WEB-BASED INTEGRATED PROJECT CONTROL

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Abstract

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Time-and-cost control is an essential management function for successful delivery of engineering, procurement, and construction projects. Considerable research efforts have been expended on this topic. However, those methods often suffer from a lack of integrated tracking and control. In general, control systems generate variance reports and provide analysis, diagnosis, and forecasts of project cost and duration at completion. Nevertheless, there is a need not only for an efficient computational environment that allows data sharing among project team members in the control process, but also for providing reasons behind unacceptable performance and for improving forecasting capabilities.

This research presents a web-based system that supports project time-and-cost control in an integrated manner. The developed system utilizes object-oriented modeling to represent project deliverables. A set of control-objects is designed to represent the work tasks in the construction process. A hierarchy structure using a three-level performance evaluation method not only identifies the time-and-cost

variances at each control level, but also evaluates the calculated variances against a pre-defined criterion. Eighteen key indicators chosen from the literature serve as sensors to highlight problematic areas associated with unfavorable performance. Four causal models are developed to define the relationships among the indicators. Fuzzy binary relation and union operations are employed to explain the reason(s) behind unfavorable performance and to suggest related corrective action(s). An indicator-based fuzzy forecasting model is developed to assist in predicting time and cost at completion and at interim future horizons.

A prototype system "IT/CC" (Integrated time and cost control) is developed in the structure of Three-Tier Client Server architecture to implement the developed methodology. Sixty web forms serving different input, browsing, and editing purposes are developed. Five databases, namely, *Project*, *Factor*, *Reason*, *Case,* and *Historical* are developed to facilitate the implementation of the IT/CC system. The IT/CC system takes advantage of the World Wide Web to provide an efficient data sharing and collaborating environment for tracking and control of construction activities. It also provides timely generation and dissemination of site progress reports. Daily, weekly, monthly and/or yearly, period-by-period, and to-date project performance reports are generated to provide the status at project, control-object, and resource levels. The on-line data sharing ability provides real-time data for team members and allows them to react in a timely manner.

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Very special thanks to my parents and brothers for their irreplaceable generosity, constant motivation, and unfailing support.

Last but not the least, I would like to express to my wife, son, and daughter my deep appreciation for their love, patience, encouragement, and sacrifice.

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Nomenclature

A_r	subset of corrective actions for the r resource
a_m	corrective actions
ACV	at completion variance
ACWP	Actual Cost of Work Performed
$ACWP_i$	Actual cost of work performed at the i^{th} percentage completion
BAC	Budgeted cost at completion
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
$BCWS_r$	Budgeted Cost of Work Scheduled based on PC_b
$BCWS_s$	Budgeted Cost of Work Scheduled based on PC_s
c	constant for individual
C	Composition operator
C_b	budgeted cost
C_i	predicted cost using performance data from the previous reporting period
$C_k^{'}$	adjusted cost at the k^{th} future horizon
C_k	as in $C_k^{'}$, but based on performance data up to the previous reporting period;
CN_a	current-period or to-date average number of crew
CN_b	planned number of crew
CP_a	current-period or to-date average crew payment
CP_b	budgeted crew payment
CP_r	crew payment rate
CPI	Cost Performance Index
CR	Cost Rate
CV	Cost Variance
CV_{cn}	variance caused by crew attendance
CV_e	equipment cost variance
CV_{ep}	variance caused by inferior equipment productivity
CV_{epd}	allocation of the variances caused by control-object production
CV_{eq}	allocation of the variance caused by control-object quantity
CV_{eu}	variance caused by equipment unit cost
CV_{ur}	variance caused by equipment usage rate
CV_{hr}	variance caused by labor hourly cost
CV_l	labor cost variance
CV_{lp}	variance caused by labor productivity
CV_{lpd}	allocation of the variance caused by control-object production
CV_{lpdt}	production variance caused directly by inferior labor productivity
CV_{lq}	allocation of the variance caused by control-object quantity
CV_{lstart}	start-variance contributed to labor cost variance
CV_{lu}	variance caused by labor unit cost
CV_{cp}	variance caused by crew payment rate

CV_m	material cost variance
CV_{mpd}	allocation of the variance caused by control-object production
CV_{mu}	variance caused by material unit cost
CV_{ms}	variance caused by material usage
CV_{mp}	variance caused by material price
CV_{mq}	allocation of the variance caused by control-object quantity
D	estimated duration at completion for a control-object
d	the number of days that have passed
D_a	current-period or to-date duration of a control-object
D_b	planned duration
D_c	estimated duration at completion
$D_i^{'}$	predicted duration using the performance data from the previous reporting period
D_i	actual duration elapsed at the reporting date
$D_k^{'}$	adjusted duration at k^{th} future horizon
D_k	as in $D_k^{'}$, but based on data up to the previous reporting period
D_p	project duration
D_s	number of days to-date since scheduled start of an operation
$D_{to\text{-}date}$	number of days to-date since actual start of an operation
e	earning to-date (actual cost)
e'	error term
E	measured total earning (actual cost) over the period
EAC	forecasted cost at completion
EC_a	current-period or to-date cumulative actual cost of equipment
EC_b	budgeted equipment cost
ECAC	estimated cost at completion
EP_a	current-period or to-date average unit productivity
EP_b	budgeted unit productivity
EP_r	ratio of equipment productivity
EU_a	current-period or to-date average equipment unit cost
EU_b	equipment planned unit cost
EU_r	ratio of equipment unit cost
EV	earned value
F_p	planned finished date
F_r	subset of the problem source factors for the r resource
f_1'	performance of management
f_2'	cash flow situation
f_3'	material and equipment availability
f_4'	labor availability and productivity
f_5'	weather and other environment influences
f_6'	amount of rework, extra work, work difficulty
f_7'	percentage of work completed
f_8'	past project's performance trend
f_k	problem-source factors
i	the i^{th} percentage completion at reporting date

k	at future horizons, k=1 to10
J	judgment of an individual
j	number of the increments up to PC_s
L_b	lag time
LC_a	current-period or to-date cumulative actual cost of labor
LC_b	budgeted cost of labor
LH_a	actual current-period or to-date average labor hourly cost
LH_b	budgeted labor hourly cost
LH_r	labor hourly cost ratio
LP_a	current-period or to-date average unit productivity
LP_b	labor planned productivity
LP_r	ratio of labor productivity
LU_a	current-period or to-date average labor unit cost
LU_b	labor planned unit cost
LU_r	labor unit cost ratio
LU_s	planned labor unit cost
m	measured mean value
MBL	baseline average slope after report date
MC_a	current-period or to-date cumulative actual cost of material
MC_b	budgeted cost of material
$Mhrs_a$	current period or to-date cumulative actual man-hours consumed
$Mhrs_b$	budgeted man-hours
MP_b	estimated material price
MP_a	actual material price
MP_r	material price ratio
MQ_a	current-period or to-date average material usage of a control object
MQ_b	budgeted material quantity
MU_a	current-period or to-date average material unit cost
MU_b	material planned unit cost
MU_r	ratio of material unit cost
n	number of units in the job or total number of control-objects
n'	total number of on-going and finished control-objects
N_a	current-period or to-date average number of crew
N_b	budgeted number of crew member
N_r	crew attendance rate
N_t	actual number of crew member on the t^{th} day
PC_a	control-object actual to-date percentage completion
PC_b	to-date revised percentage completion
PC_p	actual percentage completion of a project
PC_s	planned to-date percentage completion
PERA	number of tasks (activities) actually completed up to report date
PERAC	number of tasks (activities) completed as planned at completion
PERBL	number of tasks (activities) completed up to report date as planned
PS_{in}	percentage strength of n^{th} factor for v_i variance

Q_a	actual quantity installed of control object
Q_b	revised cumulative quantity
Q_{object}	total quantity of control-object
Q_s	planned quantity allocation
Q_{sa}	actual quantity installed of sub-contractor(s)
Q_{sb}	revised cumulative quantity of sub-contractor(s)
Q_{ss}	planned cumulative quantity of sub-contractor(s)
Q_v	control-object revised quantity
r	number of rules
RPI	crew productivity index
S_r	subset of the performance indicators, (r=1...4)
s_j	performance indicators, (j=1...14)
s^2	variance of the individual units
SA	actual average slope before report date
SC_a	actual cost of sub-contractor(s)
SC_b	budgeted cost of sub-contractor
SBL	Baseline average slope before report date
SPR	Schedule Performance Index
SC_b	budgeted sub-contractor(s) cost
SC_a	cumulative actual sub-contractor(s) cost
SPI	schedule performance index
SV	schedule variance
SV_{start}	control-object start-variance
$SWhrs_a$	actual working-hours of sub-contractor(s)
$SWhrs_b$	planned working-hours of sub-contractor(s)
T	getting well date, which is the crossing point of MBL and SA
T_a	control-object actual starting date
T_c	actual finished date
T_f	planned finished date
T_p	project planned start date
T_r	reporting date
T_s	scheduled start date
T_v	Control-object time variance
TAC	estimate project completion date
TBL	baseline completion date (as planned),
TCI	total cost performance index
UR_a	current-period or to-date average usage rate
UR_b	planned equipment usage rate
UR_r	equipment usage rate ratio
V_r	subset of cost and schedule variances for the r resource, (r=1...4)
v_i	cost and schedule variances respectively, (i=1,2)
w_k	weights for the cue variables,
W_r	relative weight of the r resource under a control-object
$Whrs_a$	current period or to-date cumulative working hours
$Whrs_b$	budgeted working hours for equipment

x	crisp value of an input variable or the center of an area
x_i	cues used to make the judgments
x_{COS}	center of sums
μ (x)	degree of membership
σ	measured standard deviation
α%	Management and job condition factor
α_k	10 percent increments for k^{th} future horizons measured moving forward from the reporting date.

Abbreviations

AEC	Architecture Engineering and Construction
ASP	Active Server Pages
BOD	Basic construction operation required by a design object
CBS	Cost Breakdown Structure
CBR	Case-Based Reasoning
CGSB	Canada General Standards Board
CRI	Compositional Rule of Inference
C/SCSC	Cost/Schedule Control Systems Criteria
DBMS	Database Management System
DoD	Department of Defense
EPC	Engineering Procurement Construction
EVMS	Earned Value Management System
GDP	Gross Domestic Products
GMP	Generalized Modus Ponens
HTML	Hyper Text Markup Language
IAI	International Alliance of Interoperability
IFC	Industrial Foundation Class
IT	Information Technology
IT/CC	Integrated time and cost control
KBES	Knowledge-based expert systems
OBS	Organization Breakdown Structure
OOM	Object-oriented modeling
OOP	Object-Oriented Programming
P3	Primavera Project Planner
PBS	Product Breakdown Structure
PERT	Program Evaluation and Review Technique
SPEs	Scheduled Performance Estimators
SQL	Structure Query Language
UML	Unified Modeling Language
WBS	Work Breakdown Structure
WCBS	Work Classification Breakdown Structure

Chapter 1

INTRODUCTION

1.1 Time and Cost Control

Tracking and control of engineering, procurement, and construction (EPC) projects are essential management functions for successful delivery of these projects (Moselhi 1991). Tracking refers to the process of monitoring variations during the course of project execution. Control refers to the action(s) taken to alleviate unacceptable variations. The control reference in a project control system called the baseline has to be pre-determined. It includes the budgeted data pertinent to project time and cost. The primary objective during the construction process is to complete the project on time and within budget while meeting established quality requirements and other specifications (Singh 1991). As such, a project time-and-cost control system should be able to identify time and cost deviations from its baseline and to take action(s) to remedy any differences in order to be within budget and on target schedule.

Construction industry plays a major role in Canada's economy, employing nearly 931400 people and accounting for over 5.4% of the Gross Domestic Products (GDP) in 2003 (Statistics Canada). Canada statistics reveal that the capital expenditure on residential construction was 61,405.9 million dollars in 2003. There were about 218,000 small and medium sized Canadian construction companies in the year of 2000 (Statistics Canada). 920 construction companies went bankrupt in 2000 across Canada (Statistics Canada). The reason(s) for the bankruptcy may vary, but with a large amount of investment in the construction industry and the high rate of bankruptcy of construction companies, tracking and control of the construction process are necessary.

A well-defined control system can maximize profit. It can also minimize the possibility of delays and cost overruns for the project. In practice, a majority of construction projects already employ methods for time and cost control during construction. However, those methods often suffer from a lack of integrated tracking and control. In the past decades, the integration of time and cost for project control has received considerable attention (Singh 1991, Diekmann and Al-Tabtabai 1992, Abu-Hijleth and Ibbs 1993, Abudayyeh and Rasdorf 1993, Moselhi 1993, Ballard and Howell 1998, Fayek et al. 1998, Alshaibani 1999, Fayek 2001, Moselhi et al. 2001, 2002, 2004). However, a system that can group the main issues associated with project control such as performance evaluating, reasoning, forecasting, and reporting is still under development.

This research presents an integrated web-based time-and-cost control system that is designed to evaluate the project performance and diagnose the factors behind unacceptable variances. It also recommends the most suitable corrective actions for the identified factors. It forecasts expected performance at user-specified time periods and at completion. The system utilizes earned value method, fuzzy reasoning, fuzzy rule-based inference process, Internet-based

Database Management System (DBMS), and the programming language of ASP (Active Server Pages), Java Applet, JavaScript, VBScript, and HTML (Hyper Text Markup Language) to perform its tasks.

1.2 Background

The control process generally consists of five major operations as shown in Fig. 1.1: control baseline generation, performance evaluation, forecasting, diagnosing, and corrective action.

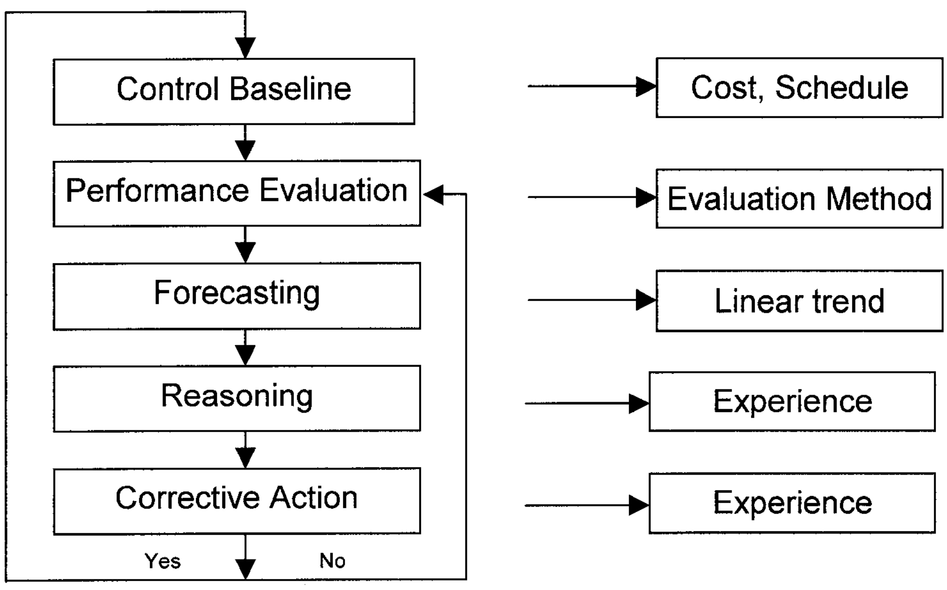


Figure 1. 1 Control System Components

Control Baseline serves as a reference in a project control system. It contains the budgeted cost and the estimated duration of control units in a project. The budgeted cost includes the planned cost of labor, material, and equipment. The work scope of a control unit is defined by Work Breakdown Structure (WBS), which progressively breaks a large complex project down into small and operative units (Moselhi 1991). The schedule of the project determines the planned start date and planned finish date of the control units. The baseline is a preset, time-dependent, and accumulated cost. It reflects planned resource consumption during the course of construction. The baseline curve generally was an "S"-shape, and is often referred to as "S" curve.

Performance Evaluation is carried out using algorithms designed to calculate time and cost variations against the baseline. Traditionally, the methods used in project control often suffer from a lack of integration of cost and schedule (Douglas III 1993). To avoid this, the earned value method proposed by the U.S. Department of Defense (DoD) in 1967 calculates the time and cost variances in an integrated manner (Christensen 1994). This method has been widely accepted by the Architecture Engineering and Construction (AEC) industry to track the performance of EPC projects. In a project control system, the earned value method can identify the cost and schedule variances, but not the reasons behind detected unacceptable performance.

Forecasting predicts the time and cost at completion. Prediction of the future impact based on the current performance could help project managers or contractors make the right decision. Many methods, therefore, have been proposed, such as DoD (1967), and others as will be described later in Section 2.5. In most cases, those methods are based solely on a linear-trend forecasting technique, assuming that the past performance to the present will still prevail in the future.

Reasoning is a procedure of detecting the cause(s) behind unacceptable performance. Corrective Action(s) is recommended once the reason(s) is (are) determined. In current practice, those procedures mainly rely on a project manager's or contractor's own experience or rule of thumb. Research efforts have been made to help project managers identify the reason(s) behind unacceptable performance using a knowledge-based system (Diekmann and Al-tabtabai 1992) and/or a fuzzy reasoning method (Russell and Fayek 1994). Those efforts are limited to an individual control unit such as an activity/work-element and its resource performance, for example, labor. They do not consider the impact of precedence control units and the hierarchical structure of the project itself.

Another important feature that has often been disregarded in most project control systems is the efficient computational and communicational environment. Project success relies heavily on the timely transfer of information among project team members (Rojas and Songer 1999). With the explosive development of Information Technology (IT), the Internet -- such as the World Wide Web, Intranets, electronic mail, software, data transfer, etc. -- is becoming a global communication technology (Bentley 1997). The existence of the Internet and the wealth of related technology will change engineering and construction practice

(Froese and Waugh 1996). The use of the Internet has increased significantly in recent years. With its high speed, easy access, distributed network, and cost effectiveness, the Internet provides an efficient computational and communicational environment for project control. It also provides a collaborative environment that allows project team members to work simultaneously from different geographical locations as described later in Section 7.2.3.

Taking the above into consideration, an efficient project control system should have the ability to configure the WBS in order to establish the baseline as a control reference. It could generate standardized and generic earned-value-based status reporting for performance evaluation. Further analysis and diagnostics of reported project variances are also necessary to locate the cause(s) behind unacceptable performance. Therefore, project specific knowledge is utilized in the reasoning process. The recommendations for corrective action(s) should be handled in a similar way to the reasoning process. A more realistic and practical method is also needed to improve the current forecasting process. In addition, there is a need for an efficient computational and communicational environment that allows for data sharing and collaboration among members of project teams. In a word, the major tasks of this research consist of seeking an effective way to diagnose the source of variances, forecasting future performance, and circumventing the limitations referred to in the above.

1.3 Research Scope and Objectives

This research focuses on the construction stage of a project, particularly from the perspective of contractors. The two most common objectives of time and cost are considered, i.e. excluding quality and safety control.

The main objective of this research is to develop a method for integrated project time-and-cost control and implement it as an application on the World Wide Web for EPC (Engineering, Procurement and Construction). The sub-objectives include the development of:

1. Method to integrate time and cost performance and identify variances for project control
2. Method to diagnose the cause(s) behind each individual variance and to recommend possible corrective action(s) behind unfavorable performance
3. Method to forecast project time and cost at different intervals and at completion
4. Flexible platform that supports information sharing among members of project teams
5. Prototype web-based project control system to assist project teams in time-and-cost control utilizing the developed methods referred to above

The capabilities of the developed control system are demonstrated through the use of a numerical example.

1.4 Research Methodology

The methodology adopted in this research is based on field investigation of current project control practice as carried out by contractors in Ottawa, Montreal, and Los Angeles. The first stage of this research involves a literature survey focusing on project control models, performance evaluation methods, reasoning methods, forecasting methods, project control systems, and various tools utilized in the development of a project control system. Special attention was directed towards an Internet-based system.

The second stage is to develop an effective methodology for integrated project time-and-cost control benefiting from the results of previous studies. This involves defining the basic elements of a project control system, establishing a criterion to evaluate the project performance, and designing a reasoning method to diagnose the factors that negatively impact performance, to suggest corresponding corrective actions, and to forecast time and cost at completion.

The next stage of the research involves the implementation of the developed methodology in a prototype that is web-based utilizing the ASP, Java Applet, JavaScript, VBScript, and HTML as well as a set of databases to support its tasks.

The final stage encompasses testing the performance of the developed system and validating its functions.

1.5 Thesis Organization

The remainder of this thesis is organized into the following Chapters:

Chapter 2 provides a comprehensive literature review of project control models, performance evaluation methods, reasoning methods, forecasting techniques, and existing applications on time-and-cost control. It classifies them according to their employed concepts and methods and identifies the capabilities and limitations of each component in addressing effective project control.

Chapter 3 presents the proposed control-object, the object model of a project, and the management structure of the proposed control system. It then describes the methodology involved in project performance evaluation. Detailed descriptions of the selected resource performance indicators, the identified problem source factors, the multi-level evaluation criteria, and the proposed causal model for each type of resource are provided. Also presented are the evaluation algorithm and the equations utilized to estimate the impact-cost of each highlighted indicator.

Chapter 4 describes possible corrective actions and the proposed multi-level reasoning processes. Detailed descriptions of the methods employed and the operations involved in the processes are provided.

Chapter 5 introduces the developed forecasting method. Detailed descriptions of the processes employed and operations involved in the method are provided. Chapter 6 describes the layout of the developed control system. It starts with the description of the system requirements, its functions, and the resources needed for the system development and implementation, then, followed by detailed description of the system components and their respective functions. Examples of the developed system components are also presented in this chapter.

Chapter 7 presents the implementation scenarios and the validations of the proposed control system. The different implementation scenarios of the prototype system are described. The success of the design and implementation of the integrated web-based integrated project time-and-cost control system is verified using an actual case. An evaluation and comparison of the results for the methods of evaluating, reasoning, and forecasting are provided. The use and capabilities of the system are illustrated via a numerical example.

Chapter 8 describes the conclusions of this research, highlighting its limitations, and contributions as well as suggestions for future work.

Chapter 2

LITERATURE REVIEW

2.1 General

Construction involves a number of activities that transfer drawings and specifications of a project into a real product. A substantial plan and a control system are necessary to manage the construction process. A plan establishes objectives of the project schedule, cost and resource usage, as well as tasks and methods for carrying out the work. The plan is usually developed, basing it on an historical database together with the past experience of similar projects. A short-term plan contains more detailed information than a long-term plan. A control system collects current site data on a project's schedule, cost, and resource usage giving details of the same level as planned and compares those data to the planned values in order to highlight potential problem areas that require attention; then the project manager makes decisions based on the results of the analysis. Traditionally, time is tracked and controlled through some form of schedule, which is tied to a certain measure of physical progress such as percent complete, while cost is dealt with through the use of the S-curve (Moselhi 1993).

In recent years different methods for facilitating overall project control have been developed. Some of these methods separate schedule and cost control while others integrate them (Alshaibani 1999). In fact, controlling time and cost as independent parameters is not satisfactory since the actual accumulated cost may exceed the budgeted cost at some point in time -- indicating an apparent cost overrun -- while in reality the project progress may be ahead of schedule. Accordingly, time and cost control must be integrated for efficient project tracking and control (Abudayyeh and Rasdorf 1993).

The following Sections review the existing components of a control system including: control models, performance evaluation methods, reasoning methods, and forecasting methods along with their applications. The limitations of each method are addressed.

2.2 Control Models

The control model defines a standard template for project control. Existing control models can be classified into three categories: process control models, production control models, and project control models. Process control models are developed, basing them on a process model that presents information on the process works, methods, resources, organization, etc. Production control is based on a product model which describes the product data information, the dimension, relationships, size, material, etc. There is no standard definition that is agreed upon for a product model (Al-Hussein 2000). The project control model is an integration of different systems or structure. The three models noted above are described and discussed as follows.

2.2.1 Process Control Model

The work package, activity, and work element are all process-oriented control-objects defined for project control (e.g. DoD 1967, Singh 1991, Diekmann and Al-Tabtabai 1992, Abudayyeh and Rasdorf 1993, Fayek. et al. 1998, Alshaibani 1999, Fayek 2001). All of these rely on the Work Breakdown Structure (WBS) (CGSB 1999) to define the scope of each work.

