental or mathematical relationships for determining the value of the performance measures; and, (3) factor causal models that represent hypotheses to explain performance for each of the variables in layer 2. We elaborate on each of these layers in the context of time performance of a project, in order to highlight a number of important topics dealing with efficiency of the search /diagnostic process, the requirement for multiple causal models, the desired form of these models, and the source of values for the factors. As noted previously, we could have chosen to examine

Table 1 Factors/Sub-Factors and Mapping onto Data Collected (Time Performance)

Factors affecting time performance		Factors affecting time performance	
Factors	Sub-Factors	Factors	Sub-Factors
Human resource management (20/41)	Labor skill	Planning (13/41)	Planning effort
	Labor availability		Planning deficiency
	Technical/Mgmt. staff skill		Inadequate early planning
	Technical/Mgmt. staff availability	Mistakes (12/41)	Quality of drawings
Changes orders (16/41)	Design changes		Quality of specifications
	Material changes		Construction mistakes
	Specification changes	Contract Mgmt. (12/41)	Contract type
	Construction method changes		Unrealistic schedule objective
	Frequency of changes	Subcontractor (11/41)	Portion of subcontract
Weather (14/41)	Precipitation		Subcontractor delay
	Temperature		Nominated subcontractor or not
	Wind		Bankruptcy of subcontractor
Material management (14/41)	Material availability	Schedule control (10/41)	Efficiency of delay control
	Material delivery		Schedule update frequency
	Material quality	Contractor's finance (9/41)	Inadequate fund
	Material damage		Timely payment for finished work
	Material storage (loss/theft)	Communication (9/41)	Inadequate/Inefficient communication
Equipment (tools) management (13/41)	Equipment availability	External Environment (9/41)	Strike
	Equipment delivery		Unexpected event (e.g. ground cond.)
	Equipment quality (breakdown)	Engineering(design) (9/41)	Delay in design information
	Unskilled equipment operators		Design effort (cost, duration)
Productivity (13/41)	Labor productivity		
	Equipment productivity		

Mapping Examples	Labor skill	As-built View>Daily Site>Daily Status Data>Work Force>Skill level
	Precipitation	As-built View>Daily Site>Site Environment Data>Precipitation (mm)
	Equipment availability	Process View>Resources>Resource Data>Availability
	Material damage	Process View>Resources>Resource Data>Project Records/Memo
	Quality of drawings	Physical View>Drawing control; As-built View > RFIs
	Timely payment for work	Cost View>Pay item breakdown structure>Pay item data>Scope/cost/Act.
	Communication	Organizational View>Participants>Add./Info.>Evaluation>Communication
	Material quality	Quality View>Quality Management

other measures or a subset of a more global measure – e.g. duration of a single activity. For this, only a subset of figure 1 is required, as shown by the shaded elements of figure 1.

The first layer of the causal model determines if there is a need to invoke use of the causal model – i.e. explain a variance between planned vs. actual performance. The second layer deals with the relationships used to compute values for the first layer performance measure. Not all measures (e.g. safety) can be expressed through fundamental relationships, and hence the second layer is not applicable for all performance measures of interest. For the case at hand, the basic relationships that describe time performance can be broken down into a number of sub-layers. Sub-layer 2(a) corresponds to the network of critical activities and paths which are the determinants of project duration. Thus, sub-layer 2(a) helps narrow the breadth of the diagnosis that has to be conducted. Sub-layers 2(b) and 2(c) help pinpoint which activities / precedence relationships amongst the critical ones are the