WBS is a product-oriented process which breaks the project down into progressively smaller and simpler operation units for the purposes of cost estimating, planning, scheduling, and controlling. Fig. 1.2 gives an example of such a hierarchical structure. It provides a graphical representation of a contract's statement of work, specifying the elements of work to be performed and their relationships to each other (Abu-Hijleh 1991). The WBS is generally configured in accordance with the way the work will be performed and reflects the way in which project costs and data will be summarized and eventually reported (Kerzner 1995). Usually, the lowest and most detailed level of a WBS is known as the work tasks. This represents the actual tasks that will be used in the project's activity network. An activity may contain several work tasks. A work package (DoD) is a general expression that represents a well-defined scope of work that usually terminates in a deliverable product. The work package might be a work task, an activity, a structure or a project as a whole in a control system. It could also be a service. The above-mentioned representations of work introduce activity-based or work package-based cost control concepts.

The WBS has to combine with the Organization Breakdown Structure (OBS) to correlate with tracking and control functions. OBS defines the organizational elements responsible for performance of the work. It is the hierarchical depiction of the management organization of the project that defines the functional assignments required to perform the work outlined in the work breakdown structure.

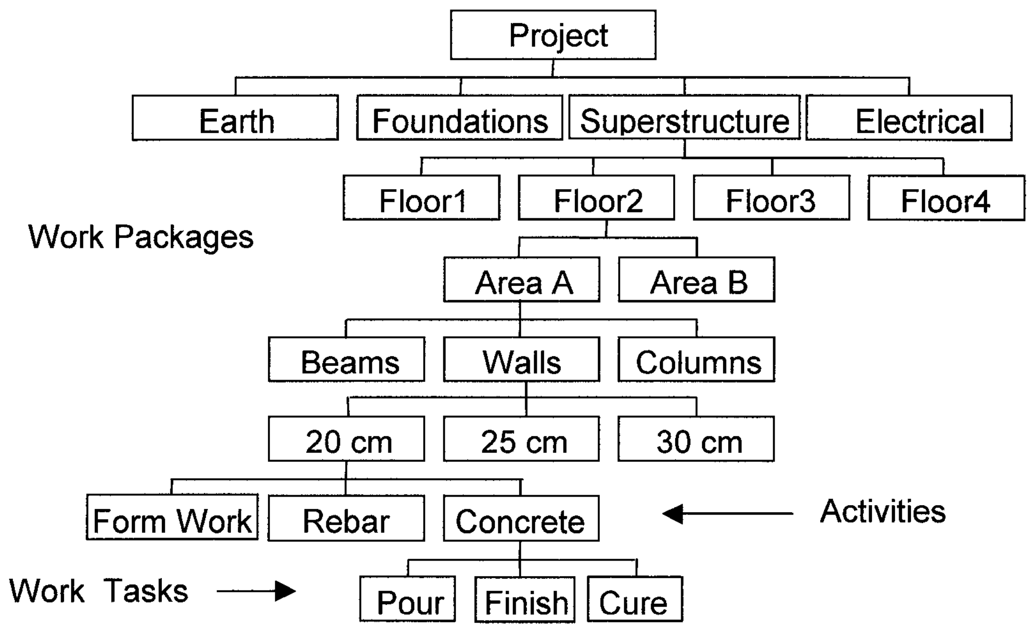
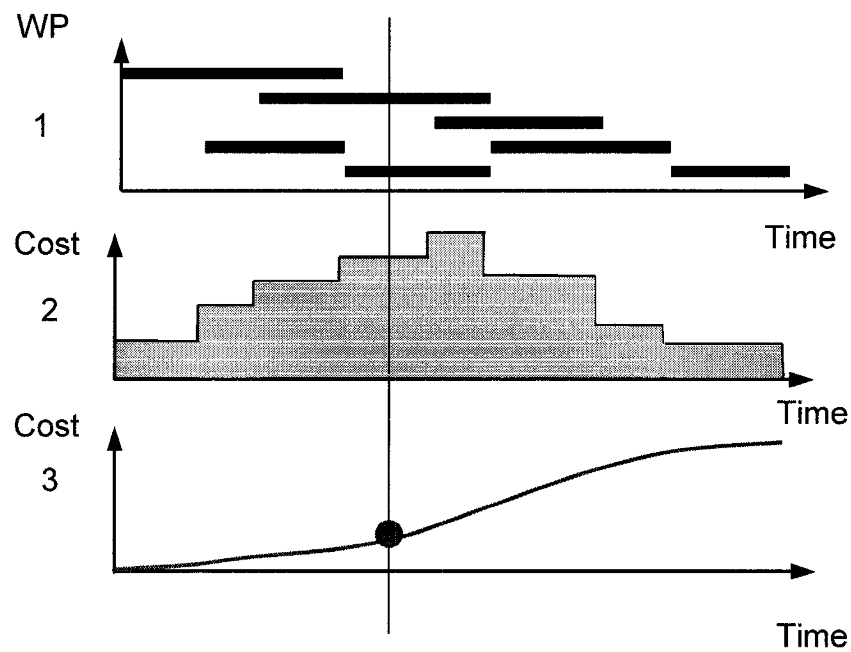


Figure 2. 1 Sample of Work Breakdown Structure

Based on WBS, cost estimation proceeds in a bottom-up fashion. The resource costs of labor, material, and equipment of work-tasks are used to estimate the activity cost. The project cost is a summation of the total cost of all activities.

During the planning stage of a project, work package productivity can be assumed, basing it on past experiences and previous project records. The duration of each work package can be computed according to its cost and productivity. The project schedule is developed, according to the work package's logical inter-dependence relationship. It should also account for all factors that can affect productivity, including anticipated weather, stacking of trades, space congestion, logistics, labor unrest, and regular requirements (Moselhi 1993). A realistic schedule, also referred to as an "as-possible" schedule (Moselhi and Nicholas 1990), is a prerequisite for effective project control.



1. Project bar chart schedule
2. Activity resource allocation
3. Baseline S curve

Figure 2. 2 Baseline Derivation Process (Moselhi 1993)

The control baseline is also known as an "S" curve that can be developed by allocating a cost to the individual activities, on a time-phased schedule, aggregating the cost on a period-by-period basis from start to completion, and plotting the cumulative cost as shown in Fig. 2.2 (Moselhi 1993). The project baseline can best be generated utilizing a realistic schedule (Moselhi 1991). The baseline is subject to change, and, therefore, the control system is required to be flexible to accommodate any variation in the method of planning.

A process is a sequence of events performed for a given purpose. It combines people, tools and procedures to achieve a desired outcome (Sarshar et al.1998). For the process model, project control is accomplished through the tracking and control of objects and their resource consumption during the procedure. Fig. 2.3 illustrates the process control cycle which starts from the beginning of a construction process. As work progresses, all the time-related schedule data and cost-related actual expenditures are collected by field personnel and communicated to management in the form of reports. The manager evaluates the performance of the construction process. If the construction process is proceeding as planned, no action is taken and the control cycle repeats itself. Otherwise, if the actual performance deviates from what was planned, the manager analyses the cause(s) of the deviation based on the data available and past experience. If the deviation is due to poor performance, new instructions are issued to field personnel to carry out future tasks in an attempt to correct the problem and improve performance. Overall, the timely arrival of quality data from the field to the management office is fundamental to the success of this control cycle (Hendrickson and Au 1989, Barrie and Paulson 1984).

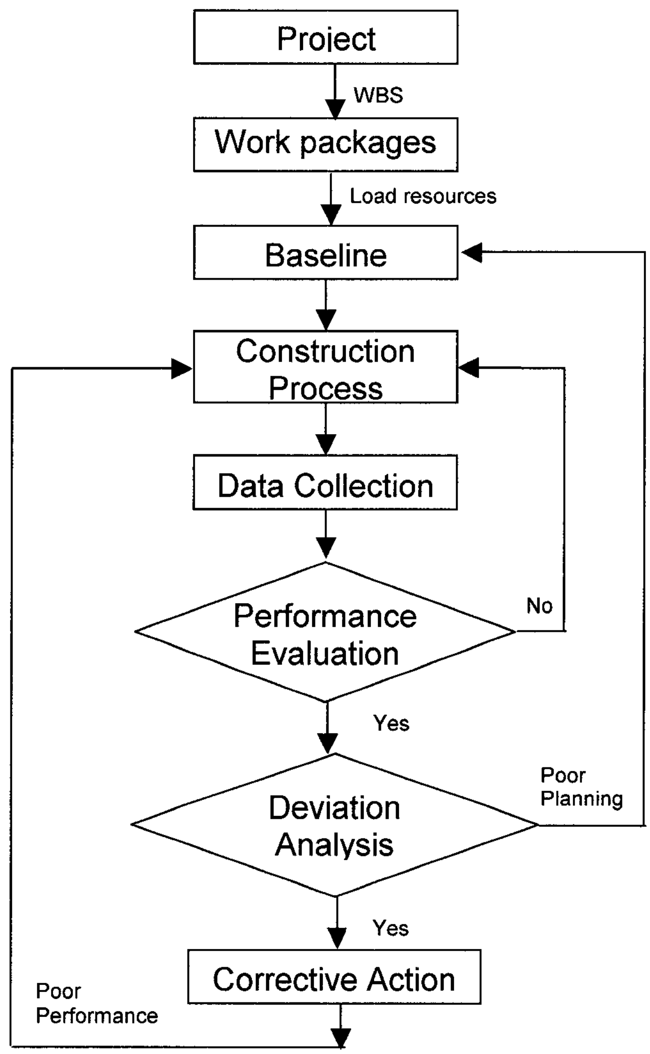


Figure 2. 3 Control Cycle of Construction Process

2.2.2 Product Control Model

In this type of model, the scope of a product unit is defined by a Product Breakdown Structure (PBS), which breaks a project down into small and simple product units according to shape and location. The product unit is the most commonly used object defined for production control (e.g. Howell and Ballard 1996). Another type of product model is the Industrial Foundation Classes (IFCs) developed by the International Alliance of Interoperability (IAI 1996). IFCs consist of a number of standard classes to describe a project including the process of design, construction and facilities management. The architecture of IFCs is based on layers containing model schemas (Froese and Yu 2000). There are four layers defined by IFCs, namely, the resource layer, core layer, interoperability layer, and domain layer. The resource layer describes geometry, units, measures, etc.; the core layer defines a kernel meta-model (i.e., product, process, projects, etc.); the interoperability layer defines data that are used across multiple domain areas (i.e. building elements, structural components, etc.); the domain layer defines data used in specific application areas (i.e. space layout, property management, etc.). The latest version of IFCs is release 2.0. The classes for cost, schedule, resources, and organizations have been developed.

Ballard and Howell (1998) at Lean Construction Institution proposed a shielding production control system. Shielding production comes originally from Toyota manufacture production control experience. The control process consists of workflow control and production unit control. Workflow can be defined as the movement of information and material through the network of production units (Ballard and Howell 1998). The workflow includes information on cost estimation, material supply, design change, and product unit location. Workflow control is accomplished primarily through the look-ahead schedule process. Production unit control is accomplished primarily through a weekly work-planning method.

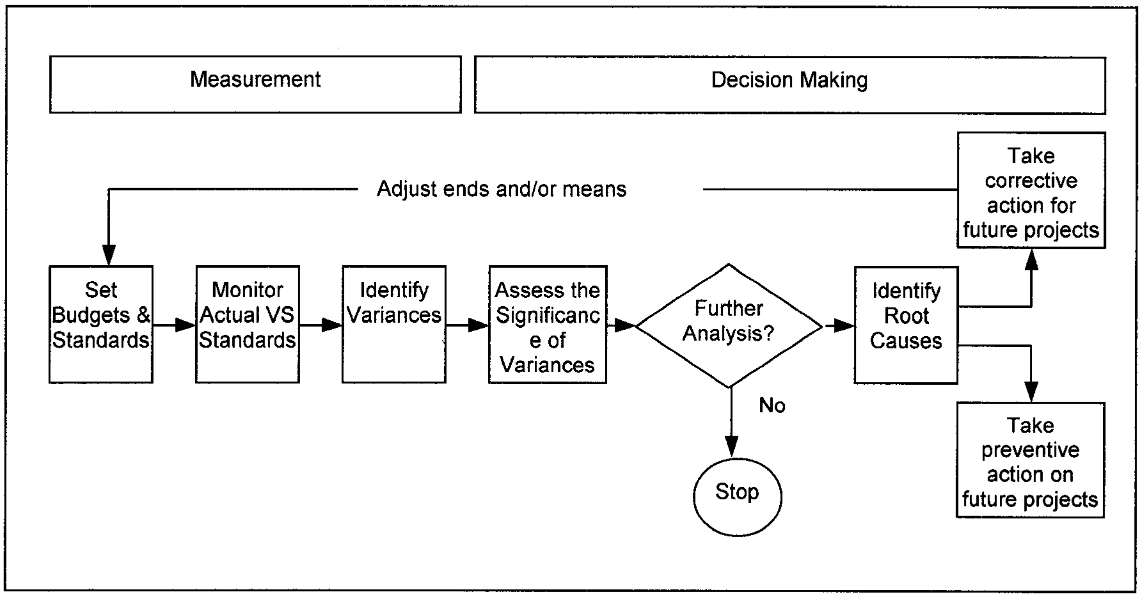


Figure 2. 4 Control Process for Dynamitic Projects

There is some debate about this method: in some of the discussions it is claimed that shielding is unnecessary. In another refutation it is said that the shielding is impossible. Furthermore, some of the literature expresses surprise in that they cannot believe they are already doing it (Ballard and Howell 1998). Their work focuses mainly on the improvement of the planning of a project on weekly basis. The implementation of this method is still under development.

2.2.3 Project Control Model

Project model adds Cost Breakdown Structure (CBS) to WBS and defines the common denominator as an object for project control. The percent allocation concept proposed by Teicholz (Teicholz 1987) and the work elements concept proposed by Hendrickson (Hendrickson and Au 1989) are two examples of these types of models. CBS defines the cost account for accounting control purposes. The problem is that both WBS and CBS present different levels of detail. The question is how to integrate both structures in order to perform time and cost control functions.

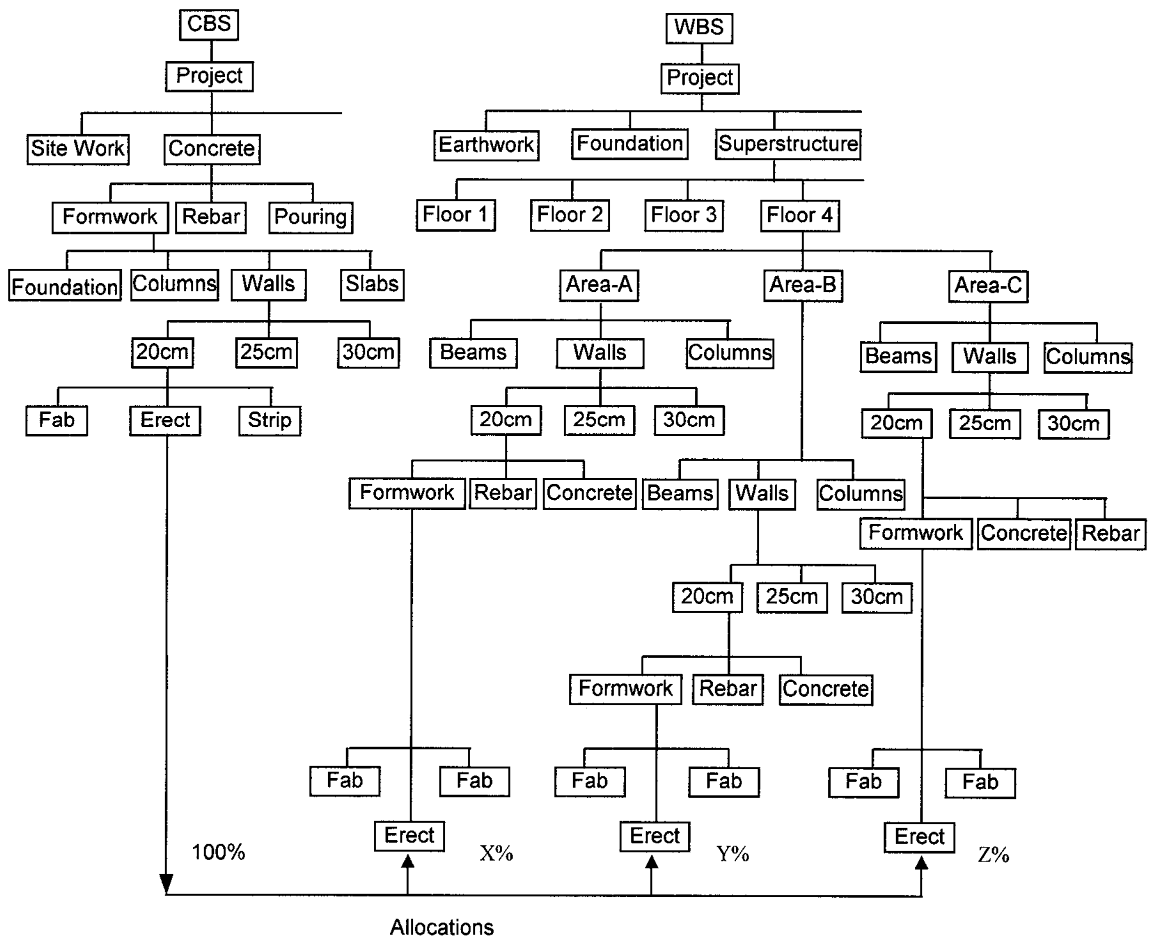
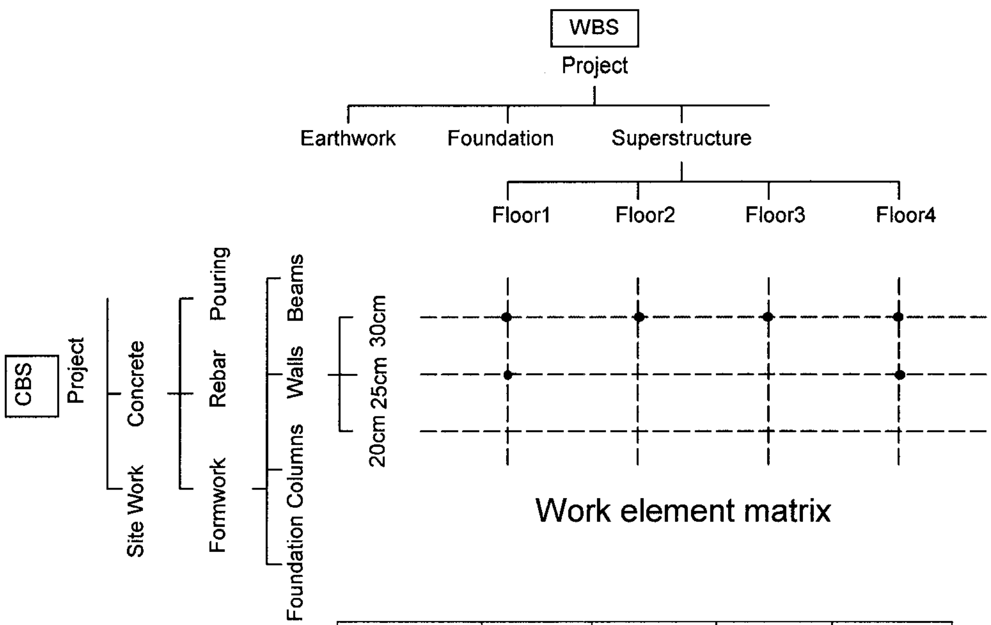


Figure 2. 5 Percent Allocation Model (Teicholz 1987)

The percent allocation model (Fig. 2.5) provides a mapping mechanism according to which specific percentages of a given resource (labor hours, material qualities, etc.) in a CBS cost account should be allocated to a given activity on the WBS. This many-to-many mapping between cost account and scheduled activities allows one cost account to be related to one or more activities, and one activity to be related to one or more accounts. In discussing this method, Teicholz has identified a number of limitations that should be carefully considered when implementing his model. When the use of non-uniform distribution of resource over the duration of an activity is considered, the use of historical data to define the percent allocation is suggested. Additionally, maintaining the links between the cost and schedule control account creates an extra computational overhead that may affect the effectiveness and efficiency of data processing and reporting. In sum, the "percent allocation" concept is approximate and based on judgment.

Hendrickson and Au (1989) proposed a work element model for project control. The three-dimensional work element concept was initially defined by Neil (Neil 1983). A work element is a control account defined by a matrix of work packages from the WBS and of cost accounts from the CBS, as shown in Fig. 2.6. In this model, a work element represents a resource in a particular cost category associated with a particular activity. It provides a link between the WBS and the CBS, where a cost account may be related to one or more activities and at the same time an activity may be related to one or more cost accounts. This many-to-many relationship again uses a work element as a common denominator that achieves the desired integration. According to the Hendrickson's model, the accumulation of cost at a highly disaggregated level results in a more precise and detailed project control. Therefore, problems occurring in a specific activity can be easily isolated and analyzed. Clearly, this leads to improved project control. However, linking two structures involved in summarizing data for cost and schedule control functions creates an extra computational overhead.



		First Floor	Second Floor	Third Floor	Fourth Floor
Cost Accounts	30cm Wall	X	X	X	X
	25cm Wall	X			X
	20cm Wall				

X: work element

Figure 2. 6 Work Element Model (Hendrickson and Au 1989)

BOD (Basic construction Operation required by a Design object) is an example of another type of project model, which integrates WBS, CBS, and the design object as well. It was proposed by Kim (Kim 1989) in order to improve construction project planning and control using an Object-Oriented Programming (OOP) method. The BOD addresses the lowest level of construction tasks needed to build a specific mechanism between a design object and its corresponding construction operation and control functions (WBS and CBS). An example of this model is shown in Fig.2.7. A BOD structure has three dimensions: a work package on the WBS, a cost account on the CBS, and a design object on a drawing.

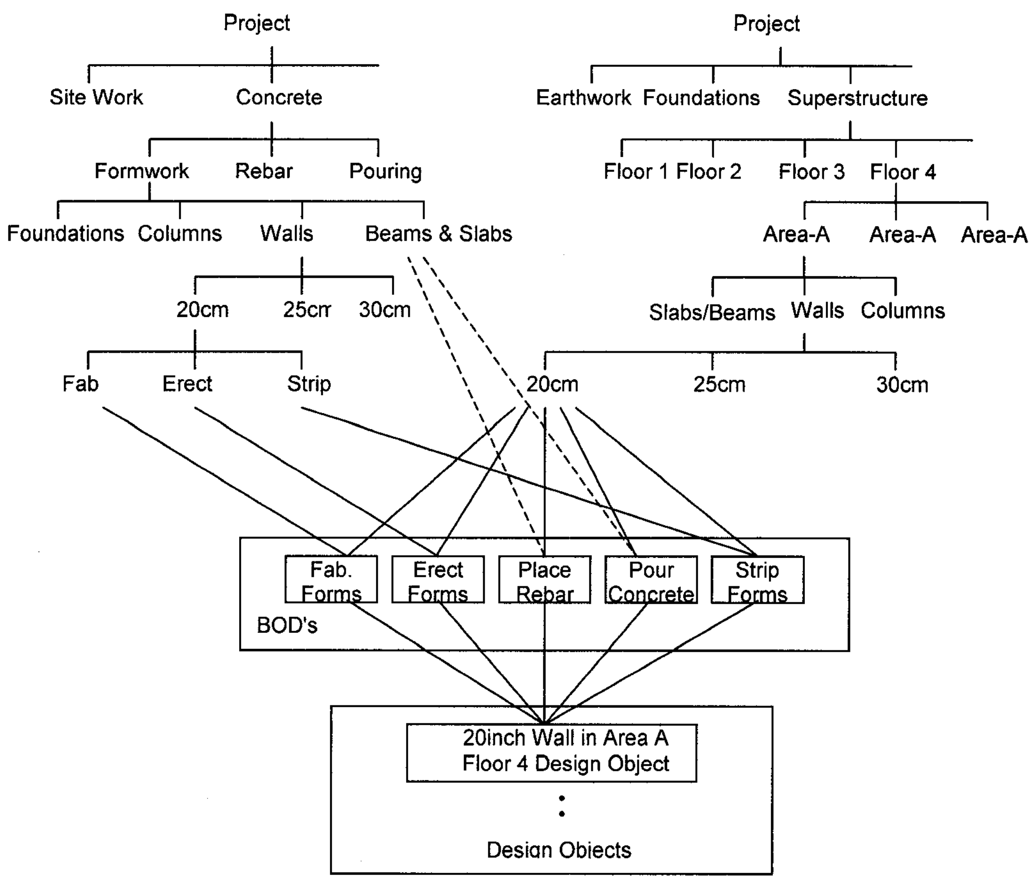


Figure 2. 7 BOD Model (Kim 1989)

This model addresses the data representation aspects of integrating cost and schedule control by developing storage and manipulation mechanisms using the OOP method, but each BOD is defined to such a detailed level that it may be quite difficult to acquire data to support the model. The control procedure implemented for the project model is the same as the process model described in Section 2.2.1.