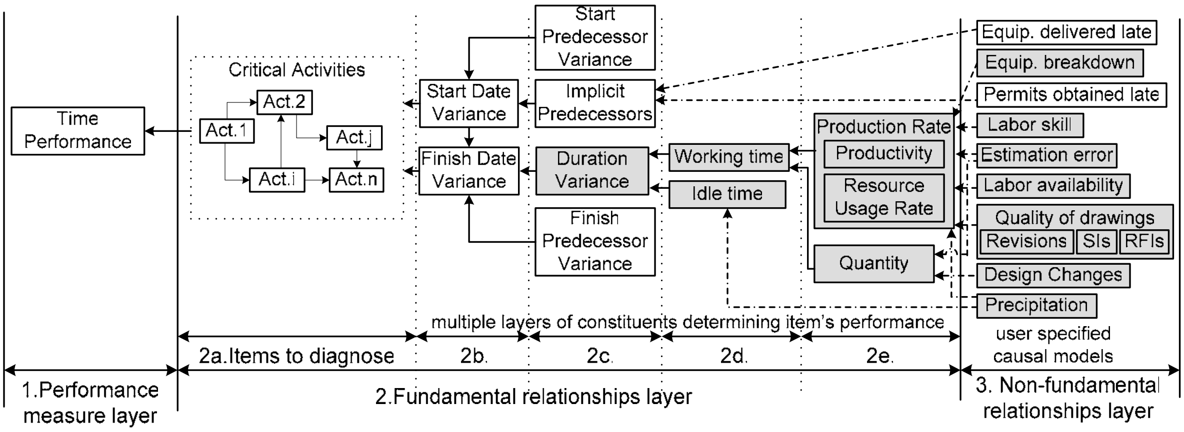

Figure 1: Cause-Effect Diagram for Construction Time Performance

determinants of the variance in time performance. Thus checks are run on the duration and start and finish date variances of all critical activities to identify the items requiring further investigation. These checks can all be performed using quantitative data from the base schedule and the current updated schedule. The only non-quantitative check made occurs in sub-layer 2(c) and it relates to the notion of implicit predecessors – e.g. were the required permits in place and was the space required for the work accessible. Diagnosis of this variable for activities requiring further analysis is conducted by a causal model of relevant factors, as shown in layer 3 – only a subset of relevant factors is shown in figure 1. Sub-layers 2(d) and 2(e) deal with the analysis of an activity's duration, and makes use of another fundamental relationship, activity duration D (days) equals scope Q (e.g. m^3) divided by the product of productivity P (e.g. m^3/mhr) and resource usage rate R (e.g. mhr/day) or production rate Pr (e.g. m^3/day) which is the product of P and R (alternatively, one could choose to work directly with a causal model for activity duration without consideration of its constituent variables). Using the former for purposes of discussion, actual duration D_a of an activity is equal to working time plus idle time. Again, we seek to pinpoint the basis for activity duration variance. If actual working time corresponds to what was planned, but considerable idle time (IT) was encountered, then to explain idle time another causal model is used, with the factors considered for idle time being relevant to the type of work performed. Alternatively, if variances are found in one or more of Q, P or R, then the appropriate causal models for each of the variables are explored to see if they explain the variance. Layer 3 corresponds to the causal models themselves, which represent the knowledge and experience of construction personnel, expressed in terms of data collected directly or derived from data collected in support of construction management functions. It is here that we wish to make sure that the factors considered embrace factors / sub-factors identified as being important in the literature. Key challenges deal with how to let construction personnel formulate these models and factor states / thresholds simply and in an easily comprehendible way.

Based on the foregoing discussion, and so that a practical approach can be developed for diagnosing reasons for performance that is applicable to a broad range of measures, a number of assumptions have to be made and several important issues addressed, as follows:

- Planning and control at the same level of detail: The diagnostic schema proposed assumes that planning and control will be conducted at the same level of detail.
- Overall framework: An overall framework needs to be formulated that minimizes the burden on users for setting up the diagnostic process for the measure of interest. Ease of use and transparency of approach are essential to influence actual practice.
- Modular approach: The approach should be as modular as possible, allowing reuse of lower level models for higher level ones.
- Factor interaction and single layer causal models: In formulating causal models, it is possible to generate models that involve many factors along with complex interactions amongst them. What is not clear is how to account for these interactions, especially with respect to combinations of factor states. We have opted for single layer models because they can be readily specified by construction personnel with access to the full set of factors for which data is collected.
- Values or states of factors in causal models: A major challenge is how to define and compute states of factors to determine if they are a possible driver of poor performance. Factors can be classified into at least two types: (i) those that have a direct influence on performance – e.g. the factor of labour skill level on productivity; and (ii) those that have an indirect influence on performance and which are assessed through one or more surrogate measures – e.g. the factor of drawing quality which may be assessed through number of drawing revisions and number of RFIs. For the first type of factor, one has to determine how best to express the factor and how to aggregate through time. For the second type of factor, some kind of index needs to be determined that reflects the norm in the industry vs. what is experienced on the project at hand. A paucity of such benchmarks is available in the literature.
- Ability to function with missing or erroneous data: A reality of the industry is that data sets are incomplete, and data recording errors occur. The diagnostic process still has to function, even if it means simply reporting that no data had been recorded for one or more factors.
- Classification of causal models: It is important to avoid a proliferation of causal models. Models should be categorized by performance measure of interest, and within a measure, models can be developed to reflect types of work – e.g. unprotected vs. a protected work environment, and labour vs. equipment intensive.
- Ability to conduct analysis on the search results: For measures at the trade or project levels, once a search has been conducted for evidence to explain performance, an analysis should be conducted to identify factors common to multiple variables.