2.2.4 Discussion

Researchers have recognized and strongly stated the need for integrating cost and schedule control functions and have developed models that attempt to provide the desired integration. They suggest that integration is better achieved when common denominators are established. Project models define linking mechanisms between the WBS and the CBS as the common denominators, but still maintain both views. Product model and process model provide a unified view of project cost-and-schedule control data using either PBS or WBS to define common denominators. The elimination of the linking mechanisms needed by the project model creates a computationally inexpensive data processing environment for both cost and schedule control. Moreover, product models are visual and physical models. Their progress is easy to measure and the actual cost is easy to calibrate; their resource has a one-to-many relationship with construction methods. Whenever there is a cost overrun or schedule delay, an extra computational effort is required in order to identify the reasons behind the variance. However, the process model can fill this gap by providing a one-to-one relationship between the resource and construction methods. Compared with the project model, the product model and the process model require less development effort, and may indeed be more efficient to execute for the reasons mentioned above. These facts contribute substantially to the improvement of the efficiency of an integrated cost-and-schedule control system, and hence to the time independence of the reporting system. Therefore, the product and process models are suggested as a strong integration model candidate for this research project.

2.3 Performance Evaluation Methods

The performance evaluation method is used to calculate the deviation of time and cost from its control baseline and assesses the value of the deviation. Over the years, a number of methods have been developed to facilitate overall project control. Some of these methods separate schedule and cost control, while others integrate them (Moselhi 1993). The following Sections describe and discuss the existing performance evaluation methods.

2.3.1 Traditional Evaluation Methods

Traditionally, time is tracked and controlled through some form of schedule, tied to some measure of physical progress such as percentage completion, while cost is controlled through the use of the S-curve. The S-curve methods include the standard S-curve, single S-curve, Double S-curve, Superimposed Cost and % Complete S-curves method.

THE STANDARD S-CURVE METHOD, where the project progress is compared to three stages that begin slowly up to 25% of the project duration, accelerate from 25% to 75% of the project duration, and then slow again to completion (Fig. 2.8). This method compares the actual progress with the standard S-curve to evaluate project performance. In this figure, BCWS is the Budgeted Cost of Work Scheduled; ACWP is the Actual Cost of Work Performed.

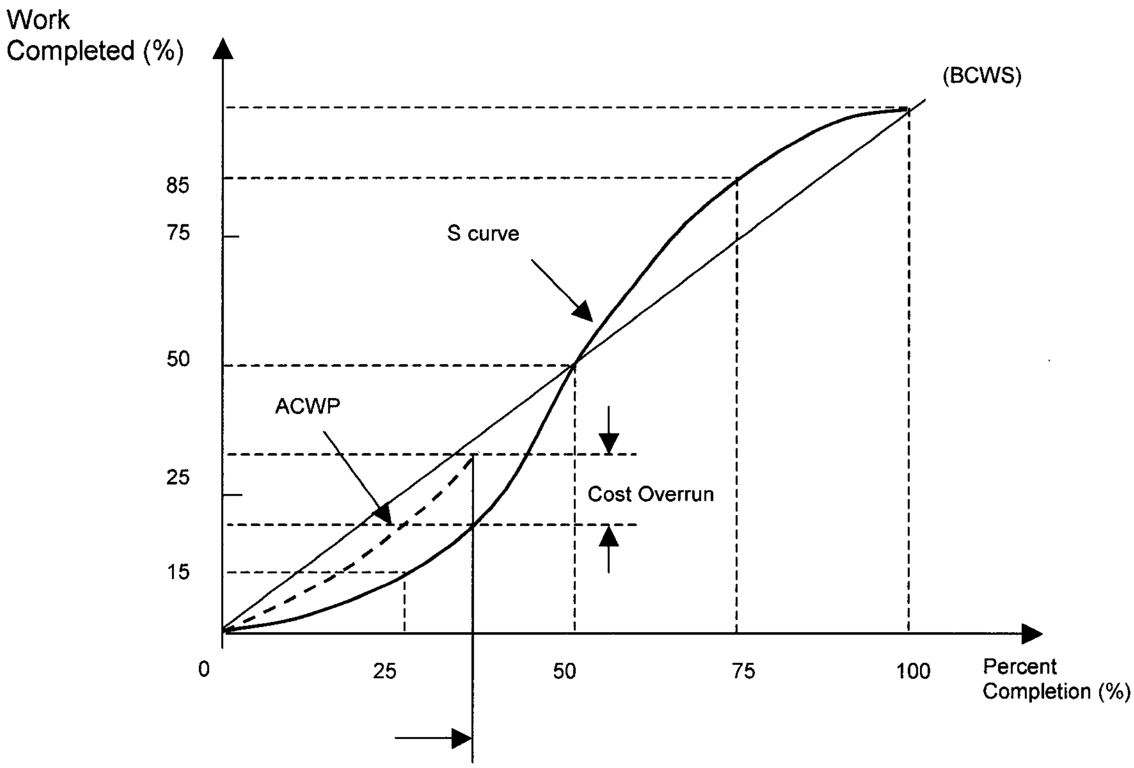


Figure 2. 8 Standard S Curve for Project Control

THE SINGLE S-CURVE METHOD is project-dependent. The baseline may or may not be schedule-based. Those that are schedule-based projects only compare the budgeted S-curve with the actual progress S-curve for performance evaluation. Those that are not schedule-based projects use a 'Standard S-curve' for comparison. Different curve-fitting models are employed to use the cost and progress data that has been collected from previously constructed projects of different types such as schools, hospitals, and residential buildings to derive the 'Standard S-curve'.

Double S-Curve Method employs two S-curves as a basis for comparison with the project's actual progress. They may or may not be schedule-based with either an arbitrary specified range of variation from the single S-curve or with a range based on early and late start schedules as shown in Fig. 2.9. If the actual cost of work-performed S-curve is located inside the range of the two S-curves, it indicates a cost underrun.

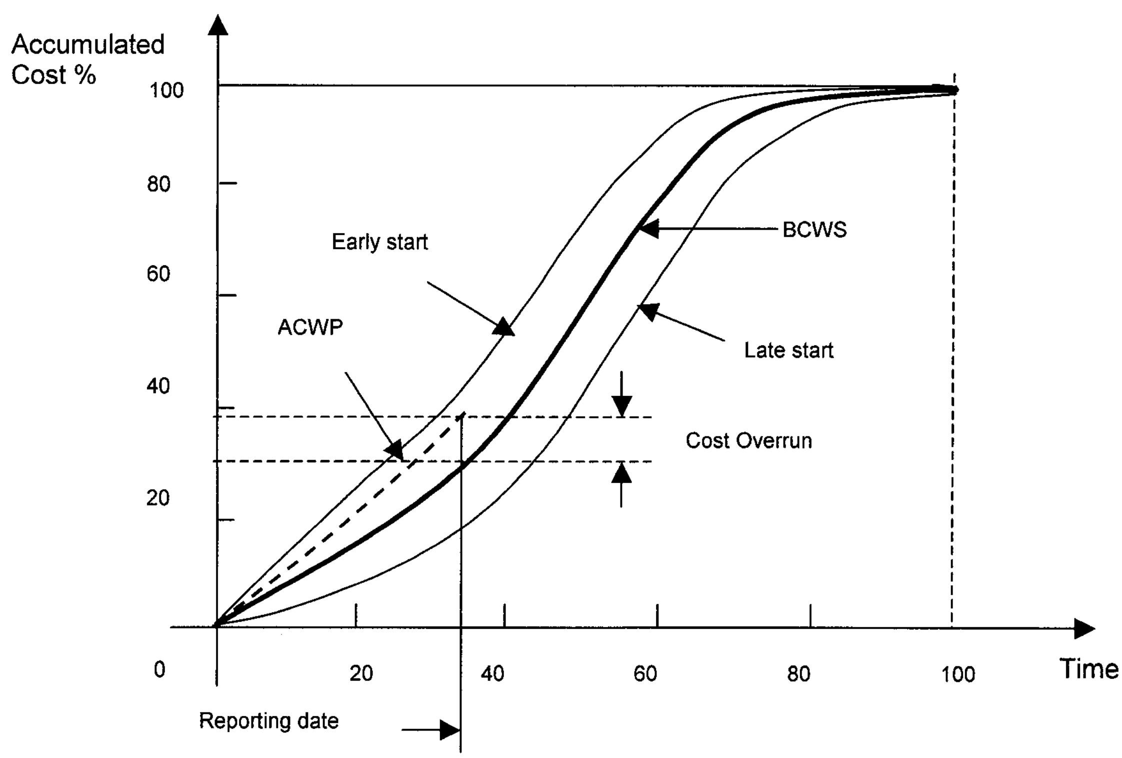


Figure 2. 9 Double S Curve for Project Control

Superimposed Cost and % Complete S-Curves use two S-curves (one represents the budgeted cost of work scheduled and the other represents the percentage schedule accomplishment) as the basis for evaluating project performance. They are schedule-based. Two parameters, which are the actual cost of work performed and the actual percentage of accomplishment, are measured by comparison with the budgeted value to control project performance. This is an integrated cost and schedule control (Fig. 2.10).

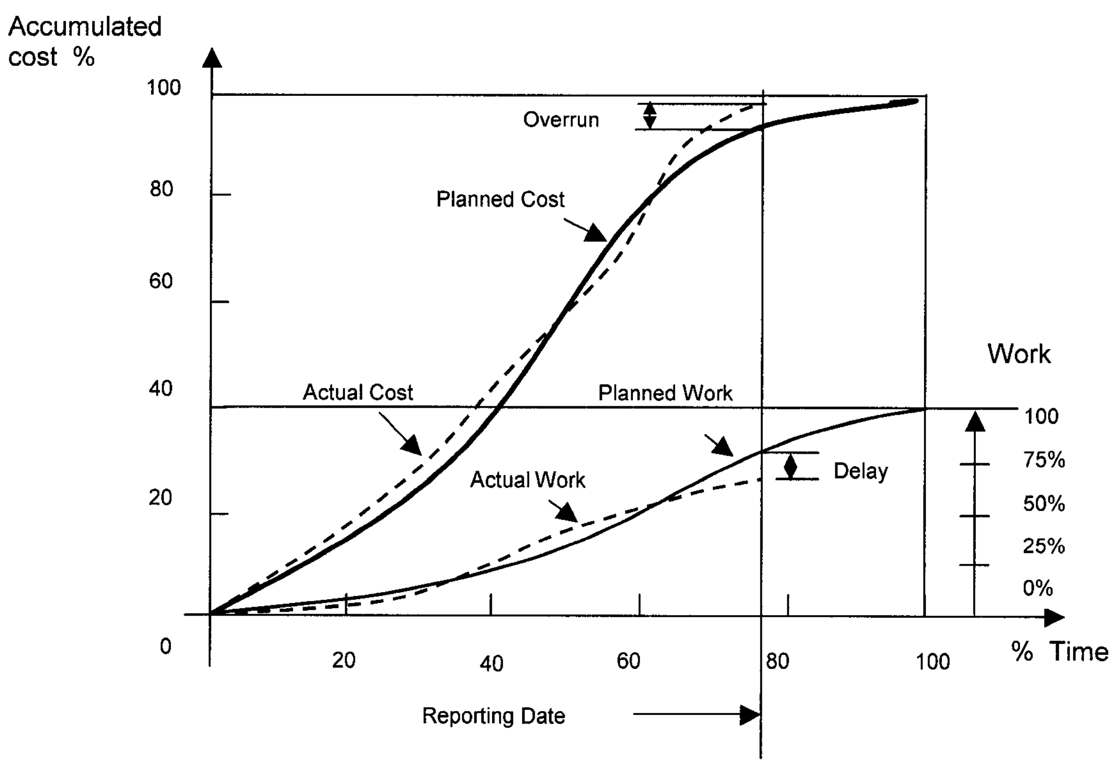


Figure 2. 10 Superimposed Cost and Percent Completion Method

2.3.2 PERT/Cost Method

Program Evaluation and Review Technique (PERT) was first introduced to industry as a network-scheduling device by the U.S. Navy in 1958. This method tries to improve the project control function using simulation and statistical probability methods. In 1962, resources were added to the network that resulted in PERT/Cost to allow for the management of both time and cost. PERT/Cost uses not only the budgeted and actual cost data, but also the cost estimation of the work performed according to the contract terms and conditions (Moselhi 1991). Therefore, earned-value as a project management tool was first formally introduced to modern industry in 1962 (Fleming and Koppelman 2000). Neither computers nor software programs were available to support the concepts of PERT or PERT/Cost at that time. The concepts were too complex and burdensome for such a large project. But, it did leave an important legacy: the use of earned-value data to monitor the true cost performance during the life of a project (Fleming and Koppelman 2000).

2.3.3 Integrated Evaluation Method

In December 1967, the US DOD formally issued their Cost/Schedule Control Systems Criteria, shortened to simply C/SCSC (Fleming and Koppelman 2000). C/SCSC carefully incorporated the earned-value concept in the form of 35 criteria imposed on any contractor wishing to be selected for a major systems acquisition contract or subcontract over a certain threshold (Fleming and Koppelman 1994). These 35 criteria applied to a contractor's management control system whenever a cost or incentive-type contract was used. In 1995, the industry version of C/SCSC is called Earned-Value Management System (EVMS) criteria. And it contained just 32 criteria, each of them rewritten in a simpler form. The Canadian version of EVMS called project performance management was proposed in 1999 by the Canadian General Standards Board (CGSB 1999).

The main issue of the EVMS lies in the earned-value method. According to this method, three S-curves are used for performance evaluation as shown in Fig. 2.11. They are BCWS, ACWP, and the Budgeted Cost of Work Performed (BCWP). BCWS represents the baseline of control reference. ACWP is the actual cost occurred. BCWP is the earned-value (EV). BCWS and ACWP constitute exactly the traditional control system. While, BCWP brings into play a third curve and represents the improvement introduced to the inadequate traditional control system. Earned-Value is the value of completed work expressed in terms of the budget assigned to that work (Christensen 1994). It is a time-dependent budgeted cost and a metric devised to achieve meaningful comparisons between planned and completed work. According to this method, cost and schedule variances are routinely computed during the construction stage for performance evaluation. The Cost Variance (CV) is the difference between BCWP and ACWP (Equation 2.1) (CGSB 1999). The Schedule Variance (SV) reflects the difference between BCWP and BCWS (Equation 2.2) (CGSB 1999). The WBS supports the application of the earned-value concept.

$$CV = BCWP - ACWP \tag{2.1}$$

$$SV = BCWP - BCWS \tag{2.2}$$

Performance evaluation scenarios for permutations of the three curves (BCWS, BCWP, and ACWP) can be summarized into six cases as shown in Fig. 2.12 (Singh 1991). The baseline is identical in all six cases. Only ACWP and BCWP vary in relation to the baseline and to each other. Case 1 is cost overrun (CV<0) and schedule delay (SV<0). Case 2 is cost underrun (CV>0) and schedule advanced (S>0). Case 3 is cost underrun (CV>0) and schedule delayed (SV<0). Case 4 is cost underrun (CV>0) and schedule advanced (SV>0). Case 5 is cost overrun (CV<0) and schedule advanced (SV>0). Case 6 is cost underrun (CV>0) and schedule advanced (SV>0).

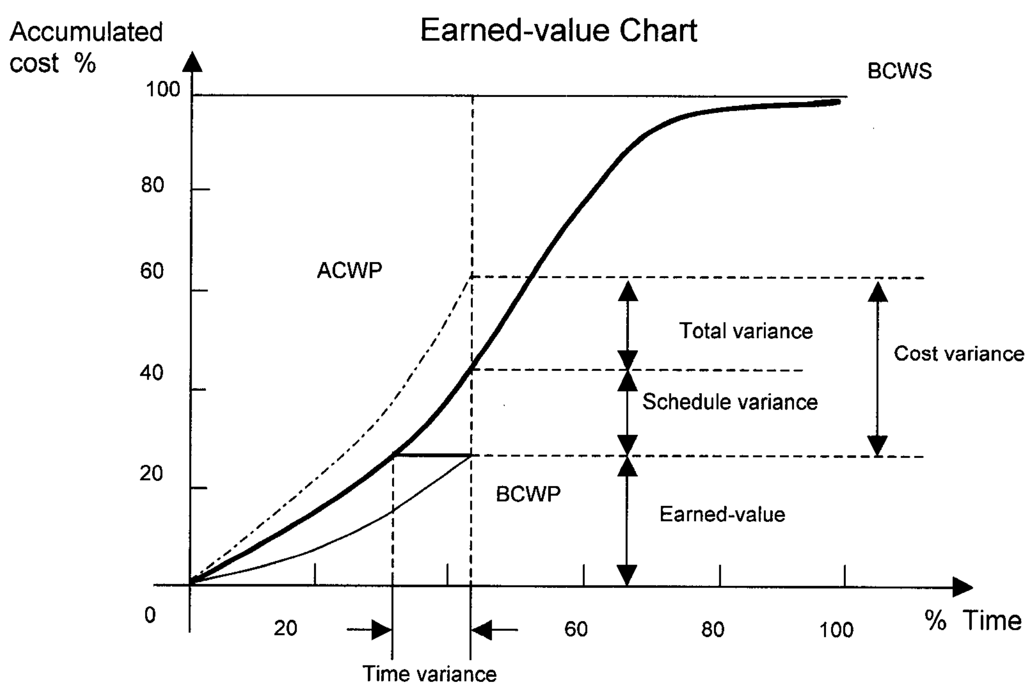


Figure 2. 11 Earned-Value Method

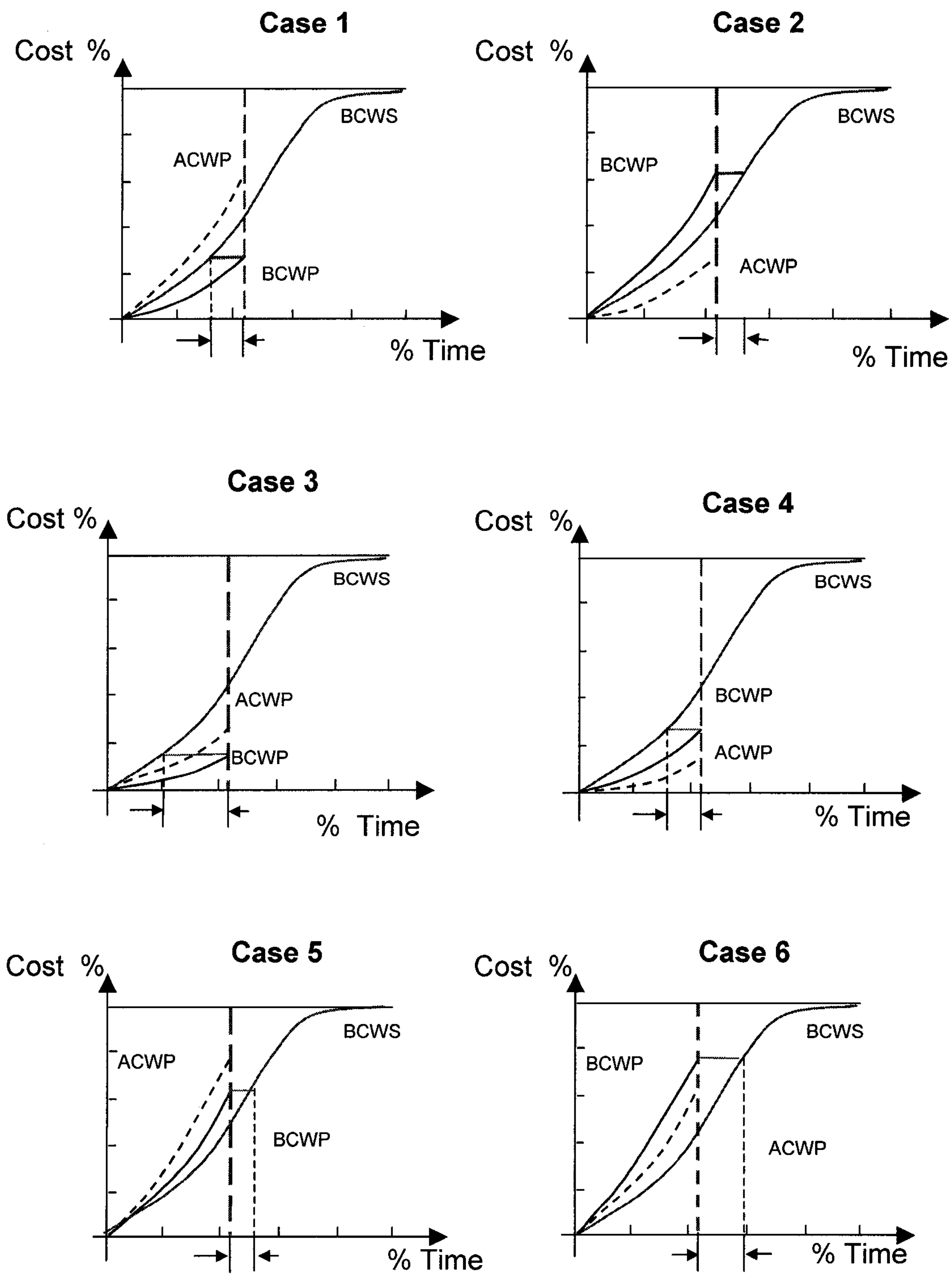


Figure 2. 12 Performance Evaluation Scenarios

2.3.4 Discussion

The traditional S-curve methods use only cost as an indicator to evaluate the project performance. This can mislead the decision maker when the cost is overrun and the actual project progress at this stage may equally be ahead of schedule. The superimposed cost and percent completion method is an effort towards the integration of time and cost using two indicators: cost and percentage completion. To do this, two baseline (one is cost and the other is budgeted percentage completion) curves have to be developed for control purposes. This will encounter computational overhead on planning and scheduling. The PERT/Cost method is another effort towards the integration of time and cost using simulation and statistical probability methods. However, it has the difficulty of implementation. The earned-value method, however, overcomes the limitations of traditional control using progress dependent budgeted value. By doing so, the time and cost variances can be evaluated in an integrated manner. Nowadays, the EVMS has been widely accepted as an integrated project control tool not only for government projects, but also for those of private industry because it represents a viable, best-practice tool that project managers everywhere can use (Fleming and Koppelman 2000). Although this method can track the time and cost variances, it cannot diagnose the causes of those variances. As a control method, there is still a room for improvement.

2.4 Reasoning Methods

Satisfactory project control needs a method that is effective in detecting the cause(s) behind unacceptable performance. Research efforts have been made in this field (Diekmann and Al-tabtabai 1992, Russell and Fayek 1994, Moselhi et al. 2002, 2003). These methods can essentially be grouped into two categories: Knowledge-based expert systems (KBES) and fuzzy reasoning methods. The existing applications based on the above-mentioned methods are discussed in the following. The latest reasoning tool -- Case-Based Reasoning (CBR) -- is also discussed.

2.4.1 KBES

A KBES is a computer-based system that emulates the reasoning process of a human expert within a specific domain of knowledge (Klir and Yuan 1995). The kernel of any expert system consists of a knowledge base, a database, and an inference engine. The knowledge base contains general knowledge pertaining to the problem domain. It is usually represented by a set of production rules, which connect antecedents with consequences, premises with conclusions, or conditions with actions. The most commonly used rules have the form of "If A, then B."

The purpose of the database is to store data for each specific task of the expert system. The parameters of the problem or other relevant facts are typical data in the database. The inference engine operates on a series of production rules and makes inferences. There are two distinct methods to evaluating relevant production rules in the design of any diagnostic knowledge-based system. The first is "evidential diagnosis", in which the diagnostic knowledge base directly represents the observed symptom. The expert system searches in the IF clauses of production rules for data that will lead to the observed symptom. An alternative method of evaluation is "causal diagnosis", which reasons from some other knowledge to make its diagnosis. In this case, the system reasons in terms of a causal model or an explicit representation of how it is that hypothesized causes bring about conclusions. The causal diagnosis process includes three steps: symptom collection, hypothesis generation, and hypothesis confirmation.

KBES and their applications in the project reasoning have been extensively described in the literature of Singh (1991), Diekmann and Al-Tabtabai (1992), Fayek et al. (1998), and Alshaibani (1999). The "evidential diagnosis" method was used by Singh (1991) to assess the variations of the designed parameters. When the deviations of the parameters have been determined by actual information, the correspondence rules are fired to explain the reason(s) for the unfavorable performance. A causal model was established by Diekmann and Al-Tabtabai (1992) for "causal diagnosis" in their system. Fayek et al. (1998) has used fuzzy membership functions to represent the causal links among the problems caused by levels of supervision, activity, and project. Alshaibani (1999) uses a variance analysis path diagram to diagnose the source of the problem. A detailed discussion of those systems can be found in Section 2.6.1.