OVERVIEW OF PROPOSED APPROACH

In this section, we overview the four main components of our construction performance diagnostic approach, as illustrated in figure 2: (1) the project data base that contains factor values and other performance related data; (2) a library of causal models; (3) a hypothesis generating, search and reporting component; and (4) a data visualization component.

The project data base component, as illustrated in figure 2, is the source of factor values, which can be organized in a hierarchical fashion (indicated as categories, factors, sub-factors in figure 2). The causal models are formed using the lowest level in the hierarchy. We observe that for the case of sub-factors, there is no obvious way to integrate across different sub-factors to create some kind of index at the factor level that represents the combined effects of the sub-factors. An underlying assumption of our approach is access to the necessary data either through a fully integrated system that supports multiple construction management functions or through an environment which supports interoperability of various applications in support of these functions. We use the former approach herein.

The second component of the approach corresponds to a library of causal models expressed in terms of the factors contained in the first component, as shown on the right hand side of figure 2. Central to this component is a user interface which allows ready access to these factors, a simple way of defining and editing a causal model and relevant meta data, and an effective way of organizing the models developed. We believe that the most useful way to organize the library is in the form of a hierarchy, with the first level in the hierarchy corresponding to basic performance variables/measures as shown. Under each performance variable, a number of factor models can be formulated by practitioners to represent different working contexts (e.g. for activities, protected vs. unprotected work). Also included as applicable would be default casual models which reflect findings in the literature. By organizing the models in the manner suggested, it is possible to compose higher level models from lower level ones. Then, if the request as part of the query process in the third component of the approach is to find any and all evidence in support of the causal models used for diagnosing reasons for extended project duration, then a higher level causal model could be assembled in accordance with figure 1.

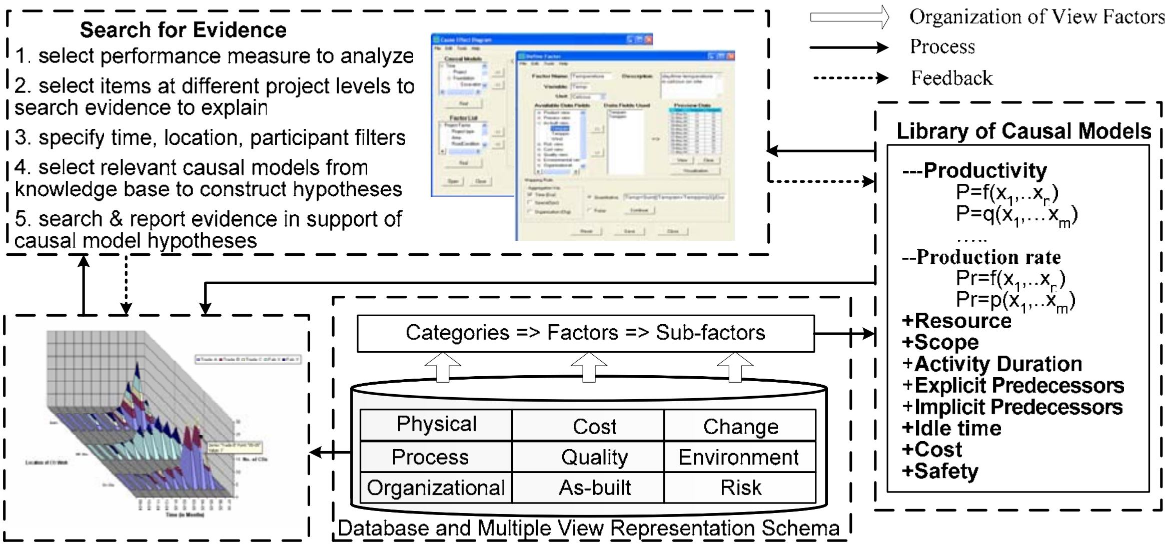

Figure 2. Main Components of Approach to Diagnosing Reasons for Performance

As shown in the upper left hand side of figure 2, the third component relates to the actual search for data in support of the performance hypothesis of interest. Steps in this process are basically self explanatory and consist of: (i) selecting the performance measure to be examined (e.g. project duration); (ii) choosing the system entities of interest (e.g. all critical activities); (iii) specifying filters as to the breadth of the query in terms of one or more of time frame, spatial dimension and project participants of interest (e.g. for our project duration measure, set the time frame to be project start to time of last schedule update); (iv) selecting/developing the relevant causal model from the library of causal models either manually or with assistance by the system depending on the level of information specified by the system user and specify relevant user tests and corresponding thresholds for factors as appropriate; and (v) executing the search for supporting evidence and presenting it in various user specified reporting formats.

Finally, while not central to our approach, a fourth component, as shown in the lower left hand corner of figure 2 relates to the ability to visualize project data. Such a capability can assist with the inspection of masses of data as part of the process of formulating causal models, and for viewing evidence found as part of the search process in component 3.

APPLICATION OF APPROACH TO AN EXAMPLE PROJECT

In this section, we demonstrate selected aspects of our approach by way of its application to an example project which consists of a 6 story residential building and single level underground parkade. The current construction market is very hot, with shortages of labour occurring in several key trades, and overburdened design offices. Notice to Proceed was received in time for a 20 October 2003 start of fieldwork. The project must be completed no later than 31 August 2004. Since the project is being built in a relatively quiet residential area, working hours must conform strictly to existing by-law requirements. As per the geotechnical report, the potential for encountering large size boulders was noted. The expectation was that the chances of encountering contaminated soil were low to very low. A shotcrete shoring system was specified, and it was anticipated that surrounding soil would provide good anchorage for the anchoring rods. Unfortunately, not all of the expectations have been met, and in addition, the weather has proved to be atypically bad for this time of year. It is now 28 November 2003, and to date work has not progressed well. While the original scheduled completion date was 31 August 2004, the new projected completion date is 21 September 2004, assuming no revisions are made to the schedule to make up lost time. Using an extended causal model that conforms to the structure of figure 1, the contractor wants to find all evidence in the project data base to the effect that the causal model factors explain performance to date.

From the project description it is observed that there is an unacceptable variance in project duration (step 1 in figure 1). Thus, the next step (2a) involves identifying the critical activities and paths. This step relates to the upper left hand component in figure 2, in which project duration has been selected as the performance measure, all critical activities have been selected, a time window of 20 October (project start) to 28 November 2003 (current progress date) has been selected, and activity duration causal models from the causal model library selected for unprotected, equipment intensive, substructure work. The analysis that relates to steps 2(b) and 2(c) is then conducted in order to narrow the search for factors that describe performance. Partial results from this analysis are shown in Table 2. Only one activity, Bulk Excavation, shown shaded in Table 2 is identified for further investigation (our example is intentionally simple because of space constraints). Based on the profile specified in the upper left hand component in figure 2, the appropriate casual model is selected, as shown on the left hand side of figure 3. This model is meant to be defined by construction personnel, using the factors contained in the project data base. These factors are shown on the right hand side of figure 3, organized first by project view, then categories and subcategories of factors, and then the factors themselves. The source of the factors specified is the as-built view of the project. A visual representation of two causal model factors and activity status on a daily basis is shown in figure 4. Given a specification of thresholds by the user for various factors (e.g. precipitation levels), then the search process will explore the project data base and find which factors of the ones identified in the causal model, along with their associated values and links to other information (e.g. correspondence, photos, etc.), explain, at least in part, reasons for performance to date.

Table 2. Critical Activities and Their Properties

Act. Code	Act. Description	Location	Critical Activity	Pred. Relation	Pred. Variance	Start Variance (days)	Duration Variance (days)	Idle Time (days)	Finish Variance (days)
01	Receipt of notice to proceed	GLOB	Y	N/A	N/A	0	0	0	0
02	Mobilize and clear site	SITE	Y	01(FS0)*	0	0	0	0	0
03	Bulk excavate substructure	PKDE	Y	02(FS0)*	0	0	[11]	[4]	[11]
04	Shotcrete shoring	PKDE	Y	03(SS2)* 03(FF2)	0 [11]	2	4	2	6
05	Excavate footings	FDN	Y	03(FS0)*	[11]	6	[0]	[0]	[6]
06.01	F/P/S perimeter wall footings	FDN	Y	05(SS2)* 05(FF5) 04(FS0)* 44(FS0)	6 [6] 6 [1]	5	[0]	[0]	[5]
06.03	F/P/S column footings	FDN	Y	06.01(SS2)*	5	4	[0]	[0]	[4]