The main advantage of KBES is to solve the problem based on heuristics rather than arithmetic. Building a knowledge base for performance evaluation needs a theoretical description of all relevant information and practical domain knowledge, which is provided by human experts. The heuristic rules, which represent human expert knowledge, are used to solve domain-specific problems. Since human expertise is not available in all situations where it is needed, a KBES could not cover all possible reasons behind poor performance. Therefore, knowledge acquisition is often referred to as the bottleneck of the KBES (Hamiani 1987). Software compatibility is another issue that slows down the speed of the KBES application, because many expert system shells run on different computer platforms.

2.4.2 Fuzzy Reasoning

Fuzzy sets, originally introduced by Lotfi Zadeh (1965), are functions that map a value, which might be a member of a set, to a number between zero and one, indicating its actual degree of membership. A degree of zero means that the value is not in the set and a degree of one means that the value is completely representation of the set. Whereas a fuzzy set gives the degree of membership of each element in the set. Fuzzy logic, based on the fuzzy set theory, provides a modeling technique designed to handle uncertain or imprecise data and knowledge for approximate reasoning in a manner similar to human reasoning process. It is specially designed to deal with uncertainties that are not statistically in nature (Zadeh 1965). Fuzzy reasoning refers to processes by which conclusions about new data are derived from fuzzy data and fuzzy rules or fuzzy relations (Klir and Yuan 1995). In fuzzy reasoning, there are two well-known inference procedures: the Compositional Rule of Inference (CRI) and the Generalized Modus Ponens (GMP). The first procedure uses a fuzzy relation to represent explicitly the connection between two fuzzy propositions. Consider the fuzzy relation R that describes the causal link between two fuzzy sets U and W. Suppose the fuzzy set $A^{'}$ is a fuzzy subset of U. Then the conclusion on this set is obtained by (Klir and Yuan 1995):

$$C^{'} = A^{'} \circ R \tag{2.3}$$

where,

$C^{'}$= subset of fuzzy set W.

When the CRI is used, an explicit fuzzy relation R must be given a priori, which is not necessary in the GMP. The GMP procedure uses an If-Then rule that implicitly represents a fuzzy relation. When the causal link between domains U and W of concern is not known, i.e. partial knowledge about the relation between these domain exists in the form of fuzzy rules, the GMP reasoning is used. The GMP has the following form (Zimmermann 1996):

Rule: if X is A then Y is C

Observation: X is $A^{'}$

Conclusion: Y is $C^{'}$

The application of fuzzy reasoning in project control system has been described by Russell and Fayek (1994). Russell and Fayek (1994) use fuzzy binary relations to select the corresponding corrective actions for the reported problem sources. Two schemas, which use the same principle, are proposed by them. Schema A, for example, selects the corrective actions for a problem source based on the activity's attributes. Two relation sets are defined to represent their intermediate relationships. One is a user-defined set that describes the relation of problem source and activity attribute. The second set, which is generated using a set of expert rules, represents the relation between activity attribute and corrective action. CRI is used to link two data sets through their respective relationship to a third set that represents the relation between the problem source and the corrective action. Then, corrective actions are ranked in terms of their membership values. The users can select the most suitable corrective action(s) based on this ranking.

Fuzzy binary relations have the advantage of not relying on pre-defined membership functions, which can require substantial data sets formed on expert opinions (Knight and Fayek 2002). Instead, dynamitic user-specified membership functions may apply. Linguistic terms defined by a fuzzy set can establish communication channels with users. This provides an opportunity that allows users to handle events likely to occur during construction process.

In order to establish a reasoning process for an on-going project performance control, factors that affect project performance need to be identified. The corresponding corrective actions also need be classified. Therefore, a set of indicators related to the project performance has to be determined in order to bridge the gaps between the impact factors and project performance. There are two ways of reasoning about performance according to the methods mentioned above. CPI method uses fuzzy binary relation. GMP method builds a set of rules. Since many impact factors and corrective actions will be involved in the reasoning process, it is very difficult to solicit a set of universal rules from knowledge of experts. Therefore, CRI reasoning method is preferred.

2.4.3 CBR

"A Case-Based Reasoner solves new problems by adapting solutions that were used to solve old problems" (Reisbeck and Schank 1989). Case-Based Reasoning (CBR) solves the current problem by relating it to past experiences (cases). The basic algorithm of CBR includes: 1) Inputting problem, 2) Finding the cases similar to the current problem (characterizing the input problem, retrieving cases with matching features, picking the best match), and 3) Adapting a previous solution to fit the current problem. Today CBR is presented as a methodology for dealing with large quantities of information (Watson 1998) where various technologies (nearest neighbor, fuzzy logic, Structure Query Language (SQL), etc.) are applied to the original algorithm.

Applications of CBR to the AEC industry include design (proportionally much higher), contracting, and the application of scheduling and estimating. Fleming et al. (1994) presents CBR in support of the early phases of building design. CADRE (Bailey and Smith 1994) is a method that focuses on the dimensional and topological adoption of the geometric models of existing buildings to find a solution to new design problems. Ng et al. (1998) address cases of representation, indexing and retrieval, and adoption for contractor pre-qualification by guiding the user through the processes of criteria formulation, screening and reviewing, and final assessment based on financial and performance issues. CBI-CONPLAN (Kawooya and Aouad 1997) is a case-based integrated construction planning system. By using this, users do not construct plans from first principles; rather they try to find the best previous plan and adapt it to the current situation. CBRMID (Morcous et al. 2000 and Morcous 2000) is a CBR for bridge deterioration management.

CBR has many advantages over traditional knowledge-based systems. Remembering previous situations similar to the current one in order to solve the new problem is a more plausible method for problem solving than always reasoning from first principles. It can also be used in domains where no causal model is available, as the reasoner does not need explicit rules or models to reason from -- it makes use of the implicit knowledge contained in cases. This also means that CBR does not suffer from knowledge elicitation problems that characterize expert system development. The limitation of CBR is size of its case library. When new cases arise, a previous case may not fit.

CBR is a potential tool for interpreting the reason(s) behind unacceptable performance using previous cases. However, it is difficult to handle the dynamic reasoning process for on-going performance evaluations since a large number of cases is needed.

2.4.4 Discussion

KBES are good at consolidating human expert knowledge into heuristic rules for problem solving and for reasoning purpose. The upgrade of their knowledge base, however, could be difficult. The application can only be applied in a very specific domain. Compared with KBES, the fuzzy reasoning method has more flexibility over expert systems that are based on pre-set rules. It takes advantage of the fuzzy set and fuzzy logic that describes relations in an approximate manner, i.e. from 0 to 1. Not only numerical values, but also linguistic terms can be used to define a rule or a relation. Linguistic terms can establish a communication channel with users. Therefore, the users can be involved in the reasoning process. This provides an opportunity that allows users to handle events likely to occur during the construction process. It is an ideal method for performance reasoning, which must deal with the uncertainty involved in the reasoning process for an on-going project. CBR is a recent diagnostic tool that interprets the collected symptom by retrieving previous cases. For the in-progress project reasoning, a huge number of cases must be collected before the reasoning process begins. After a due comparison of KBES, fuzzy reasoning, and CBR, fuzzy reasoning is selected to explain the reasons behind any unfavorable performance revealed by the developed control system.

2.5 Forecasting Methods

Forecasting project status is essential function in tracking and control. Large variances in costs and/or schedules can impact profitability, cash flow and, in extreme cases, the viability of projects (Al-Tabtabai 1996). The sooner one can predict the extent of the deviation and the more accurate that prediction is, the more helpful it is in managing the project to a successful completion. Considerable research efforts have been made in developing effective methods to predict cost and duration at completion (Al-Jibouri 1985, Eldin and Hughes 1992, Diekmann and Al-Tabtabai 1992, Christensen 1992, 1996, 1999, Shtub et al. 1994, Fleming and Koppelman 1994, 1995, 2000, Christensen et al. 1995, Al-Tabtabai 1996, Robinson and Abuyuan 1996, Fayek et al. 1998, Alshaibani 1999, Fayek 2000, Zwikael et al. 2000, Fayek and Zhuo 2001, Christensen and Rees 2002, and Knight and Fayek 2002). These methods can essentially be grouped into stochastic, earned-value based and its related extensions, social judgment theory, and fuzzy-logic based methods. They are discussed in detail in the following.

2.5.1 Stochastic Methods

The traditional stochastic forecasting models are the exponentially moving weighted average method (Al-Jibouri 1985). Al-Jibouri (1985) proposed two stochastic forecasting models called independence and dependence cost models to predict cost at completion for control purposes. These models are based on the actual cost of work performed (referred to author as mean cost of unit earning) and its standard deviation for each cost account being considered to predict cost at completion. The independence model assumes that each unit of earning is independent as shown in Equation (2.4).

$$CV = \frac{E(E-e)}{e}\sigma^2 \tag{2.4}$$

where,

E = the measured total earning (actual cost) over the period,

e = earning to-date (actual cost),

σ = the measured standard deviation by assuming that the distribution is normal.

The dependence model assumes that the n^{th} unit of earning is based on the $(n-1)^{th}$ unit as shown in Equation (2.5).

$$CV = \frac{E^2 s^2}{3}\left(\frac{e}{n^2} + E\right) \tag{2.5}$$

where,

s^2 = variance of the individual units,

n = number of units in the job.

The study reveals that the independent forecasting model produces more reliable results than those produced by the dependence model. The reliability of the two models, however, depends fully on the measurement of the cost of unit of earning at each reporting period.

2.5.2 Earned-value Based and Its Extension Methods

In reality, the most commonly used forecast techniques are based on linear trend analysis. The earned-value-based and related parts of extensions methods are examples of them. In the past decades, many studies exploring the problem of estimating at completion (EAC) have been published. These models along with their respective sources and assumptions are summarized as below.

Fleming and Koppelman (1994) describe a constant budget model (Equation 2.6). This model assumes that all cost deviations can be corrected by the time the project is completed, implying that the final cost will be equal to the planned budget. Actually, the project manager cannot overcome all cost deviations experienced to date and cannot complete the project within the original budget when a cost overrun occurs.

$$EAC = BAC \tag{2.6}$$

where,

BAC = Budgeted cost at completion.

Shtub et al. (1994) describes a constant performance efficiency factor model (Equation 2.7). This model assumes that the performance efficiency achieved prior to the reporting date remains unchanged throughout the rest of the project. The research of Fleming and Koppelman (1995) and Zwikael et al. (2000) suggests that this model provides better results than other earned-value-based cost forecasting models. The corresponding schedule-forecasting model is derived as Equation (2.8).

$$EAC = \frac{BAC}{CPI} \tag{2.7}$$

$$D = \frac{D_b}{SPI} \tag{2.8}$$

where,

D = estimated duration at completion,

CPI = cost performance index,

SPI = schedule performance index,

D_b = planned duration.

Fleming and Koppelman (1994) describe the constant-cost and schedule-performance efficiency factor model (Equation 2.9). This model assumes that the final cost is affected by both the cost efficiency factor and the schedule efficiency factor. Research has suggested that this model is inferior to the model based on CPI only (Zwikael et al. 2000). The corresponding schedule forecasting model is derived as in Equation (2.10).

$$EAC = \frac{BAC}{CPI \times SPI} \tag{2.9}$$

$$D = \frac{D_b}{SPI \times CPI} \tag{2.10}$$

$$EAC = ACWP_{to-date} + (\frac{BAC - BCWP_{to-date}}{index}) \tag{2.11}$$

where,

subscript to-date indicates cumulative to-date data.

Christensen (1992) and Christensen et al. (1995) describe a generic index-based formula to calculate EAC (Equation 2.11). It is assumed that the contractor's past performance will continue to the end of the contract. Based on the research finding, the performance indexes used in this model are classified into seven groups: 1) index=1; 2) index=CPI; 3) index=SPI; 4) index=α%+CPI; 5) index=CPIxSPI; 6) index=(α%+CPI)(α%+SPI); 7) index=W1xCPI+W2xSPI. The coefficient α represents future improvement from 0 to 100. The weights (W1 and W2) can only take on any value from 0 to 1, and normally add to unity. When index =1, the equation could have been shortened to simply: $EAC=ACWP_{to-date}+(BAC-BCWP_{to-date})$. This means the remainder of the project will be executed precisely at the full budgeted rate. This formula is not widely accepted in government quarters and has actually been called "useless" (Fleming and Koppelman 2000). However, it is a frequently used formula in private industry for a couple of valid reasons (Abu-Hijleh 1991, Fleming and Koppelman 2000). Christensen (1992) compares the forecasting results for the indexes in groups 2, 3, 5, and 7 by using 12 development and 18 production contracts (Navy). The indexes are calculated based on monthly, cumulative, and average data. Considered in his study are three completion stages: early (0-40%), middle (20-80%), and late (60-100%). The results found that the three-month average CPI was accurate, irrespective of the stage of the completion. Fleming and Koppelman (2000) suggested that the cumulative CPI formula is supported by the largest amount of accumulated scientific data, supporting its reliability as a forecasting tool. Beach was highly critical of the reliance on the cumulative CPI as a ceiling, rather than as a floor, for higher estimates (Beach 1990). Christensen (1996, 1999) confirmed that CPI-based EAC is a reasonable lower boundary of a final cost of a contract. This rule is valid in the early and middle stages of a project, but it is not valid in the later stages of a project (Christensen and Rees 2002). However, the group 5 index is one of the most widely used and accepted indexes to statistically forecast the high-end cost requirements for any project (Fleming and Koppelman 2000). The indexes in groups 4 and 6 are proposed by Alshaibani (1999). He adds the future improvement coefficient in the forecasting indexes and addresses similar indexes for schedule forecasting. Air force system command (AFSC) uses group 7 index with w1=0.8 and w2=0.2 as a formula in all stages of the life of a contract (Abu-Hijleh 1991). In addition, Al-Tabtabai (1996) presents another method that modifies the performance index by considering eight impact factors in the forecasting of EAC (Equation 2.12). The modified performance index considers the current performance, the project manager's experience, and future situation. The accuracy of this model greatly depends on the quality of the judgments for project performance and the ability to represent project-specific data.

$$index^{-1} = 0.3f_1' + 0.26f_2' + 0.2f_3' + 0.15f_4' + 0.09f_5' + 0.17f_6' - 0.02f_7' + 0.15f_8' - 1.09 \quad (2.12)$$

where,

f_1' = Performance of management,

f_2' = Cash flow situation,

f_3' = Material and equipment availability,

f_4' = Labor availability and productivity,

f_5' = Weather and other environment influences.

f_6' = Amount of rework, extra work, work difficulty,

f_7' = Percentage of work completed,

f_8' = Past project's performance trend.

Some of methods, in an effort to improve forecasting accuracy, utilize cost components that make use of cost breakdown structure (Eldin and Hughes 1992, Robinson and Abuyuan 1996, Alshaibani 1999). Eldin and Hughes (1992) proposed a project ratio method to forecast the final cost-based on the ratio of unit cost to quantities. Cumulative to-date unit cost and current period average unit cost are employed to forecast linearly the cost at completion as defined by Equations (2.13) and (2.14). Two cost values, one high and the other low, are obtained from the proposed forecasting method. Their mean value is the prediction of cost at completion.

$$EAC_1 = Q_s \times (\frac{\$}{Q})_a \tag{2.13}$$

$$EAC_2 = Q_a \times (\frac{\$}{Q})_a + (Q_s - Q_a) \times (\frac{\$}{Q})_{cp} \tag{2.14}$$

where,

EAC_1 and EAC_2 are the forecasted costs at completion;

Q_s = planned quantity to-date;

Q_a = installed quantity to-date;

$(\$/Q)_{cp}$ = current-period unit cost;

$(\$/Q)_a$ = cumulative to-date unit cost.

Similarly, high and low work hour forecasts for a cost item can be derived by using the cumulative to-date work hours and current period average work hours as shown in Equations (2.15) and (2.16).

$$Whr_1 = Q_b \times (\frac{Whr}{Q})_a \tag{2.15}$$

$$Whr_2 = Q_a \times (\frac{Whr}{Q})_a + (Q_b - Q_a) \times (\frac{Whr}{Q})_{cp} \tag{2.16}$$

where,

Whr_1 and Whr_2 are the forecasted working hour;

$(Whr/Q)_{cp}$ = current-period unit working hour;

$(Whr/Q)_a$ = cumulative to-date unit working hour.

This model assumes linearity of performance over the duration of a cost item, as well as correct quantities, unit costs, and unit work hours. The advantage of the ratios over absolute data is that ratios provide earlier warnings and also isolate the effect of labor productivity (Eldin and Hughes 1992). The method can automatically handle the changes of work scope. Alshaibani (1999) improved this method by adding the management and job condition factor α to Equation (2.14) as shown in Equation (2.17). The work-hour forecasting methods are modified in a format that is very similar to the earned-value-based method. Not only the productivity ratio but also the unit cost ratio is taken into consideration as shown in Equations (2.18) and (2.19).

$$EAC_2 = Q_a \times (\frac{\$}{Q})_a + (Q_b - Q_a) \times \left((\frac{\$}{Q})_b - (\pm\alpha) \times (\frac{\$}{Q})_a \right)_{cp} \tag{2.17}$$

where,

$(\$/Q)_b$ = budgeted unit cost;

$\alpha\%$ = Management and job condition factor, if the future is better than the planned, the sign is positive; otherwise it is negative.

$$Whr_1 = \frac{D_b}{(\pm\alpha\%) + RPI} \tag{2.18}$$

$$Whr_2 = \frac{D_b}{(\pm\alpha\%) + RPI \times ((\pm\alpha) + TCI)} \tag{2.19}$$

where,

RPI = crew productivity index (Productivity ratio), $RPI = (\frac{Whr}{Q})_b / (\frac{Whr}{Q})_a$;

TCI = total cost performance index (unit cost ratio), $TCI = (\frac{\$}{Q})_b / (\frac{\$}{Q})_a$.

Robinson and Abuyuan (1996) propose a simplified method called SPEs (Scheduled Performance Estimators) to make a quick top-level assessment of project schedule performance. The schedule performance curve is assumed to be S-shaped. The performance parameter SPR (Schedule Performance Index) is defined as the number of tasks completed to-date versus the number of tasks planned (Equation 2.20). Other parameters such as SBL (Baseline average slope before report date), SA (actual average slope before report date), MBL (baseline average slope after report date) are defined by the Equations (2.21), (2.22), and (2.23).

$$SPR = \frac{PERA}{PERBL} \tag{2.20}$$

$$SBL = \frac{PERBL}{report\ date} \tag{2.21}$$

$$SA = \frac{PERA}{report\ date} \tag{2.22}$$

$$MBL = \frac{PERAC - PERBL}{TBL - report\ date} \tag{2.23}$$

where,

PERBL= number of tasks (activities) completed up to report date as planned;

PERA= number of tasks (activities) actually completed up to report date;

PERAC= number of tasks (activities) completed as planned at completion;

TBL= baseline completion date (as planned);

TAC= estimate project completion date.

The estimated schedule performance is computed using the above-defined slope parameters and a couple of assumptions regarding how the project will proceed in the future. Four assumptions are chosen for their models.

1) Future work follows the actual performance achieved (no resource constraints).

$$T = \frac{PERA - PERBL}{MBL - SA} + report\ date \qquad (2.24)$$

$$Months\ behind\ schedule = T - report\ date \qquad (2.25)$$

where,

T = getting well date, which is the crossing point of MBL and SA.

2) Future progress proceeds with constrained resources.

$$TAC = \frac{PERAC - PERA}{PERAC - PERBL} \times \frac{TBL - report\ date}{SPR} + report\ date \qquad (2.26)$$

$$SV_{at-completion} = TAC - TBL \qquad (2.27)$$

3) Future performance proceeds with no constrained resources and the past problem is resolved.

$$T = \frac{PERBL - PERA}{SBL - MBL} + report\ date \qquad (2.28)$$

Months behind schedule are same as Equation (2.24).

4) Future performance proceeds with constrained resources and the past problem is resolved.

$$TAC = \frac{PERAC - PERA}{PERAC - PERBL} \times (TBL - report\ date) + report\ date \tag{2.29}$$

$$SV_{at-completion} = TAC - TBL \tag{2.30}$$

SPEs assume that all the work tasks (activities) have equal weight. Alshaibani (1999) improved this method by adding the duration of each work task (activity) as a weight to SPR. This addition alleviates the impact of the previous assumption. The modified SPR is defined in the Equation (2. 31).

$$SPR = \frac{\left[\sum_{i=1}^{PERA} \frac{D_{b_j} \times PERA}{\sum_{i=1}^{n} D_{b_j}}\right]_a}{\left[\sum_{j=1}^{PERBL} \frac{D_{b_j} \times PERBL}{\sum_{j=1}^{m} D_{b_j}}\right]_b} \tag{2.31}$$

where,

D_b = planned duration of each work task (activity).

The equations are further improved to better fit the actual application based on the four assumptions as shown in Equations (2.32) to (2.39).

1) Assuming future work follows the actual performance achieved.

$$SV_{at-completion} = \frac{PERAC - PERA}{SA} + report\ date - TBL \tag{2.32}$$

$$SV_{report-date} = \frac{PERBL - PERA}{SBL} \tag{2.33}$$

2) Assuming future work proceeds at the planned rate.

$$SV_{at-completion} = \frac{PERAC - PERA}{MBL} + report\ date - TBL \tag{2.34}$$

$$SV_{report-date} = \frac{PERBL - PERA}{SBL} \tag{2.35}$$

3) Assuming future work proceeds at a rate which is worse than the planned rate

$$SV_{at-completion} = \frac{PERAC - PERA}{MBL - (\%\beta \times MBL)} + report\ date - TBL \tag{2.36}$$

$$SV_{report-date} = \frac{PERBL - PERA}{SBL} \tag{2.37}$$

4) Assuming future work proceeds at a rate which is better than the planned rate

$$SV_{at-completion} = \frac{PERAC - PERA}{MBL + (\%\alpha \times MBL)} + report\ date - TBL \tag{2.38}$$

$$SV_{report-date} = \frac{PERBL - PERA}{SBL} \tag{2.39}$$

2.5.3 Social Judgment Theory

Diekmann and Al-Tabtabai (1992) proposed a method based on the social judgment theory, originally developed by Brunswik (1956). The method provides a way to predict the future based on a set of cues, which comes from human judgment rather than purely mathematical algorithms. Equation (2.40) describes such models. To predict the quantity, labor productivity, labor wage rate, material price, and schedule variance, a set of cues was identified respectively by a survey of industry experts. The weights of these cues were determined by regression analysis.

$$J = w_1 x_1 + w_2 x_2 + \cdots + w_k x_k + c + e' \tag{2.40}$$

where,

J = judgment of an individual;

x_i = cues used to make the judgments;

w_k = weights for the cue variables;

c =constant for individual;

e' = error term.

This method improves the previous forecasting technique by considering not only current variance, but also the other impact factors. However, method based on such judgment requires expert project managers to get satisfactory results.

2.5.4 Fuzzy Modeling Methods

The application of fuzzy set and fuzzy logic regarding the reasoning process has been discussed in Section 2.4.2. Fuzzy modeling methods discussed here are further applications of GMP type reasoning. These methods can be classified into two categories: subjective modeling and objective modeling. The subjective models are directly solicited from experts in an attempt to model the reasoning process of an expert. By contrast, the object models are constructed from input and output data of the system using a systematic process with a specific objective function. The subjective model was first introduced by Mamdani and Assilian (1975). The objective model was initially proposed by Sugeno (1985) and Takagi and Sugeno (1985). In either model, a set of fuzzy if-then rules form the fuzzy knowledge-based model of the system. The difference between these two models lies in the consequence of their fuzzy rules.

The subjective modeling is a qualitative expression of the system using natural language, for example, *Large*, *Medium*, and *Small*. Fuzzy quantities are associated with linguistic terms. The linguistic terms will be defined by a fuzzy membership function (discussed in Section 5.4). They are utilized to describe the antecedent and consequent parts of if-then rules. The output of the model is a fuzzy set, and a defuzzification method (discussed in Section 5.5) is needed to translate the model's output into a crisp value. An example of subjective modeling rules can be written as:

IF *Productivity is Decreased* THEN *Actual cost is increased*

The objective modeling is a quantitative expression of the system. The antecedent part of if-then rules consists of fuzzy sets equivalent to the subjective modeling, while the consequent part are functions of antecedent variables. A defuzzification procedure is therefore superfluous, since the consequent parts of the rules are crisp values rather than a fuzzy set. An example of objective rules can be written as:

if *x (t) is 25* AND *y (t) is 30* **then** *z (t+1)=5x(t)+8y(t)*

where,

x(t) and y(t) represents two fuzzy sets which have the values of 25 and 30 with the membership equal to 1;

z(t+1) represents the output function.