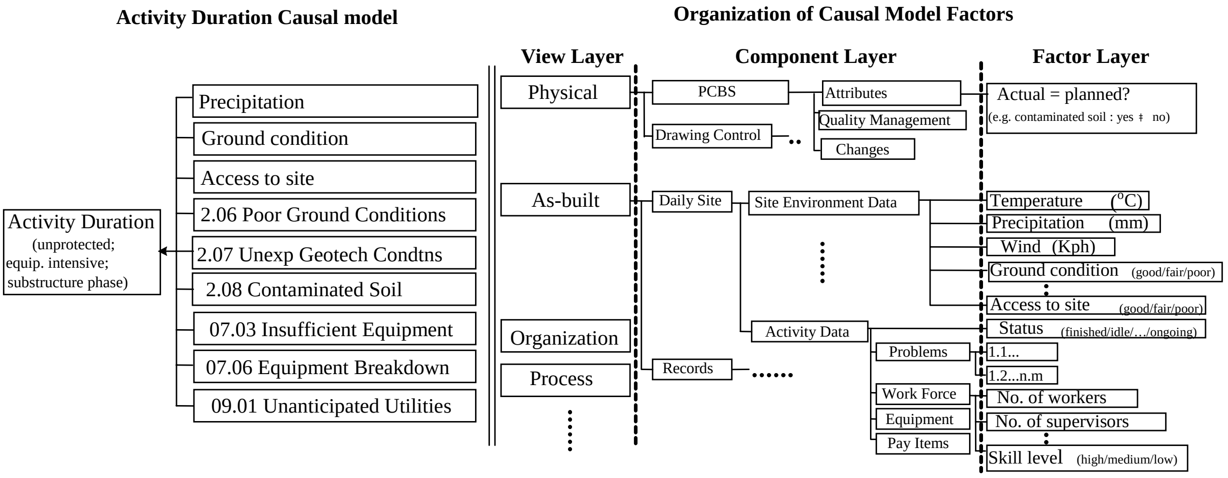

Figure 3. Formulation of Causal Model for Activity Duration

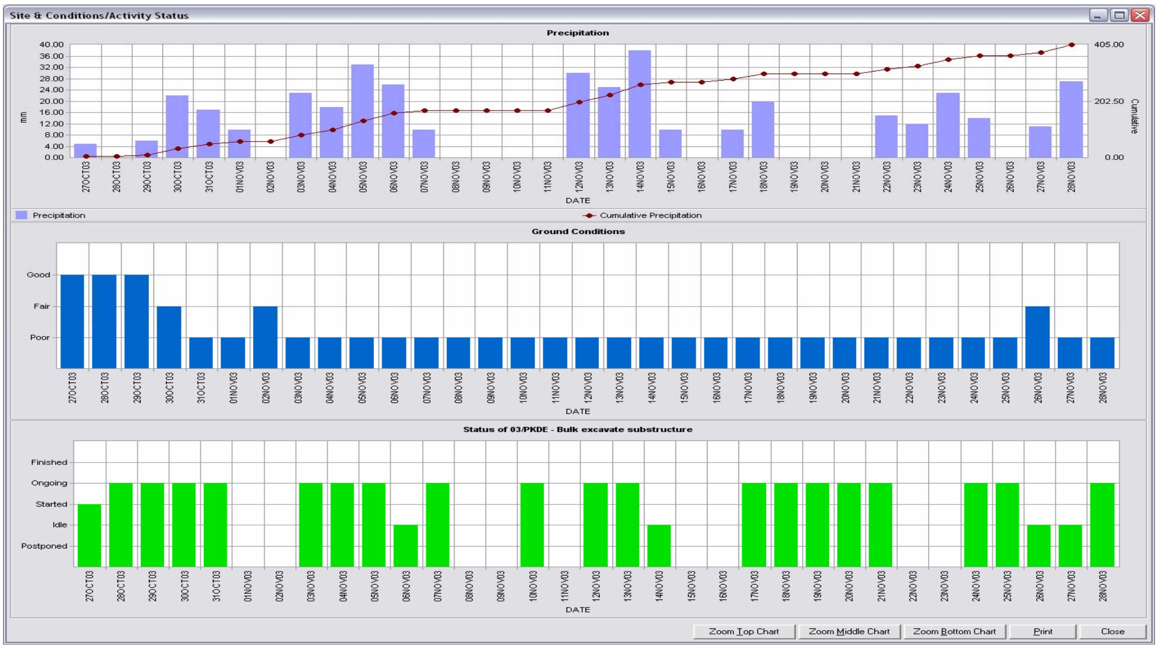

Figure 4. Data in As-Built View

CONCLUSIONS

In this paper the authors have designed a comprehensive schema for diagnosing reasons for performance for a broad spectrum of performance measures. Central to the schema is the ability to capture the diagnostic expertise of seasoned construction personnel in the form of causal models which build on data collected in support of management functions. Factors deemed to be important by other researchers for predicting and explaining construction performance are treated, either directly or through related surrogate measures. Ongoing work is directed at eliciting causal models from construction experts in combination with continued exploration of the literature, determining meaningful tests for factor values in order to assess when negative states of a factor will impact performance, implementing the causal model library component and data search aspects of the schema, and demonstrating the efficacy of the approach using actual project data.

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