The objective model has been used in industrial control process, for example, the control of a model car (Sugeno and Nishida 1985). This case enjoys an advantage in that the model is based on raw input and output data. A priori knowledge about the system is not necessary. However, as the number of input parameters increases, the process of building a system becomes very complex. Therefore, only a limited number of variables can be considered whenever this method is applied. Unlike the objective modeling method, there is no limitation on the number of parameters when the subjective modeling method is applied to formulate a system. The subjective modeling method has been used in a control system whenever a large quantity of data is not available and a priori knowledge about the system is possible. The applications of the subjective modeling method in a project control system have been developed by Boussabine and Elhag (1999), Fayek (2000), Fayek and Zhuo (2001), as well as Knight and Fayek (2002). The detailed descriptions of the above mentioned applications can be found in Section 2.6.2.

2.5.5 Discussion

It is said that a conventional forecast is developed, basing it on events of the past. Since the project performance can be impacted by many factors, and corrective action(s) is one of them, forecasting becomes a difficult task because one needs to understand the effect of past performance and the impact of future events. In practice, a project manager can intuitively adjust the standard rates from past experience to predict an operation cost and duration in given conditions. However, such practices do not guarantee a consistent forecast due to the lack of a binding mechanism that relates the present case to past patterns (Boussabaine 1995). The stochastic methods (Al-Jibouri 1985) utilized mean cost of unit earning for a cost account and its standard deviation to predict the future cost of that cost account being considered. However, the reliability of this model depends fully on the measurement of the cost of unit of earning during the performance periods. The earned-value methods (Christensen 1992, 1996, 1999, Shtub et al. 1994, Fleming and Koppelman 1994, 1995, 2000, Christensen et al. 1995, Al-Tabtabai 1996, Alshaibani 1999, Zwikael et al. 2000), and its extension methods (Eldin and Hughes 1992, Alshaibani 1999, Robinson and Abuyuan 1996, Alshaibani1999) are all assumed that past performance prior to the reporting date remain unchanged throughout the rest of the project. Even future impact factor(s) can be considered as a coefficient in their prediction processes, but it does not change the nature of these methods. The method (Diekmann and Al-Tabtabai 1992) based on the social judgment theory provides a way to predict the future based on a set of cues, which comes from human judgment rather than purely mathematical algorithms. Method based on such judgment requires expert project managers to get satisfactory results. Fuzzy logic, however, provides a better way to model future outcomes considering ambiguous and imprecise data in a manner similar to human judgment process. It is specially designed to deal with uncertainties that are not statistical in nature (Zadeh 1965).

Fuzzy-based forecasting refers to methods by which conclusions about future behaviors are derived from fuzzy data and fuzzy rules, similar to the applications developed by Boussabine and Elhag (1999), Fayek (2000), Fayek and Zhuo (2001), and Knight and Fayek (2002). Linguistic terms are utilized to represent the ambiguous and imprecise facts and future behaviors during the forecasting process. The application of a subjective modeling method is explored in this research to predict the time and cost at completion and at interim future horizons for a given project.

2.6 Control Systems

A number of control systems have been developed by using different techniques and computer platforms to facilitate integrated project control. Each of them has advantages and limitations, which are discussed in the following.

2.6.1 Application of KBES

Several models have been developed to investigate the application of KBES for time and cost control (e.g., Singh 1991, Diekmann and Al-Tabtabai 1992, Fayek et al. 1998, Alshaibani 1999). The following will review those systems in a level of detail.

Singh (1991) proposed an earned-value-based KBES. The work package is the basic control element. The baseline is the control reference. Seven parameters, such as CV, SV, CPI (cost performance index), SPI (schedule performance index), CR (cost rate), ACV (at completion variance), and ECAC (estimated cost at completion) are applied to identify the cost and schedule status. The "evidential diagnosis" method was used to explain the variations for the detected parameters. The system called PCPLUS is developed in BASIC program and knowledge-based shells. Up to fifty-five rules are input into the root frame of PCPLUS to express the major situations of project performance. These rules are formulated on the value of pre-set parameters. When the values of the parameters have been determined by the actual information, the rule is fired to explain the project performance.

The system identifies the deviations from the project baseline not only using earned-value-based parameters such as CV, SV, CPI, SPI, but also using CR, ACV, and ECAC. It can help project managers to find the source of the problem. However, there is no clear indication of the factors that are related to the identified parameters. Thus, the project managers themselves have to determine the cause of the deviations or to devise suitable corrective action(s) based on their own judgments. This is not only the limitation of the system, but also the limitation of C/SCSC.

The system is cumbersome as Singh notes, "the user has to perform many manual calculations prior to using the program" and the conventional program for depicting and consulting with the earned-value method is more practical, easier, and more user-friendly than to use expert system programs (Singh 1991).

Diekmann and Al-tabtabai (1992) presented a knowledge-based method for project control (PRCON). The earned-value method is used to identify problems on the basis of performance measures that fall beyond acceptable thresholds. The work package is the basic element of control. "Casual diagnosis" is used to explain the reasons behind non-favorable performance. Five cost components (quantity of work, labor productivity, labor wage rates, material unit prices, and equipment costs) are chosen as performance indicators. Their relationships between the work package cost and schedule variances establish the causal model as shown in Fig. 2.13. A set of pre-established production rules is used for both system control and data processing. These rules represent the application of human expert knowledge to project control. A database management system is used to store the work package information that supports the system implementation.

A forecast model based on social judgment theory is used to predict the expected performance of quantity, labor productivity, labor wage rate, material price, and schedule variance at completion. It is a way of predicting the future variance not only by considering the current variance, but also other impact factors. However, each project is unique. It is difficult to get accurate results based on the project manager's own judgment.

The developed prototype PRCON combines a knowledge-based shell with database management to form a whole system, not only evaluating the work package status, but also diagnosing the reasons for a non-favorable performance. It enhances the features of an existing project control system by adding human knowledge to a control system. As a knowledge-based system, its application is very specific due to knowledge acquisition. The system does not design any corrective action(s). The control function is limited to an individual work package.

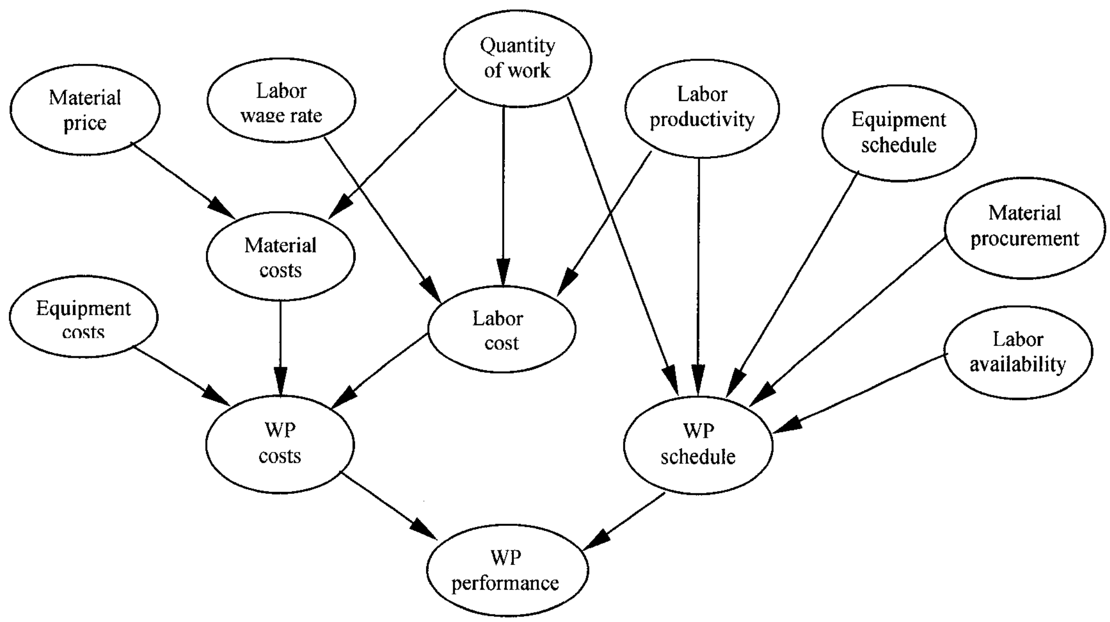


Figure 2. 13 Causal Model (Diekmann and Al-tabtabai 1992)

Fayek et al. (1998) proposed a prototype rule-based expert system to improve project control. The system is developed, basing it on an automated data collection system. Activity is the basic control element. Seven activity parameters such as production quantity, labor hours, equipment hours, material quantities, subcontractor quantities, and days lost and man-hours lost serve as indicators of problems. Variances can be tracked and detected when the performance measurements of these parameters fall below acceptable thresholds. Project performance can be evaluated at the supervisor, activity, and project levels. A fuzzy membership function is defined to describe the causal links between problem sources and problem indicators at the three levels of project control. This system was developed in the M.4 expert system shell. There are two sources of data for the proposed expert system, one is from the user, and the other is a database compiled from the automated data acquisition system.

Instead of a fixed relationship causal model, this system uses a fuzzy membership function to describe the causal links between problem sources and problem indicators. It also considers the management hierarchy structure that provides three levels of project control. Due to the complexity and flexibility of a project in nature, it is very difficult to represent the relationships between the indicators and problem source factors in a set of pre-defined values of membership functions.

Alshaibani (1999) presented a computerized cost and schedule tracking and control system (CSTCS). The system is designed to control project progress at the activities cost account level. The basic control elements for this research are work packages that mainly focus on activities. The system integrates the control function with Primavera Project Planner (P3). All the control source data come from P3. Four parameters (labor cost, labor productivity, crew pay rate, and crew mix) work as indicators to assist in detecting the unforeseen reasons, which may cause cost overrun and schedule delay.

The system starts by computing the cost performance index and schedule performance index for each cost account using the earned-value method. If one of these indices is less than one, it indicates that the project is experiencing an unacceptable performance. The ratios of the indicators such as cost unit rate, productivity unit rate, average crew cost unit rate, and crew mix rate are examined to analyze the causes of an unacceptable performance. The variance analysis path diagram, which has been developed by Abu-Hijleh and Ibbs (1993), was used to represent the causal links of these indicators. Once the cause has been detected, it recommends corrective action(s) if needed. A performance algorithm is developed, basing it on the project ratio method (Eldin and Hughes 1992) to estimate the impact-cost of each indicator.

Three forecast techniques such as the project ratio method (Eldin and Hughes 1992), earned-value method (DoD 1980), and schedule performance estimator (Robinson and Abuyuan 1996) are adopted. Each of them is improved when applied. An optional selection module was established that provides more flexibility to the end user selecting alternatively the preferred forecasting method. There is no comparison of the results of the three above-mentioned forecast methods.

In this work, relative values are taken for tracking and control of the labor cost and schedule performance. That means the cost account size is not considered. In fact, the size of a cost account has a great impact on the efficiency of the project control. The absolute value is another very important factor that needs to be accounted for. The system was developed in a Level 5 Object-Oriented expert system shell.

CSTCS integrates commercial planning software P3 in a control system that provides the project manager with a very powerful tool for control. The system can carry out routine scheduling, earned-value analysis, and the diagnosis of the reasons for unacceptable performance. It can also suggest corrective action(s) and predict future performance under different management and job conditions. Since the indicators can be caused by many factors, only identifying the indicator itself can not exactly locate the reason(s) for poor performance. The control system is focused on activity level. Only labor time and cost control are considered in this system.

2.6.2 Application of Fuzzy KBES

Modeling of system behavior has been a challenging problem in various disciplines. A fuzzy knowledge-based system modeling method provides a very useful tool for modeling complex problems. This has been verified by the applications developed by Boussabine and Elhag (1999), Fayek (2000), Fayek and Zhuo (2001), and Knight and Fayek (2002). The following will review those systems in a level of detail.

Boussabine and Elhag (1999) proposed a subjective model to predict cash flow at the project level. Fuzzy inference is utilized to model the relationship between the current and future project cash flows. The duration of a project is divided into nine valuation periods corresponding to 10%, 20%, ..., 90% completion. The statistical results of data from 30 cases establish the fuzzy membership functions for each evaluation period. Three linguistic terms such as "*Low*", "*Medium*", and "*High*" are utilized to describe the scope of an evaluation period. The current cash flow status is described as degrees of belief in terms of "*Pessimistic*", "*Moderately optimistic*", and "*Optimistic*". The degrees of belief are subjectively assigned by the decision maker. Nine rules are formulated, basing on different combinations of their linguistic terms for each evaluation period. Each combination represents an S curve. The fuzzy weighted average computational method proposed by Dong and Wong (1987) is employed to defuzzify the resultant fuzzy set. It should be noted that only one parameter of project level cash flow was utilized in their proposed model for project level cash flow forecasting. When more parameters are involved, a practical method is needed.

Fayek (2000) proposed a framework of GMP-based reasoning in the prediction of design performance. Fourteen input factors that affect design performance and three output factors that measure design performance were compiled. Each factor was further divided into sub-factors. Linguistic terms and corresponding numerical measures were chosen to describe each factor and sub-factor. A series of If-Then rules is established to define the relationship between: input-sub-factors and input-factors, input-factors and output-factors, output-factors and output-sub-factors. These rules form the basis of a fuzzy expert system that predicts design project performance.

Fayek and Zhuo (2001) proposed a fuzzy expert system for design performance prediction and evaluation. Fuzzy inference is utilized to model the relationships between the input variables and output variables. Fourteen input factors, fifty-nine input sub-factors, three output factors, and thirteen output sub-factors are considered in their system. The membership functions of the input and output variables are defined by objective data, which comes from a questionnaire survey. The developed system suggests a method to predict design performance using impact factors.

Knight and Fayek (2002) proposed a fuzzy logic model for use in predicting potential cost overruns on engineering design projects. Thirteen project characteristics and eight risk events are used in the model. Fuzzy binary relation is utilized to model the relationships between the characteristics of a project and the potential risk events that may occur, and the associated cost overruns caused by combinations of the project characteristics and risk events. The degrees of cost overrun/underrun are classified into 10 different ranges from increase very high to decrease very high. The model is useful in assessing the amount of possible risk on a project and the likelihood of making a profit on the job.

2.6.3 Application of OOP

OOP provides a highly flexible and modular programming environment for the analysis and design of computer systems that are capable of solving complex engineering problems (Al-Hussein 1999). OOP paradigm and characteristics of abstraction, inheritance, modularity, and encapsulation of data (Booth 1994) have received considerable attention among professional and academic groups. Nowadays, no matter what kind of system development is used, in most cases, it is based on OOP concepts.

In 1993, Abu-Hijleth (1991) proposed a variance-based exceptional report system in the Unix operating system using the OOP concept. The work element is the basic control unit of a project. Performance can be evaluated from the perspective of WBS, Work Classification Breakdown Structure (WCBS), OBS, and the cost account by summarizing the work elements data in a bottom-up fashion. The WCBS combines performance data from similar work elements that are packaged separately.

The system focuses on the weekly job-oriented exception reports to ping-pong the problem areas in direct labor cost and schedule performance. The reports identify exceptions based mostly on work quantity, man-hour, and labor cost data. Seven parameters (labor cost, man-hours, work quantity, unit labor cost, unit productivity, labor unit price, and craft rate) were used as performance indicators in the system. The proposed variance analysis paradigm was used to specify the problem sources of variances. The evaluation procedure starts at the top report level. Any variance in the work quantity, man-hour, and labor cost data where either its absolute value or relative value exceeds its user-defined thresholds, can be treated as poor performance of that aspect. The corresponding exception report is generated, and suggestions are provided.

The project exceptional report is a special report generated by the control system when the project is experiencing unacceptable performance in a control aspect (cost or schedule) represented by the indicator whose value is out of the ordinary range (acceptable range) so as to address the project manager's attention for control purposes. This is an efficient way of project controlling which enhances management's productivity by focusing on the most critical subset of performance information. Only direct labor cost is considered in the system. As a control system, only identifying the indicator, which causes the poor performance, is not enough to locate the problem source factors. Further analysis is still needed in order to precede the control action accordingly.

2.6.4 Application of the Internet

With the explosive use of the World Wide Web (WWW), the Internet has become a very powerful platform for system development. The major advantage of the Internet is that its distributed network systems provide data-sharing ability, which significantly improve information flow and communication among the participants. It also provides a collaboration environment that allows the participants to cooperate without being present at one place at the same time. The Internet can operate in a highly modular, open, flexible, and distributed framework, rather than in a prescriptive and restrictive manner (Froese and Waugh 1996). The use of the Internet in project control has been explored by Liu and Stumpf (1996), Abdelsayed and Navon (1999), Villeneuve and Fayek (2003), and Moselhi et al. (2001, 2002, 2004). However, the most common use of the Internet at present is still limited in gathering information about daily project status and publishing the project performance reports on the Internet.

Liu and Stumpf (1996) presented an HTML-based system to store and retrieve construction project information. The system is limited to transferring data (text, sound, images, and video) pertaining to daily site status to be published to a World Wide Web site.

Abdelsayed and Navon (1999) recognized the importance of establishing a system that enables project members to share and access project information while maintaining the integrity of the data. They developed an Internet-based information sharing system for project control. The system consists of five modules: daily site reports, change order management, schedule control, and database of correspondence. The daily site-reports module facilitates adding data, updating, or reporting a new day of work. The change order management module is a simplified workflow process that utilizes pre-programmed e-mail routing to facilitate the exchange of data between contractors and owners in order to handle change notices and change orders. The schedule control module updates the schedule status and generates the earned-value-based performance reports and as-built versus as-planned schedule reports. The database records both incoming and outgoing correspondence documents. Each of the modules has a database to support its designed functions. A common work breakdown structure is incorporated with various relational databases to ensure the integrity of the system. The developed system provides an Internet-based information-sharing model for efficient communication among project team members. As a project control system, it only evaluates the performance of individual work and does not provide any control functions.

Villeneuve and Fayek (2003) described the functionality of a prototype project website (PWS) and introduced its design and implementation. It serves as a template that helps construction companies to adopt the Internet in project data dissemination. PWS is a guide to construction companies for website design and implementation. The described project control considers only the current and cumulative progress reports that reflect the tracking function.

Moselhi et al. (2001, 2002, 2004) presented a web-based integrated project time-and-cost control system, which used the earned-value method to track and control project performance for an on-going project. The developed system identifies not only the deviations from the baseline, but also diagnoses the reason(s) behind individual variance and suggests corrective action(s) based on the detected reason(s).

2.6.5 Discussion

Great effort has been made to establish an effective project control system, for example, Singh (1991), Abu-Hijleth (1991), Diekmann and Al-Tabtabai (1992), Fayek et al. (1998), Alshaibani (1999), Abdelsayed and Navon (1999), Moselhi et al. (2001, 2002, 2004), and Villeneuve and Fayek (2003). However, almost all the developed project control systems take their control functions only on an individual work element, and do not consider the entirety of the project, except that developed by Moselhi at al. (2004). The idea of using indicators to diagnose reasons behind variances has been applied by Abu-Hijleth (1991), Diekmann and Al-Tabtabai (1992), Fayek et al. (1998), Alshaibani (1999), and Moselhi et al. (2001, 2002, 2004). The corresponding causal link connects the selected indicators to the identified variances. Since each project is unique, a fixed relationship between the selected indicators and the identified variances could not reflect the uncertainty involved in the reasoning process. Therefore, fuzzy membership function, as used by Fayek et al. (1998), is preferred. It provides a more flexible but very practical way to describe a relationship. Also the currently selected indicators are limited to a specific area, for example, the labor impact factor. None of the literature provides a comprehensive review of all the possible indicators identified by the previous research. The authors of the literature do not utilize all the possible indicators in their developed control system. Also, the existing reasoning process only explains the reason(s) based on the indicator itself. It does not go further to locate the impact factors. The developed system runs on a different platform. The incompatibility of the computer system also limits the spread of the application. On the other hand, the Internet provides an efficient network for system implementation. It allows users to access the system simultaneously and provides information sharing among users. The collaboration among project team members creates an effective working environment for successful project implementation. None of the developed systems, however, focus on web-based project control functions, except those proposed by Moselhi et al. (2001, 2002, 2004). As a control system, they only support project performance evaluation and do not provide the function for control. The developed system is one of the explorations on web-based applications.

2.7 Summary

The issue of project control is of paramount importance to the construction industry, particularly for companies undertaking high-risk projects (Fayek 2000). The financial success of a contractor is greatly dependent upon his or her ability to control and meet budgeted project costs. Integrated time and cost control is still an essential for a contractor who wishes to survive the competition. An overview of the existing control system proves that, no matter what effort has been made up to today, there is still a room for improvement, especially in the diagnosis of reasons for poor performance, recommendation of corrective action(s), prediction of future performance, and effective communication.

To be an efficient project control, the control model is crucial. There are three types of project control models in the literature. The product and process models are the most efficient models. For existing control systems, the process model is used more frequently.

The earned-value method is still an effective way to integrate time and cost performance and identify any deviation from planned value. Nothing other than the project baseline itself may serve as a control reference. Whenever there is a change in the baseline, all calculations are to be re-performed consecutively. This is in essence the implementation of any method to baseline management (Fleming 1983).

For the reasoning method, the KBES performs well in consolidating the expert's knowledge in order to detect the problem source and suggest corrective action(s). The existing control systems employ indicators that are associated with identified variances to detect the problem sources. A set of rules describes the causal links between the indicators and the identified variances. Since, each project is unique, the fixed one-to-one relationship cannot handle the changed situations. Fuzzy membership function is, by contrast, the best available tool to deal with the uncertain nature of this relationship. The existing reasoning process needs further extension to locate the performance impact factors and to suggest the corrective action(s) based on those identified impact factors. CBR is the latest tool for reasoning purposes. However, it is difficult to deal with the reasoning process for an on-going project. In order to have a feasible system for project control, the fuzzy reasoning method seems the best available method for dynamic reasoning since, in practice, the situations might change from one project to another.

Forecasting is always a great challenge for effective project control. Researchers in the literature have made considerable efforts on this aspect. In most cases, the existing forecasting method is developed, basing it on the linear trend prediction. None of the existing methods, however, could predict cost and duration at user-specified interim horizons. Also, the parameters utilized by the developed fuzzy-based forecasting methods are risk factors that do not have direct link with the previous performance process. A fuzzy subjective modeling method is explored in this research project.

Another challenge facing the construction industry derives from the need to devise effective communication strategies for project control. The existing project control system, no matter what type it is, has its limitations and lacks effective communication and collaboration with the project team members when the project is far away from the contractor's head office. The Internet, as a global communication tool, provides an efficient and effective network for information sharing and transfer. It also provides a network-based collaboration environment. It is strongly believed that establishing an integrated Internet-based project time-and-cost control system that is incorporated with an object-oriented model could significantly improve communication and collaboration among project team members and hence increase productivity and reduce potential risk for financial failures on construction projects.

Chapter 3

PROPOSED EVALUATION METHOD

3.1 Object Oriented Modeling

Project time and cost control requires a large amount of different types of data. Typically, many different computer systems keep track of this information, such as Timberline for cost estimation, Primavera for scheduling. Future Project Management software must be more integrated so that project control can be managed in a more comprehensive manner throughout the life cycle of the project.

Object-oriented modeling (OOM) is considered useful tool to provide integration. The OOM method (Booch et al. 1999, Boggs 2002) was adopted in this research to model factors and represent the dynamic nature of the object being controlled. The fundamentals of the Object-Oriented method are based on the synthesis of data, and the process to a concept called objects, which comprise both data (attributes) and methods (the process that acts on the data). These objects should reflect the real-world parameters such as concept, abstraction or any related matter, with clear boundaries and meanings for the problem at hand (Booch et al. 1999). The major characteristics of the OOM include data abstraction, encapsulation, and inheritance. The object-oriented abstraction appears to naturally exhibit the real life objects with their characteristics, behaviors, and communications with each other. It is based on a set of conceptual and physical models and represents different aspects of complex engineering systems. Using encapsulation, an object combines data, operations, and functions and hides them from other objects in order to ensure their integrity (Martin 1993). Objects with similar attributes and methods are grouped by class. A class represents a concept that has a structure and a behavior. Inheritance allows new classes to expand and to build on the basis of an existing parent or super class when the subclass shares the structure and/or behavior of the super-class. Each super class can have several children or sub-classes.

Through the OOM method, the entire system is made up of many classes and objects (Quatrani 2002). System behavior is achieved through the collaboration of the objects in the system. Two types of relationships, association, and aggregation provide the conduit for object interaction. An association is a bi-directional semantic connection between classes (Quatrani 2002). An association between classes means that there is a link between objects in the associated classes. An aggregation relationship is a specialized form of association in which a whole is related to its part(s) (Quatrani 2002). An aggregation is known as a "part of" something or a containment relationship. This containment may be done by value or by reference. Containment by value implies exclusive ownership by the contained class. It is depicted as a line with a filled diamond next to the class denoting the whole. A containment by reference does not mandate exclusive ownership. It is depicted as a line with an open diamond next to the class denoting the whole. When the relationship is either association or aggregation, it should be attached with multiplicity indicators. Multiplicity defines the minimum and the maximum number of objects that participate in the relationship from the connected classes. Two multiplicity indicators should be written at the two ends of the relationship line.

There are several notations for the graphical representation of the components of an Object-oriented model in order to facilitate its development (Booch 1994, Martin 1993, Booch et al. 1999, and Ericksson and Penker 1998, Boggs 2002). The Unified Modeling Language (UML) (Ericksson and Penker 1998, Quatrani 2002, Boggs 2002) is chosen to develop the conceptual model for this research project. UML is "a language for specifying, visualizing, and construction of the artifacts of software systems" (Booch 1997), where artifacts are diagrams and documents that comprise system models. It is a comprehensive modeling language that can be used to represent system models during the whole system development process. UML uses different types of diagrams at different development phases/sub-phases, such as Use Case, Sequence, Static Structure, Class, State Transition, Component, and Deployment diagrams. The Class diagram is the diagram that represents concept, data, and relationships of a conceptual model. This diagram is used in the system analysis sub-phase as a high level representation of the Class. Examples of relationship notations used in UML are given in Fig. 3.1.

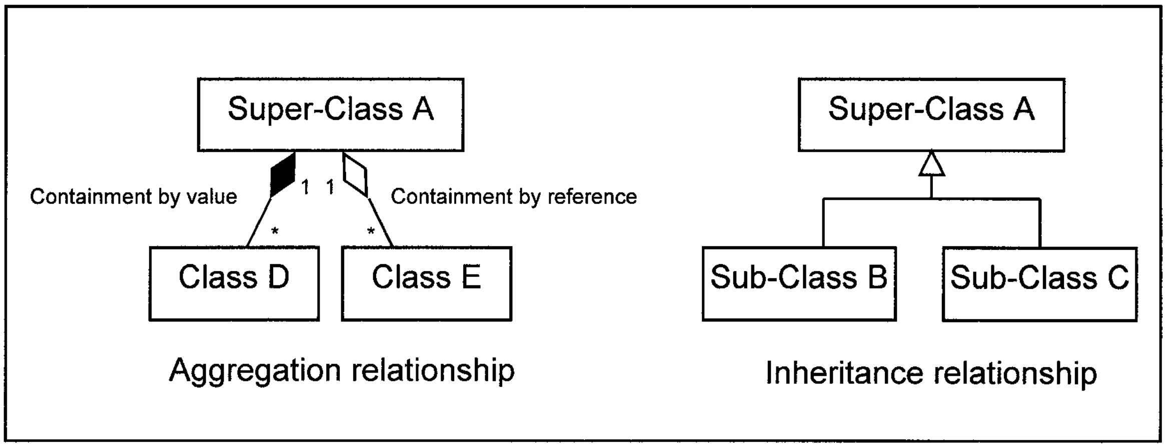


Figure 3. 1 UML Relationship Notations

This chapter analyzes the major components of the proposed control system and describes the methodology for integrated time and cost control. An object-based model is proposed to represent the hierarchy data structure of a project. Three levels of project performance evaluation are established. Earned-value method is utilized to identify the time and cost variations for each evaluation level. At the lowest evaluation level, a set of performance indicators is designed to help find the source of the variances. Causal models related to the indicators are developed to identify the problem-source factors for unacceptable performance.

3.2 Object-Based Model

The analysis of the current project control model, discussed in Section 2.2.4, reveals that the process and product models are possible candidates for integrated time and cost control. The common problem that exists in the utilization of computer applications and data exchange in the AEC industry reveals that different applications are not capable of exchanging information due to the lack of a common data representation. The various computer applications generate data in different formats, data types, level of detail, and scope. To overcome this problem and to ensure that the proposed control model is capable of supporting time and cost integration and establishing a single data source for the entire project control, a control-object is necessary.

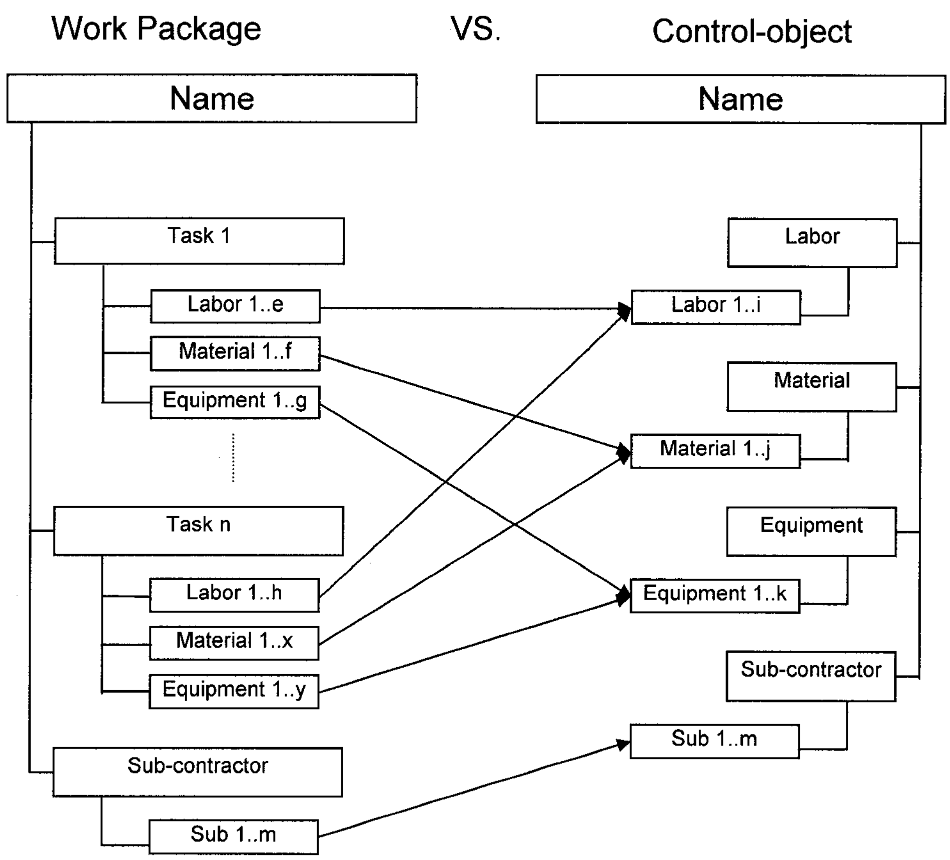


Figure 3. 2 Work Package vs. Control-Object

In order to define a control-object, a work package model is analyzed (Moselhi at al. 2002). Fig. 3.2 presents the relationship between a control-object and the common structure of a work package. The work package contains a number of work tasks directly performed by contractors and other tasks that can be sub-contracted out. The resources utilized in each work task can be divided into labor, material, and equipment, along with their budgeted and actual data. These resources are encapsulated in a conceptual model referred to here as a control-object. Sub-contractors in a work package are treated as a type of resource. Each control-object takes the attributes of the name and the resources from the work package. It also accounts for the relation to other work packages and the method of resource allocation. In addition, the proposed control-object has the attributes that describe its characteristics such as sensitivity to weather and site congestion, and the threshold values for unacceptable performance. Each type of resource in a control-object may have single or multiple sub-resources. The proposed control-object is an abstract concept of a physical component of a project. There are budgeted resources that serve as a control reference as they are actually consumed over the project duration.

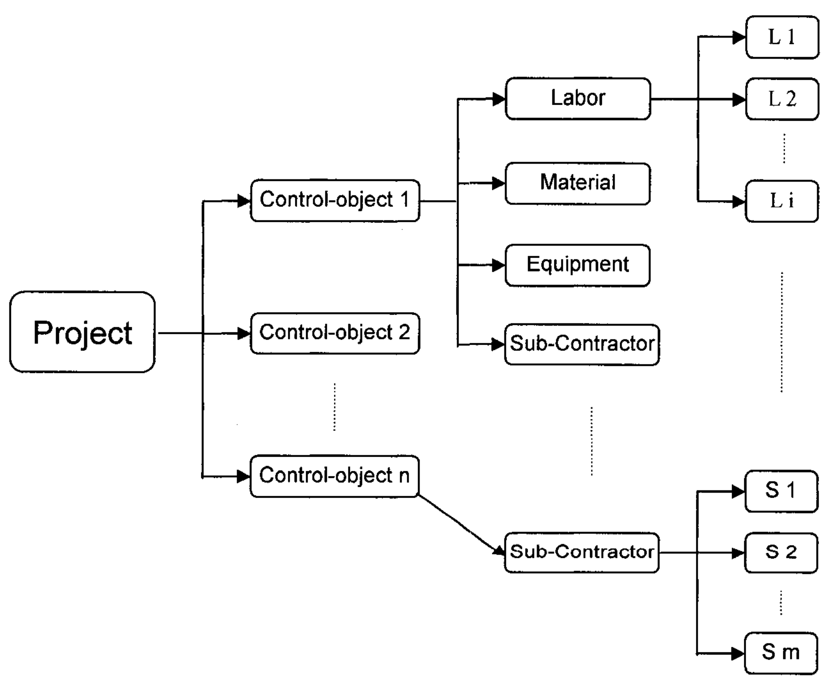


Figure 3. 3 Proposed Project Breakdown Structure

Based on the proposed object-based model, the whole project breakdown structure can be established as shown in Fig. 3.3. The proposed control-object serves as the basic control element in the control system. It is considered as a product unit or a work package. If the control-object is a product unit, it relies on the PBS to define the scope and resources of the unit. If the control-object is a work package (as shown in Fig. 3.4), it relies on the WBS. In the developed model, a control-object may represent a product unit, a work task, or an activity. It may also be a structure, a sub-contractor or a project as a whole. It should be emphasized that the scope of a control-object would be explicitly defined to avoid redundancy among product units and work packages when they are at different levels.

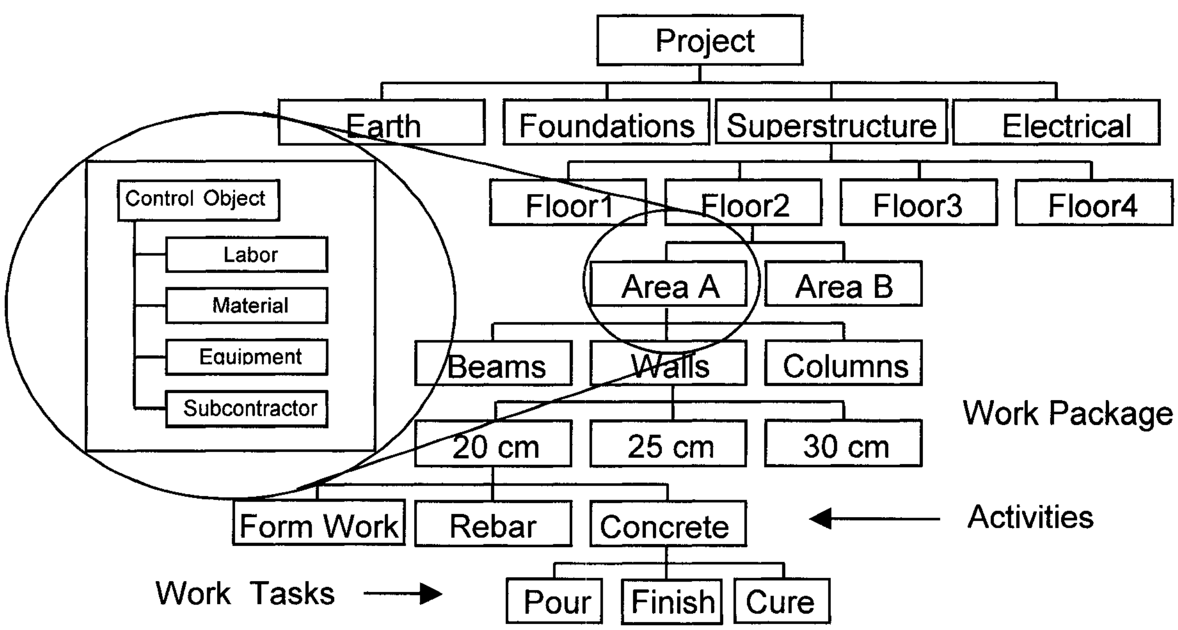


Figure 3. 4 WBS and Control-Object

According to the proposed project breakdown structure, the object-based model of a project can be defined as a static structure diagram of entity classes as shown in Fig. 3.5. In this figure, the *Project* class is an aggregation of a set of *ControlObject* classes. A *ControlObject* class has its budgeted and actually consumed resource classes. The budgeted and actual resource classes are considered here as sub-classes. Each main resource class, such as *Labor*, *Material*, *Equipment*, and *SubContractor* is considered a super-class. Their respective budgeted and actual values, i.e. *Blabor* and *Alabor,* are considered sub-classes of the *Labor class.* Super-classes can represent the common attributes of their sub-classes, such as name, type of resources, and relation to other classes, therefore avoiding redefinition of common attributes. Sub-classes, accordingly, inherit the characteristics from their respective super-classes. It should be noted that an object is an instance of a class. The case of a work package of brick wall construction is considered an instance of the *ControlObject* class. It contains resource data of bricklayers, bricks, and mortar. The bricklayers are considered an object of super-class *Labor,* and the budgeted data of bricklayers is an object of sub-class *Blabor.*

In addition, five classes are incorporated in the present model: *PFactors*, *Status*, *Progress*, *Allocation*, and *Predecessors* classes. The *PFactors* class is designed to record daily project-performance impact factors such as site and weather conditions. The *Status* class is designed to record the actual start and finish dates of a control-object. The *Progress* class is utilized to record the daily actual quantity of work installed for a control-object. The *Allocation* class is designed to define the distribution of resources over the duration of tasks performed with each control-object. The *Predecessor* class is designed to specify the relationships between control-objects.

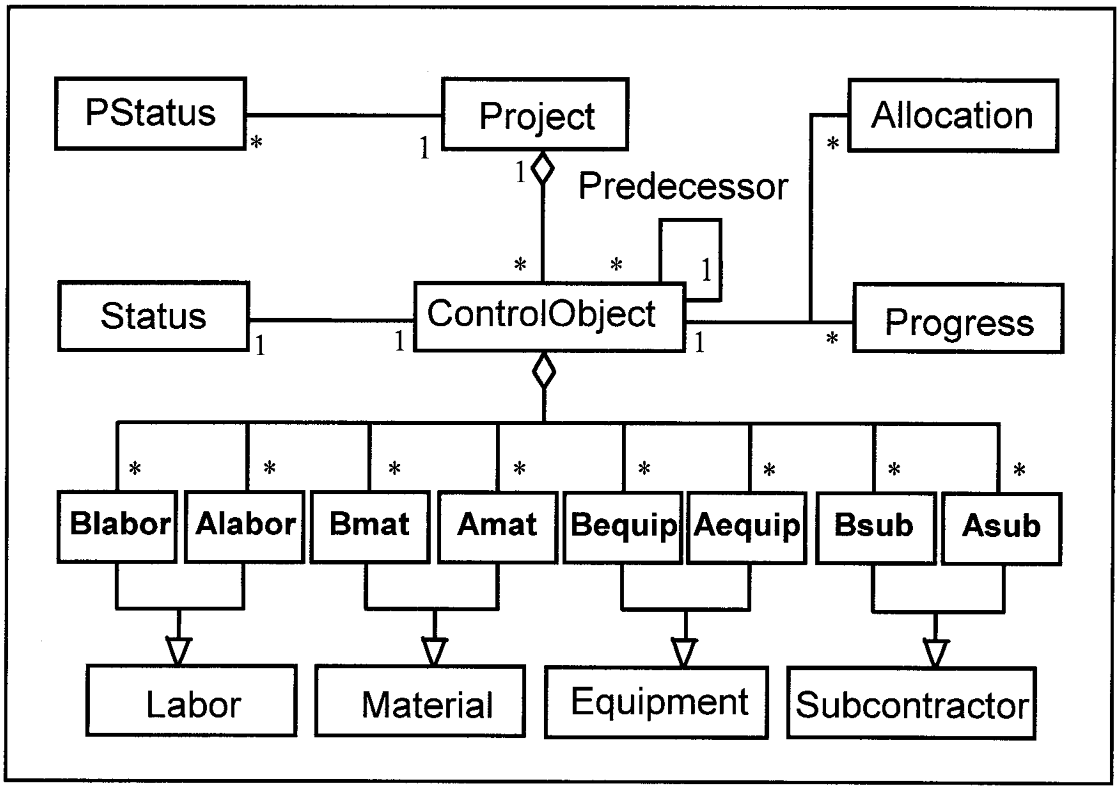


Figure 3. 5 Object-Based Model of a Project

The *Project* class is designed to represent the characteristics of a construction project and process various data of control-objects. Therefore, the *Project* class has one-to-many associations with the *ControlObject* class. Similarly, the *ControlObject* class has one-to-many associations with the *Labor*, *Material*, *Equipment*, and *SubContractor* classes respectively. Each resource class has one-to-many associations with its sub-classes. The *PStatus* class and *Progress* class is used to record the daily site data of a project and control-objects. Therefore, one-to-many associations are involved. One control-object may have relationships with many other control-objects. The *Predecessor* and the *Allocation* classes have one-to-many associations with the *ControlObject* class. A control-object can only have one actual start date and one actual finish date. The *Status* class has a one-to-one association with the *ControlObject* class.

It should be noted that the proposed object-based model is compatible with Industrial Foundation Classes (IFCs) proposed by the International Alliance of Interoperability (IAI) (1996). This facilitates integration with other software applications. The proposed model provides further efficiency in its implementation through the use of the specially designed entities described above.

3.3 Project Baseline

Control-objects are used to generate control baselines at the resource, object, and project levels. They are also used to track project progress. The control baseline for the proposed system includes information on planning and scheduling of control-objects along with the associated resources assignments. It also includes two additional attributes: threshold value and relationship. There are three types of baselines for control purposes such as project baseline, control-object baseline, and resources of labor, material, equipment, and/or sub-contractor baselines. The data in the baseline such as cost, quantity, duration, start time, and finish time are treated as constant. When the baseline changes, all the calculations are to be re-performed consecutively. This is in essence an implementation of the method to baseline management (Fleming 1983, Schenk 1985, Singh 1991)

3.3.1 Threshold Values

1. Introduction

Threshold values are essential to generating the project exception report. The term "exception reporting" seems to be more commonly recognized in schedule reporting (Abu-Hijleh 1991). Cost exception reporting can generate specialized reports for each cost type such as labor, equipment, material, etc. Variance beyond a specified threshold can be used to detect both favorable and unfavorable trends in both cost and schedule performances. A cost or time deviation in excess of the threshold value indicates a problem. Both positive and negative variances can indicate a problem. Positive variances, however, are normally tolerated at higher levels but the negative ones are not. This is because the negative ones usually experience more serious problems. In fact, some companies, including very large ones, do not highlight positive variances at all (Abu-Hijleh 1991).

The Threshold value can be determined by defining a region above and below the budgeted performance level within which actual performance is allowed to develop without sending out any warning messages. It is important that both absolute and relative thresholds be defined. This is because, for example, a small percentage overrun (5%) on a big control-object ($500,000) may be more critical ($25,000 overrun) than a large percentage overrun (30%) on a small control-object ($10,000×30%=$3000 overrun).

2. Threshold values in current practice

Construction firms do not commonly use variance thresholds for computerized cost reporting (Abu-Hijleh 1991). Some companies approach cost exception reporting differently. They use the "10 best" and "10 worst" accounts method. They highlight the accounts experiencing the largest cost under-runs and overruns. Such a ranking method conveys to management a heightened sense of urgency with regard to the selected accounts.

Four applications are discovered in the literature with such threshold values. They are C/SCSC on government contracts (Abu-Hijleh 1991), Baweja (1997) on his Statistical Control Charts in Construction, Al-Jibouri (1985) on stochastic project control and Abu-Hijleh (1993) on his exceptional report system.

Table 3. 1 An Example of Constant Variance Thresholds

Type of Variance		Variance Thresholds
Cost	Cumulative	10% and $10,000 or 200 hours
	Current period	10% and $10,000 or 200 hours
Schedule (cumulative & current period)		10% and $25,000 or 500 hours
At completion		10% and 25,000 or 500 hours

Typical C/SCSC thresholds define a constant width band of allowable cumulative deviation around planned performance (Table 3.1). In the relative form, which is expressed as a percentage, the threshold for cumulative performance is normally constant and equal to the at-completion relative threshold. In this absolute form, which is expressed in terms of dollars or man-hours, the threshold is also kept constant. Obviously, a constant cumulative threshold throughout the progress of a work package fails to address some important issues.

Baweja's (1997) statistical control chart is another format of constant threshold. The upper and lower control limits are defined by Levinson's (1992) statistical analysis method. Only absolute thresholds are considered. However, it is difficult to establish a statistical threshold value for construction projects due to its unique nature.

Al-Jibouri (1985) proposed a stochastic probability method for project cost control. The desired level of mean cost is set up to control any overhead costs that may occur. The unit cost of unit earning standard deviation is set up to control the variability of the physical process and the uncertainty in the measurement system. The standard deviations are those for the relevant earnings involved. The measured cost of unit earning for period and cumulated values are compared to the estimated values to determine the variations. The control acts on large differences between the estimated and the measured cost of unit earning.

Abu-Hijleh (1991) presents a three-stage threshold method. The percentage completion of the activity is considered when determining the threshold value for variance. For instance, in the early stage of an activity (e.g. less than 20% complete), a higher threshold for cost variance is generally acceptable due to the learning curve and mobilization effects. In the intermediate stage of an activity (e.g. 20% to 80% complete), the threshold value can be lower, indicating that planned values should be achieved and that corrective actions should be implemented if these values are not achieved. Towards the end phase of an activity (e.g. greater than 80% complete), the threshold value should be very close to zero, indicating that the planned values have been achieved; otherwise, a problem will occur. Most corrective actions would be ineffective at such a late stage in the progress of an activity. This method is adopted and modified for the proposed control system.

3. Threshold values in the proposed system

In the proposed control system, the three-stage threshold method (Abu-Hijleh and Ibbs 1993) is employed when determining the threshold values for time and cost. Threshold values of variances from the baseline at each stage can be user-defined at the resource, control-object, and project levels for time and cost control purposes. The values of threshold depend primarily on the characteristics of the control-object as well as other factors such as company policy. They may be different for each resource category (i.e. labor, equipment, material, and subcontract). Both absolute and relative values of the threshold are considered to account for the impact of the project size.

3.3.2 Relationships

The predecessor class of the control-object specifies the logical relationships between the control-objects. These relationships form the job logic. Four types of relationships, such as start-to-start, start-to-finish, finish-to-start, and finish-to-finish, with their lag constraints, have been incorporated in the proposed system. These relationships are specified when the user inputs the planned data into the system.

3.3.3 Responsibilities

Each control-object is assigned to at least one site-personnel for control purposes. For example, carpentry superintendents would normally look after wood structure or forming operations. Plumbing and electrical superintendents would be responsible for piping and electrical work respectively. It would be desirable to identify one person as responsible for each control-object. However, several personnel may be responsible for one-control-objects. A concreting control-object, for example, can encompass formwork, reinforcing rebar, and placing concrete. In such a case, more than one site-personnel may be involved, and responsibility has to be established for the individual work tasks within the control-object.

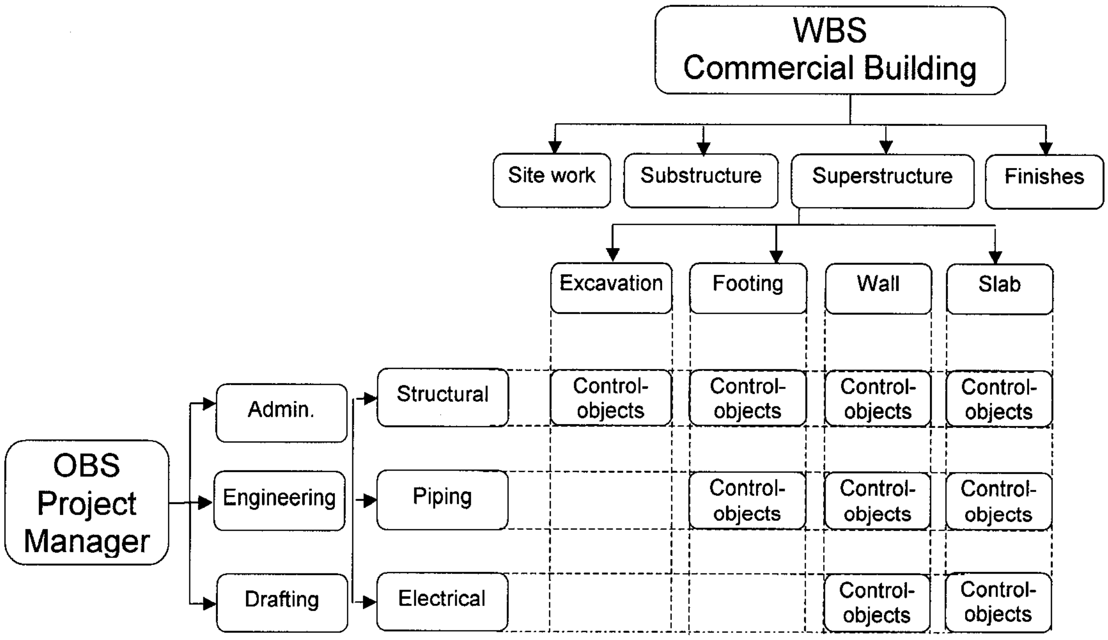


Figure 3. 6 Example of assignment of responsibility

Fig. 3.6 gives an example of the assignment of responsibility for control-objects. In general, a control-object will have only one superintendent. Fig. 3.7 shows the responsibility hierarchy structure of the proposed control system. The top-level control right is assigned to general managers, who are responsible for several projects. Each project is taken care of by a manager. The site managers are responsible for one or several control-object performances. They report to the manager about labor, material, equipment and sub-contractor performance, analyze the reasons for poor performance and forecast the future time and cost performance. The manager reports to the general manager about the whole project performance, analyzes the reasons for the poor performance and predicts the future time and cost performance. Usually, the superintendent is the site manager.

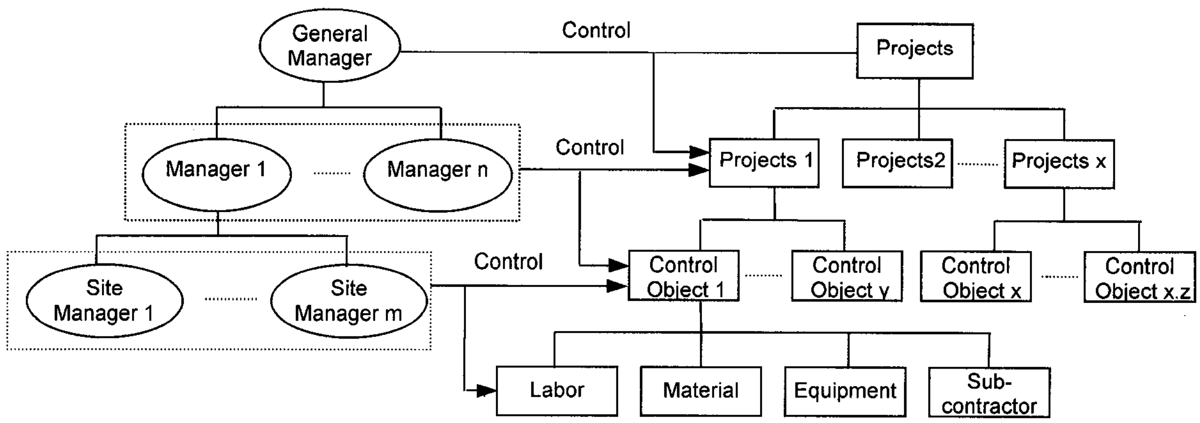


Figure 3. 7 Project Management Hierarchy

3.4 Basic Control Variables

The earned-value method is employed in the development of the performance evaluation algorithm. Some researchers have looked carefully at this aspect such as Eldin and Hughes (1992), Abu-Hijleh and Ibbs (1993), and Carr (1993). With the new mechanism proposed by IT/CC (Integrated time and cost control) system, the existing methods need modification and further development. The developed algorithm facilitates the analysis of the deviation of cost and schedule at each control level.

3.4.1 Data Needed

The budget input data in the algorithm includes the project planned start date (T_p), planned finished date (F_p), total quantity of a control-object (Q_{object}), scheduled start date (T_s), planned duration (D_b), lag time (L_b), cost of labor (LC_b), cost of material (MC_b), cost of equipment (EC_b), cost of sub-contractor(s) (SC_b), labor man-hours ($Mhrs_b$), equipment working-hours ($Whrs_b$), sub-contractor working-hours ($SWhrs_b$), material quantity (MQ_b), planned number of crew member (N_b) as well as the threshold values for time and cost control, the method of resource allocation, and the relationships to other control-objects. For control purposes, the characteristics of a control-object such as sensitivity to weather and site congestion are also considered. Table 3.2 gives an example of the integrated method to estimating the resources used by utilizing an estimation sheet (Abudayyeh and Rasdorf 1993). Users can obtain their scheduled data for each project by using commercial software such as P3 or Microsoft Project.

The period-by-period input or daily input of site data includes control-object actual starting date (T_a), control-object revised quantity (Q_v), actual quantity installed (Q_a), actual cost of labor (LC_a), actual cost of material (MC_a), actual cost of equipment (EC_a), actual cost of sub-contractor(s) (SC_a), actual labor man-hours ($Mhrs_a$), actual equipment working-hours ($Whrs_a$), actual sub-contractor(s) working-hours ($SWhrs_a$), material usage (MQ_a), number of crew member (N_a), actual finished date (T_c) as well as the weather and other related site conditions. It should be noted that only direct cost of labor, material, equipment, and sub-contractor are taken into consideration. Indirect cost and other cost types are beyond the scope of this research.

Table 3. 2 Example of Budgeted Cost Data

Construction Estimation Sheet						
Control-Object Code: 2300		Description: Concrete for Foundations				
Account Code: 12300		WBS Code: 4				OBS Code: 132
Labor						Productivity
Craft Code	Direct Crew Labor	Quantity	Cost/Hr	Man-hours	Total Cost	Bases units for productivity
12100	Concrete Worker	5	16	440	7,040	cy
						Total Quantity (Base Unit)
						40 cy/Day
Material						Duration
Material Code	Description	Unit	Quantity	Unit Cost	Total Cost	440cy/40cy/Day
22310	3000psi Concrete	cy	440	52	22,880	=11Days
						=88 Hours
Equipment						Cost Summary
Equipment Code	Equipments	Number	Hours	Cost/Hr.	Total/Cost	Labor: 7,040
32110	Small Concrete Pump	1	88	45	3,960	Material: 22,880
						Equipment 3,960
						Total: 33,880

3.4.2 Percentage Completion

Percentage completion is essential in applying the earned-value concepts. A number of methods have been proposed for estimating percent completion (DOD 1967, CII 1987, Riggs 1987, Eldin 1989, Moselhi 1993, Carr 1993, Abudayyeh and Rasdorf 1993, CGSB 1999, P3 1999). In order to calculate the earned-values at project, control-object, and resource levels, three types of percentage completion are defined in the developed IT/CC system, namely planned, revised, and actual to-date, respectively, as follows:

$$PC_s = \frac{\min(D_s, D_b)}{D_b} \tag{3.1}$$

where,

PC_s is planned to-date percentage completion (Carr 1993),

D_s is the number of days to-date since scheduled start of an operation, min (D_s, D_b) is the minimum of D_s and D_b. This constraint prevents the to-date planned percentage completion from exceeding 100%.

$$PC_b = \frac{\min(D_{to-date}, D_b)}{D_b} \qquad (3.2)$$

where,

PC_b is the to-date revised percentage completion,

$D_{to\text{-}date}$ is the number of days to-date since actual start of an operation, where

$$D_{to-date} = D_s - (T_a - T_s) \qquad (3.3)$$

min ($D_{to\text{-}date}$, D_b) is the minimum of $D_{to\text{-}date}$ and D_b. Similarly, this constraint prevents the to-date revised percentage completion from exceeding 100%.

$$PC_a = \frac{Q_a}{Q_{object}} \qquad (3.4)$$

where,

PC_a is the control-object actual to-date percentage completion.

In the case of Q_a is greater than Q_{object}, the PC_a equals 100%.

In addition to Equation (3.4), the progress measurement template developed by Moselhi (1993) can also be used to determine PC_a generically within each control-object. The template divides a control-object into control points; based on its time and cost characteristics (see Appendix B). For objects with relatively long durations, interim control points could be further introduced. A PC_a is assigned for each control point. Also, templates can be introduced for specific tasks. For example, a control-object of "piling", representing driving a set of piles into the soil, is divided into four control points: 1) rig in position, PC_a=40%, 2) drive and inspect, PC_a=80%, 3) trim and finish, PC_a=95%, 4) hand over, PC_a=100%. Such templates serve as a default option. The users, however, can overwrite these templates by introducing specifically designed templates that suit the project at hand. Equations (3.1), (3.2), and (3.4) are applicable at resource and control-object levels. The developed system also allows the user to specify the Equation (3.4) to calibrate the PC_a. At project level, the actual percentage completion (PC_p) can be defined by using earned-value method as:

$$PC_p = \frac{\sum_{i=1}^{n'} BCWP_i}{\sum_{i=1}^{n} BCWS_i} \tag{3.5}$$

where,

n' is the total number of on-going and finished control-objects,

n is the total number of planned control-objects,

$BCWP_i$ is the budgeted cost of work performed for i^{th} control-object,

$BCWS_i$ is the budgeted cost of work scheduled for i^{th} control-object.

The values of the BCWS and BCWP for an individual control-object can be found in Equations (3.7) and (3.8), which will be described later. It should be noted that when the scheduled work for a control-object is accomplished, the BCWP at completion is equal to BCWS.

3.4.3 Resource Allocation

The allocation of quantity, cost, man-hours or equipment working hours in a control-object is assumed to be uniformly distributed over its duration. However, users can specify their own distributions. In this regard, the duration of a control-object is divided by default into ten increments. Each has a value of planned percentage resource. Ten different resource distribution curves defined in Primavera Project Planner (P3) (1999) are adopted in the developed IT/CC system as shown in Table 3.3.

The control-object planned quantity allocation (Q_s) is defined in Equation (3.6).

$$Q_s = \sum_{i=1}^{j} Q_i \tag{3.6}$$

where,

j is the number of the increments up to PC_s,

Q_i is the planned quantity for i^{th} increment.

If PC_s equals one of the 10% increments, then Q_s can be easily derived from PC_s multiplied by Q_{object} ($Q_{object} \times PC_s$). If PC_s does not equal one of the 10% increments, then interpolation is used to determine the cumulative planned quantity ($\sum_{i=1}^{j} Q_i$) for all the increments up to PC_s. A similar method can be used to define the $Mhrs_b$, $Whrs_b$, and MQ_b.

Table 3. 3 Planned Resource Distribution

Item	Resource Distribution	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1	Uniform	10	10	10	10	10	10	10	10	10	10
2	Bell Shape	1	3	8	15	23	23	15	8	3	1
3	Triangular	2	6	10	14	18	18	14	10	6	2
4	Trapezoidal	2	7	11	15	15	15	15	11	7	2
5	Offset Triangular	2	5	7	10	13	15	17	14	10	7
6	Three Step	8	8	8	13	13	13	13	8	8	8
7	Front-Loaded	13	13	13	13	13	7	7	7	7	7
8	Back-Loaded	7	7	7	7	7	13	13	13	13	13
9	Triangular Increase	2	3	6	7	9	11	13	14	17	18
10	Triangular Decrease	18	17	14	13	11	9	7	6	3	2

3.4.4 Earned-Value Variables

The earned-value variables involved in the evaluation algorithm include: BCWS, BCWP, and ACWP. The system evaluates the variances at the resource, control-object, and project levels. Daily, cumulative-to-reporting-date, and/or period-by-period evaluation report(s) can be generated by IT/CC. The earned-value variables for a resource, a control-object, and a project are described as follows. Each control-object has its budgeted cost, C_b. At project level, C_b is treated as the summation of the budgeted cost of all control-objects; at control-object level, C_b is the summation of the cost of its resources; at resource level, C_b is treated as LC_b, MC_b, EC_b and/or SC_b respectively. As work is performed, its value is earned in proportion to its actual percentage completion PC_a. The actual progress is measured by earned-value (BCWP), which is C_b associated with the actual percentage completion, PC_a. Scheduled progress is measured by BCWS, which is C_b associated with the planned percentage completion, PC_s. Equations

(3.7) and (3.8) represent BCWP and BCWS at resource level defined by uniform resource distribution. It should be noted that at project level, BCWP and BCWS are the summation of the control-objects' BCWP and BCWS; at control-object level, BCWP and BCWS are the summation of the cost of its resources. For other resource distributions, interpolation is used to determine the allocation of the budgeted values, if the PC_a is not equal to one of the predefined increments referred to earlier. ACWP is the cost incurred (at project level, ACWP is treated as the summation of all the control-objects' actual cost; at control-object level, ACWP is the summation of the cost of its resources; at resource level, ACWP is treated as LC_a, MC_a, EC_a and/or SC_a respectively).

$$BCWP = C_b \times PC_a \tag{3.7}$$

$$BCWS = C_b \times PC_s \tag{3.8}$$

when PC_a is not available, use PC_b instead.

BCWP might differ from BCWS because actual quantity installed can differ from the quantity budgeted, the actual start date can differ from the scheduled start date ($T_a \neq T_s$), and unit cost per day can differ from those budgeted.

Based on the defined earned-value variables, the CV and SV for an on-going project, control-objects, and resources can be calculated using the Equations (2.1) and (2.2). In addition to CV and SV, cost performance index (CPI) and schedule performance index (SPI) (DOE 1980, Abudayyeh and Rasdorf 1993, CGSB 1999, P3 1999) are defined in Equations (3.9) and (3.10).

$$CPI = \frac{BCWP}{ACWP} \tag{3.9}$$

$$SPI = \frac{BCWP}{BCWS} \tag{3.10}$$

Favorable cost situations are observed when CPI is greater than one, indicating that earning (BCWP) is more than what is spent (ACWP) and vice versa. Favorable schedule situations occur when SPI is greater than one, indicating that what is being accomplished (BCWP) is more than what is scheduled (BCWS) and vice versa. Therefore, CPI and SPI provide assessment mechanisms for evaluating the performance as earned-value based indicators.

3.4.5 Time Variance

Time variance is variance in time after work starts. It is parallel with the earned-value-based schedule variance which is measured in dollars. Time variance, measured against its scheduled time, is very important in efficient project control. A negative time variance, delay or lag is an unfavorable variance. A positive variance is a lead (Carr 1993). Fig. 3.8 shows schedule state of a control-object, in which, T_r is the reporting date; T_f is the planned finished date, and can be derived by $T_s + D_b$; D_a is the actual duration of a control-object.

Control-object time variance (T_v) is the difference between budgeted time to produce the percentage completion PC_a, represented by $D_b \times PC_a$ and actual time to produce the output units to date (Carr 1993). Equation (3.11) defines the time variance of an in-progress control-object.

$$T_v = D_b \times PC_a - D_s \tag{3.11}$$

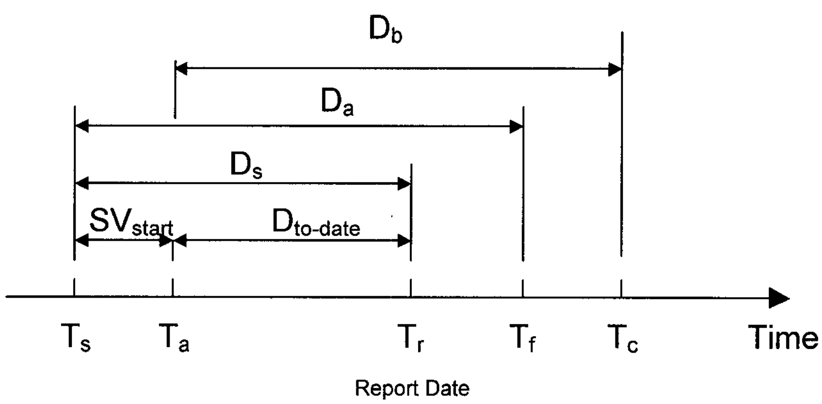


Figure 3. 8 A Control-Object Schedule Statuses

When the control-object work is accomplished, the accomplished time variance is the control-object start-variance together with the difference between the budget duration and actual duration as defined in Equation (3.12). At this time, the earned-value schedule variance is zero.

$$T_v = SV_{start} + (D_a - D_b) \tag{3.12}$$

where,

D_a is the difference between T_a and T_c as expressed in Equation (3.13).

$$D_a = T_c - T_a \tag{3.13}$$

Control-object start-variance, SV_{start}, is the difference between planned start time and actual start time, where

$$SV_{start} = T_a - T_s \tag{3.14}$$

If $SV_{start}>0$, the actual start date is later than the planned date. The delay is generated after the operation starts.

The project duration (D_p) is the summation of the control-objects' duration (D_b) on critical-path. A project-level time variance is the summation of all the progressing and finished control-objects time variance on critical-path. The resource level time variance equals the control-object level time variance.

3.5 Problem-Source Factors

A problem-source factor may affect one or more project performance measures. It is believed that commonality exists between all types of construction projects in that there are recurring sets of generic problem-source factors, which may impact the project performance. Through 10 structured interviews with project managers; 4 located in Ottawa and 6 in Los Angeles, and a literature review of previous research (Abu-Hijleh 1991, Diekmann and Al-Tabtabai 1992, Diekman and Kim 1992, Russell 1993, Yates 1993, Alkass et al. 1993, Ahuja et al. 1994, Russell and Fayek 1994, Assaf et al. 1995, Hastak et al. 1996, Hsieh 1998, Fayek et al. 1998, Hanna et al. 1999, O'Brien and Fischer 2000, Suraji et al. 2001), the total of 39 possible problem-source factors are identified and discussed as follows:

LABOR COST VARIANCES are the results of deviation in man-hours, labor productivity, labor payment, and labor attendance.

1. Deviations in man-hours are due to

- Overruns or under-runs in control-object quantities as errors of estimates,
- The work scope changes within contract limits/change orders,
- Poor workmanship/re-work,
- Acceleration of work using overtime/additional crew/extra shift.

2. Lower or higher productivity than estimation is due to

- Poor estimation of productivity,
- Inferior or improved labor productivity performance,
- Low work moral or labor fatigue.

3. Variance in labor payment rate is due to

- Acceleration of work using overtime/additional crew/extra shift,
- Inferior labor productivity,
- Inferior equipment productivity,
- Poor workmanship/re-work,
- Labor absentee/crew attendance.

4. Variance in labor attendance is due to

- Inadequate skilled labor force,
- Use of unbalanced crew/crew mix change,
- Labor absentee,
- Labor unrest/on strike.

Labor expenditures can exceed budgets by huge amounts when poor overall project management and field planning prevail. Poor estimates may result in over-optimistic production rates. These results in understaffing, lower actual production rates than expected, and overruns of estimated labor man-hours and costs. The same effect will be produced by erroneous estimation of work quantities or production units. Inferior productivity performance may be caused by many factors including:

- Inadequate skilled labor force (crew balance),
- Inadequate planning of construction work,
- Inadequate instruction on construction methods,
- Inadequate supervision of work,
- Change of construction method,
- Poor design/construction coordination,
- Inadequate control of worksite conditions,
- Restricted work area,
- Site congestion,
- Bad weather conditions,
- Shortages of tools or materials,
- Inadequate safety facilities,
- Use of untrained or inexperienced labor force,
- Poor management and labor relations,
- Crew attendance change.

Labor cost escalation can be a significant problem on long duration projects.

EQUIPMENT COST VARIANCE is usually caused by deviation of working hours, productivity and usage rate.

1. Usage of more or less equipment and working hours than planned are due to:

- Overruns or under-runs in work quantities as a result of erroneous estimates,
- Work scope changes within contractual limits/change orders,
- Poor workmanship/re-work,
- Acceleration of work using overtime.

2. Lower or higher levels of productivity than estimated is due to

- Poor estimation of productivity,
- Inferior or improved equipment performance.

3. Changes in equipment usage rate.

- Inadequate planning of equipment operations,
- Inadequate control of equipment operations,
- Equipment failure/Inadequate maintenance.

Equipment cost rates can be increased by escalation. This can be a problem in long-term projects. Poor estimates may result in over-estimated production rates. This results in lower actual production rates than expected and overruns of estimated working-hours and costs. Inferior equipment performance can be caused by:

- Use of untrained or inexperienced operators,
- Shortages of working tools or materials,
- Unexpected ground conditions,
- Bad weather conditions.

Material Cost Variances are often caused by quantity and unit price.

1. Deviations in quantity are due to:

- Poor take off quantity,
- Work scope changes within contractual limits/Change orders,
- Inadequate and/or incomplete design,
- Inferior labor productivity,
- Inferior equipment productivity,
- Material wastage,
- Material damage, loss or theft,
- Delayed Material delivery,
- Poor workmanship/re-work.

2. Variance in unit price is due to

- Escalation,
- Use of alternative material.

SUB-CONTRACTOR COST VARIANCE can be caused by deviation of working hours, productivity, and unit price of its resources of labor, material, and equipment.

1. Deviations in working-hours are due to:

- Overruns or under-runs in sub-contractor's quantities resulting from errors of estimation,
- The work scope changes within contract limits/change orders,
- Poor workmanship/re-work,
- Acceleration of work using overtime/additional crew/extra shift.

2. Lower or higher productivity than estimated is due to:

- Poor estimation of productivity,
- Inferior or improved productivity performance.

3. Escalation of unit price of labor, material, and equipment or factors other than those mentioned in labor, material, and equipment.

The inferior productivity performance may be caused by many factors including:

- Inferior labor productivity,
- Inferior equipment productivity,
- Inadequate communication and/or coordination,
- Deferred payment.

In the construction phase, work on critical path activities may be delayed for many reasons: delay of predecessor(s), poor design/construction coordination, inclement weather, non-anticipated adverse field conditions, or the inability to access a required work site (Short 1993). The above identified possible problem-source factors are intended to cover all the possible problem-source factors while maintaining direct links to the source of the problems.

For convenient data recording and future easy addition and modification of these factors, they were abstracted and classified into factor classes of *ESFactors* (environment and site conditions), *MgmFactors* (management), *CFactors* (contract), *LFactors* (labor), *MFactors* (material), *EFactors* (equipment), and *SFactors* (sub-contractor) according to their respective source field. The *ESFactors* class represents one of the most frequently occurring factors at the project level, such as the daily site and weather conditions. The *MgmFactors* class represents factors related to management such as "inadequate planning of construction work". The *CFactors* class represents factors related to aspects of contracts, such as "work scope changes within contract limits/change orders". The *LFactors*, *MFactors*, *EFactors*, and *SFactors* classes represent respectively factors that are directly related to the performance of labor, material, equipment, and sub-contractors. The attributes of the defined seven classes can be found in Table 3.4.

Based on this classification, the problem-source factors associated with labor performance indicators are aggregation of those emanating from *LFactors*, *MgmFactors*, *ESFactors*, and *CFactors* classes; the problem-source factors associated with material performance indicators are aggregation of those emanating from *MFactors*, *MgmFactors*, *ESFactors*, and *CFactors* classes; the problem-source factors associated with equipment are aggregation of those emanating from *EFactors*, *MgmFactors*, *ESFactors*, and *CFactors* classes; the problem-source factors associated with sub-contractor performance indicators are aggregation of those emanating from *SFactors*, *MgmFactors*, *ESFactors*, and *CFactors* classes. All of these problem-source factors are incorporated in the proposed reasoning method. They are evaluated independently. The interrelationships among the factors are not considered in the developed reasoning process.

In order to detect the above-mentioned source of problems during the construction process and recommend corresponding corrective actions, a set of resource performance indicators is necessarily designed to associate with the problem-source factors.

Table 3. 4 Attributes of Factors' Classes

Category	Code	Problem-source factors (attributes)
ESFactors (environment and site conditions)	1.1	Bad weather conditions
	1.2	Escalation
	1.3	Inadequate control of worksite conditions
	1.4	Unexpected ground conditions
	1.5	Restricted work area
	1.6	Site congestion
CFactors (contract)	2.1	Poor cost/duration estimate
	2.2	Inadequate and/or incomplete design
	2.3	Work scope changes within contract limits/Change orders
	2.4	Poor workmanship/Re-work
MgmFactors (management)	3.1	Inadequate planning of construction work
	3.2	Inadequate instructions on construction methods
	3.3	Inadequate supervision of work
	3.4	Change construction method
	3.5	Acceleration of work using overtime/additional crew/extra shift
	3.6	Shortages of tools and/or materials
	3.7	Poor design/construction coordination
	3.8	Inadequate safety facilities
	3.9	Delay of predecessor(s)
LFactors (labor)	4.1	Inadequate skilled labor force
	4.2	Low work moral and/or labor fatigue
	4.3	Use of untrained and/or inexperienced labor force
	4.4	Use of unbalanced crew/Crew mix change
	4.5	Labor absentee/Crew attendance
	4.6	Labor unrest/on strike
	4.7	Poor management and/or labor relations
	4.8	Inferior labor productivity
MFactors (material)	5.1	Material wastage
	5.2	Material damage, loss or theft
	5.3	Delayed material delivery
	5.4	Use of alternative material
EFactors (equipment)	6.1	Use of untrained or inexperienced operators
	6.2	Inadequate planning of equipment operations
	6.3	Inadequate control of equipment operations
	6.4	Equipment failure/Inadequate maintenance
	6.5	Inferior equipment productivity
SFactors (sub-contractor)	7.1	Inadequate communication and/or coordination
	7.2	Deferred payment
	7.3	Inferior sub-contractor productivity

3.6 Resource Performance Indicators

Performance indicators play an important role in performance evaluation and in detecting reasons behind unacceptable performance. A set of criteria is designed to select the indicators for this research project:

The indicator could highlight the source of the problem.

1. The indicator is sensitive to project performance.

2. The indicator can be calculated from the resource data that are reported from the construction site.

3. The correspondence evaluation criteria can be established by considering the indicator's value.

4. The indicator can be employed to forecast the project or control-object cost and duration.

All of the indicators are initially selected from the literature (Diekmann and Al-Tabtabai 1992, Eldin and Hughes 1992, Elazouni and Basha 1996, Abu-Hijleth 1991, Abu-Hijleh and Ibbs 1993, Sinthawanarong and Emsley 1998, Alshaibani 1999, Fayek 2000). They are then augmented by the findings of an Internet-based questionnaire survey.

An Internet-based questionnaire (see Appendix 1) survey was conducted for the convenience of experienced project managers and researchers to consolidate the information and knowledge of performance indicators. The survey was sent to the specified web communities, for example, cnbr-l@yahoogroups.com which is a web community called Co-operative Network of Building Researchers that has over 1000 members associated with more than 140 universities and research organizations in over thirty countries. Also, an email list organized by the collected construction companies is another source of respondents. The survey was conducted in October 2000. Thirty-eight responses were received--from China, Canada, the USA, the UK, and Australia. The respondents were in education/research, and in construction management. A survey database is designed to collect all the respondent results. The resultant data are analyzed and processed by using statistical methods. The data processing and the result can be found in Appendix A.

Eighteen indicators representing resources of labor, material, equipment, and sub-contractors are utilized in the proposed method. Those indicators work as sensors to detect and highlight the problematic areas of project performance. Because all the identified indicators are resource dependent, they are named resource performance indicators in this research project.

The earned-value concept provides a set of performance indicators. They include cost and schedule variances and related indexes of CPI and SPI. The performance indicators discussed here are additional parameters designed for control purposes.

3.6.1 Labor Performance Indicators

Seven performance indicators are utilized to evaluate labor performance of control-objects in the proposed system. They are Control-objects for quantity, production, Labor unit cost, Labor unit productivity, Labor hourly cost, Crew payment, and Crew attendance. Their values and ratios are described below:

The control-object quantity has its budgeted allocation value (Q_s) and revised value (Q_v), which takes into account the change of quantity. Q_v may differ from Q_s because the work scope may change within contract limit and/or there may be an issued change order. The ratio of quantity (Q_b/Q_s), which is current-period or to-date revised time-phased cumulative quantity (Q_b) (Q_b can be allocated from the control-object revised quantity Q_v to the Q_s, presents this deviation. This is an indicator of work scope change. Subscript *(s)* is the planned value; subscript *(a)* is the actual value that occurred.

The control-object production has actual installed quantity (Q_a) and Q_b. Q_a may differ from Q_b because actual productivity may differ from planned productivity and the actual starting date may differ from that which was planned. The ratio of quantity (Q_a/Q_b), which is current-period or to-date cumulative commitment quantity to the allocated revised quantity, presents this deviation. This is an indicator of production change.

Labor planned unit cost (LU_b) is a measure of cost per unit of quantity. It can be defined by budgeted labor total cost (LC_b) to Q_b. The labor unit cost ratio (LU_r), which is current-period or to-date average labor unit cost (LU_a) to the LU_b, will serve as an indicator of labor cost performance (Equation 3.15). It tracks the labor unit cost variation.

$$LU_r = \frac{LU_a}{LU_b} = \frac{LC_a \times Q_b}{LC_b \times Q_a} \tag{3.15}$$

where,

LC_a is the current period or to-date cumulative actual labor cost.

Productivity can be defined in many ways. Labor planned productivity (LP_b) is the units of work quantity (Q_b) placed or produced per budgeted man-hour ($Mhrs_b$). The inverse of labor productivity, man-hours per unit (unit rate), is also commonly used. The ratio of productivity (LP_r), which is current-period or to-date average unit productivity (LP_a) to its LP_b as shown in Equation (3.16), indicates productivity deviation. Labor productivity is a very important factor in monitoring and controlling labor work efficiency.

$$LP_r = \frac{LP_a}{LP_b} = \frac{Q_a \times Mhrs_b}{Q_b \times Mhrs_a} \tag{3.16}$$

where,

$Mhrs_a$ is the current period or to-date cumulative actual man-hours consumed.

The planned labor hourly cost (LH_b) is a measure of labor cost per hour, which is LC_b against its $Mhrs_b$. The labor hourly cost ratio (LH_r) defined by Equation (3.17), which is actual current-period or to-date average labor hourly cost (LH_a) against LH_b, reflects the labor wage change. It is a good indicator for crew performance with respect to its crew number and pay rate variance.

$$LH_r = \frac{LH_a}{LH_b} = \frac{LC_a \times Mhrs_b}{LC_b \times Mhrs_a} \tag{3.17}$$

Actual crew attendance (N_a) is current-period or to-date average number of crew. Crew attendance rate (N_r) is the ratio of N_a to the budgeted crew attendance (N_b), which is the planned number of crew, as defined in Equation (3.18). N_r is an indicator to identify the crew number variation.

$$N_r = \frac{N_a}{N_b} = \frac{\sum_{i=1}^{d} N_i}{N_b \times d} \tag{3.18}$$

where,

d is the number of days elapsed since starting of this operation,

N_i is crew attendance on i^{th} day.

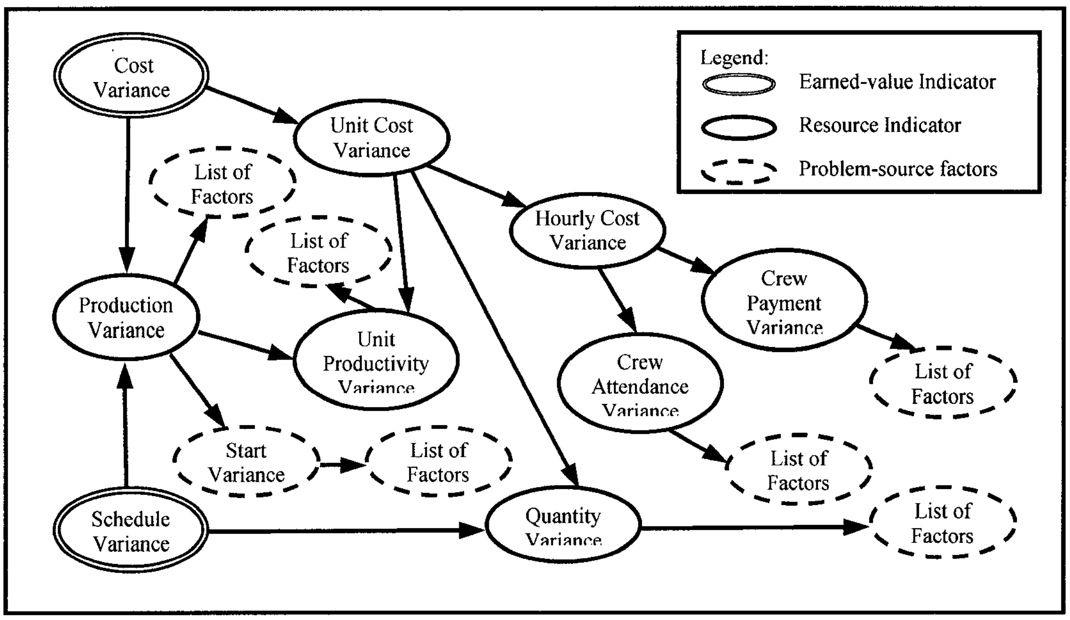
Actual crew payment (CP_a) is current-period or to-date average crew payment. The planned crew payment (CP_b) of a control-object is its LC_b divided by N_b. The crew payment rate (CP_r) is the ratio of CP_a to CP_b as defined in Equation (3.19). CP_r is an indicator to detect the crew payment change. If N_r equals one and CP_r

is greater than one that means the actual crew composition is different from the planned composition. It is an important factor that might lead to cost variance.

$$CP_r = \frac{CP_a}{CP_b} = \frac{LC_a \times N_b \times d}{LC_b \times \sum_{i=1}^{d} N_i} \tag{3.19}$$

Additionally, control-object start-variance, which represents the difference between the planned start date and the actual start date of that control-object, is considered as a factor indicator during the reasoning process. It is assumed that all the resources used within a control-object have the same start and finish dates.

The variances caused by above described indicators establish the causal model of the labor performance as shown in Fig. 3.9. The double-circled nodes represent the earned-value indicators of labor performance for a control-object. The single circled nodes represent the variances caused by the indicators. The dashed nodes represent the identified possible list of problem-source factors that might cause the variance of that indicator. Forty factors are identified through interviews of project managers and review of the literature as discussed in Section 3.5. The factors that are associated with the resource performance indicators are identified and discussed in Section 4.4. The casual model indicates that the labor cost variance can be caused by control-object production and labor unit cost variances. Labor unit cost variance can be attributed to labor unit productivity, labor hourly cost, and/or quantity variances. Labor hourly cost variance can be caused by crew attendance and/or crew payment change. Control-object production variance can be attributed to labor unit productivity. It also accounts for the start-variance of this work. Labor schedule variance is the variance caused by control-object quantity and/or production variations. This is in accordance with the source of the variance discussed in Section 4.2.1.



3.6.2 Material Performance Indicators

Five parameters are chosen as material performance indicators. They are Control-objects for quantity, production, Material unit cost, Material usage, and Material price. Their values and ratios are described as follows.

Control-object quantity and production are the same as the labor performance indicators described in Section 3.6.1.

Material planned unit cost (MU_b) is a measure of total budgeted material cost (MC_b) per unit of the budgeted material quantity (MQ_b) for a control-object. The ratio of material unit cost (MU_r), which is current-period or to-date average material unit cost (MU_a) against its MU_b, serves as an indicator of material unit cost variation as shown in Equation (3.20).

$$MU_r = \frac{MU_a}{MU_b} = \frac{MC_a \times MQ_b}{MC_b \times MQ_a} \tag{3.20}$$

where,

MC_a is the current-period or to-date cumulative material cost;

MQ_a is current-period or to-date cumulative material usage of a control-object.

The material usage ratio defined by MQ_a to MQ_b reflects the installed material quantity variation. This is an important cost indicator on material quantity change. For most projects, purchases of material in excess of bill of material requirements are standard practices of material usage variance. Material damage, wastage, or loss can also cause usage variance. The identification of excess usage that is expected to continue for future units is key in validating project material quantities and requirements.

Material price is a measure of an individual real material market unit price (MP_a). The material price ratio (MP_r), which compares the MP_a to the estimated unit price (MP_b), directly reflects the market price variation (expressed in Equation 3.21). This price variance can be recognized much earlier by comparing committed cost with planned cost. Usually, material cost is committed long before actual delivery to the contractor, or installation in the field. Committed costs are easily obtained from material purchase orders or change orders. Therefore, it is possible to achieve early detection of material price variance by referring to issued purchase orders. When material usage and price vary from the amounts planned, the contractor should update the material planned cost as appropriate to show expected cost adjustments.

$$MP_r = \frac{MP_a}{MP_b} \tag{3.21}$$

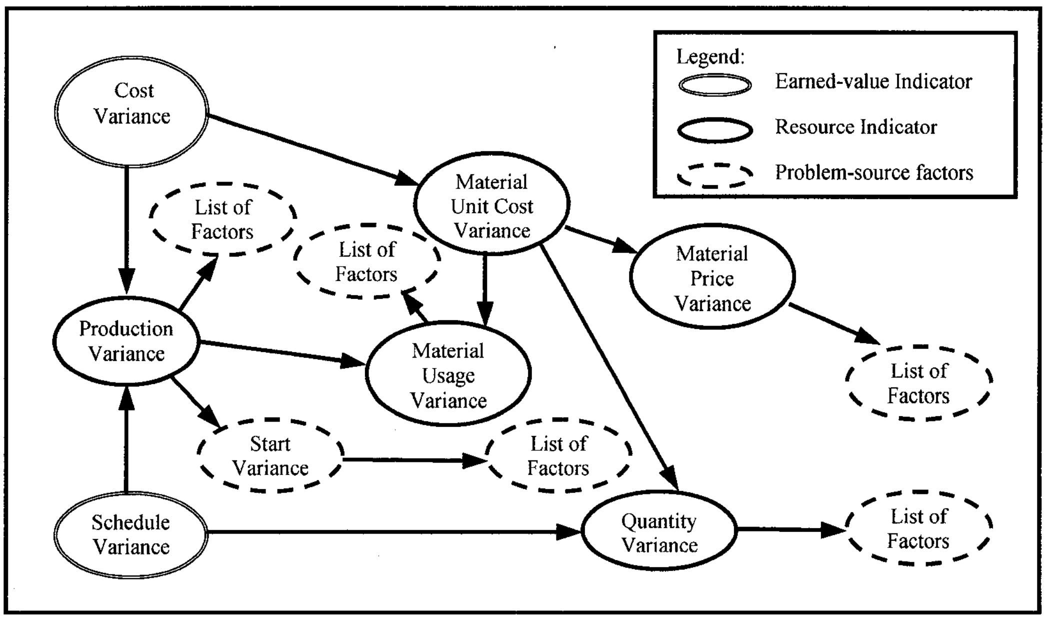


Figure 3. 10 Causal Model for Material Performance

The variances caused by the above-described indicators establish the causal model of the material performance as shown in the Fig. 3.10. The casual model indicates that the material cost variance can be caused by control-object production and material unit cost variances. Material unit cost variance can be attributed to material usage, material price, and/or quantity variances. Control-object production variance is caused by material usage variance. It also accounts for the start-variance of this work. Material itself is part of the final product; it is not a service. Therefore, its schedule variance highly depends on the control-object quantity deviations and/or the production variations caused by labor or equipment.

3.6.3 Equipment Performance Indicators

Five parameters are used as equipment performance indicators. They are Control-object for quantity, production, Equipment unit cost, Equipment unit productivity, and Equipment usage rate. Their values and ratios are described as follows.

Control-object quantity and production are same as the labor performance indicators described in Section 3.6.1.

Equipment unit cost is a measure of cost per unit of quantity. Equipment planned unit cost (EU_b) can be defined by the total budgeted equipment cost (EC_b) to Q_b. EU_a is current-period or to-date average equipment unit cost. The ratio of equipment unit cost (EU_r) will serve as an indicator of equipment cost performance (Equation 3.22). It tracks equipment unit cost variation.

$$EU_r = \frac{EU_a}{EU_b} = \frac{EC_a \times Q_b}{EC_b \times Q_a} \tag{3.22}$$

where,

EC_a is current period or to-date cumulative actual cost of equipment.

Equipment productivity is units of work quantity placed or produced per working-hour. The inverse of equipment productivity, working-hours per unit (unit rate), is also commonly used. The ratio of equipment productivity (EP_r), which is current-period or to-date average unit productivity (EP_a) against budgeted unit productivity (EP_b) as shown in Equation (3.23), indicates productivity deviation. Equipment productivity is a very important factor to monitor and control equipment work efficiency.

$$EP_r = \frac{EP_a}{EP_b} = \frac{Q_b \times Whrs_a}{Q_a \times Whrs_b} \tag{3.23}$$

where,

$Whrs_b$ is the budgeted working hours for equipment;

$Whrs_a$ is the current period or to-date cumulative working hours.

The planned equipment usage rate (UR_b) is EC_b against $Whrs_b$. The equipment usage rate ratio (UR_r), which is current-period or to-date average usage rate (UR_a) against UR_b, reflects equipment expenditure change (Equation 3.24). It is a good indicator of equipment performance with respect to its time related expenditure.

$$UR_r = \frac{UR_a}{UR_b} = \frac{EC_a \times Whrs_b}{EC_b \times Whrs_a} \tag{3.24}$$

The variances caused by above-described indicators establish the causal model of the equipment performance as shown in Fig. 3.11. The causal model indicates that the equipment cost variance can be caused by control-object production and unit cost variances. Equipment unit cost variance can be attributed to the variances of equipment productivity, usage rate, and/or quantity. Control-object production variance can be attributed to equipment unit productivity. It also accounts for the start-variance of this work. Equipment schedule variance can be caused by control-object quantity and/or control-object production variances. This draws a line, which is the same as in the source of variance discussed in Section 3.5.

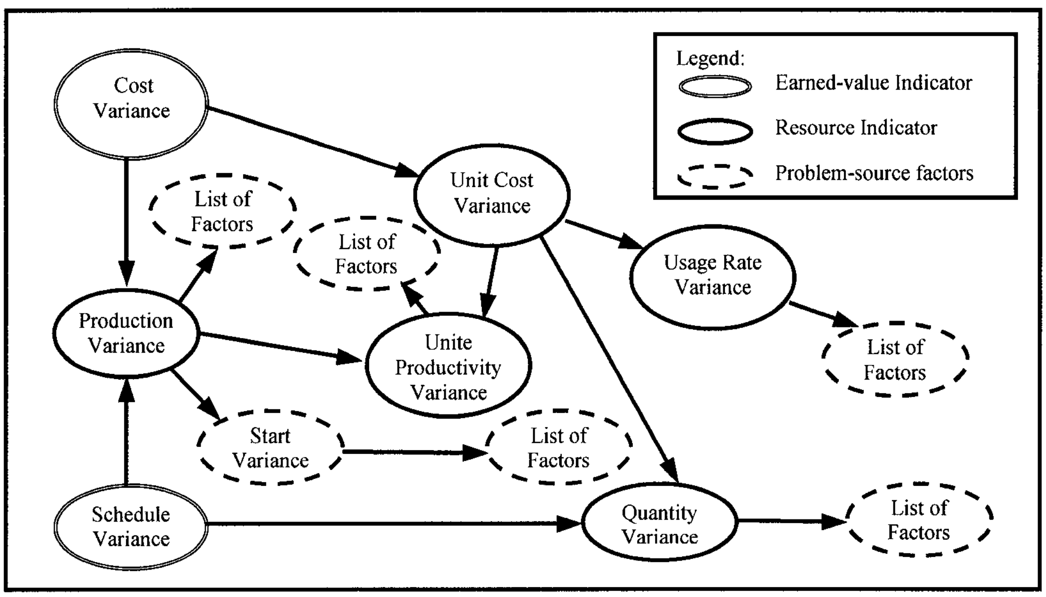


Figure 3. 11 Causal Model for Equipment Performance

3.6.4 Sub-contractor Performance Indicators

The subletting contract is a common operation for general contractors. They often sublet their work of plumbing, electricity, HVAC (Heating, ventilating, and air conditioning), and so on, to a specialized contractor. This is found through interviews with general contractors in Ottawa and Los Angeles.

To help the sub-contractors track and control their work and co-operate better with the prime contractors, five parameters will serve as indicators to measure the sub-contractor's performance. They are the total quantity of sub-contractors, the production of the sub-contractor, unit cost, unit productivity, and hourly cost of the sub-contractor. The indicators' values and ratios can be defined in a similar way as they are in the equipment performance indicators discussed in Section 3.6.3. Fig. 3.12 shows the causal model of a sub-contractor performance.

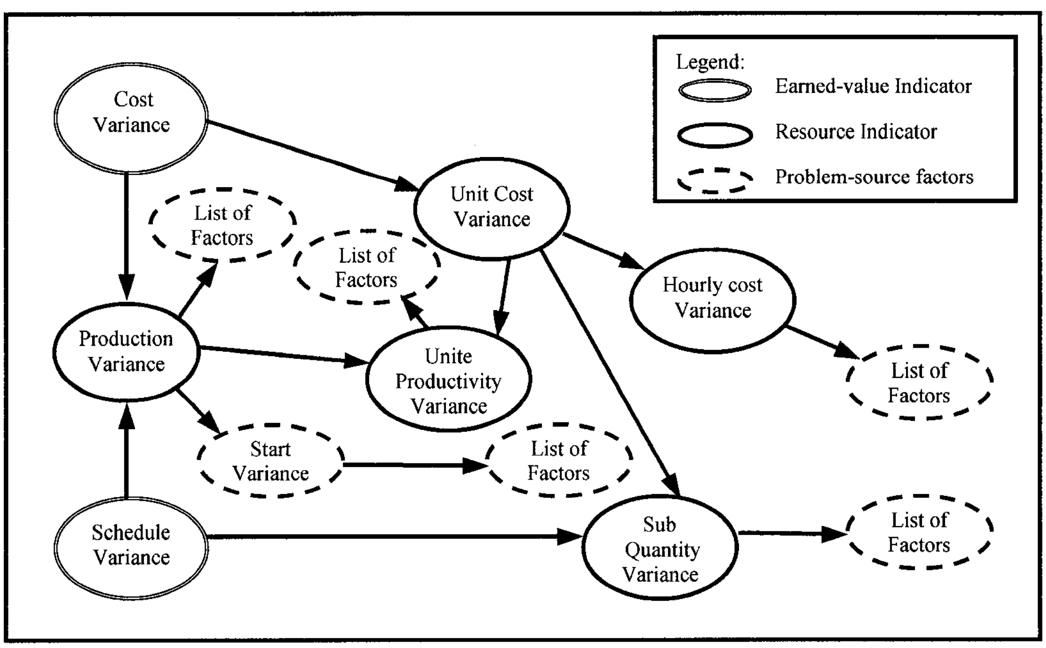


Figure 3. 12 Causal Model for Sub-Contractor Performance

It should be noted that control-object production and quantity are common indicators for the resource of labor, material and equipment except for the sub-contractor. The sub-contractor has the indicators of its production and quantity.

All the ratios of the above-mentioned parameters, which compare the budgeted value with the actual one, would serve as resource performance indicators in this research project to highlight the source of the problem. The casual links among these indicators take the form of fuzzy binary relations as described in Section 4.6. Other forms of causal links such as stepwise, sigmoid and Gaussian are not considered in the proposed fuzzy reasoning process.

3.7 Impact-Cost of Indicators

In order to define the relationships between the performance indicators and the variances caused by these indicators, the impact-cost of each proposed indicator is estimated based on the assumption that each indicator is activated independently.

3.7.1 Impact-Cost of Labor Indicator

According to the proposed causal model in shown Fig. 3.9, labor cost variance (CV_l) can be caused by allocation of the variances of control-object production (CV_{lpd}) and labor unit cost (CV_{lu}). The variances caused by labor unit cost can further be broken down to variances caused by labor hourly cost (CV_{hr}), productivity (CV_{lp}) and/or allocation of the variance of control-object quantity (CV_{lq}). Equation (3.25) represents the relationships described above.

$$\begin{aligned} CV_l &= CV_{lpd} + CV_{lu} \\ &= CV_{lpd} + CV_{lp} + CV_{lq} + CVl_{hr} \end{aligned} \tag{3.25}$$

The variance caused by labor hourly cost can further be broken down to variance of crew attendance (CV_{cn}) and/or crew payment rate (CV_{cp}) as shown in Equation (3.26).

$$CV_{hr} = CV_{cn} + CV_{cp} \tag{3.26}$$

CV_{lpd} occurs when current-period or to-date cumulative Q_a is different from the revised time-phrased cumulative quantity (Q_b) (Q_b can be allocated by PC_s from the control-object revised quantity Q_v which takes into account the change of quantity). Equation (3.27) is employed to calculate the production contribution to the labor cost variance.

$$CV_{lpd} = (Q_b - Q_a) \times LU_s \tag{3.27}$$

where,

LU_s is the planned labor unit cost.

CV_{lpd} can be caused by labor productivity and/or the start-variance of this work. The start-variance contributed to labor cost variance (CV_{lstart}) can be estimated in dollars as:

$$CV_{lstart} = LC_b(PC_b - PC_s) \tag{3.28}$$

The control-object production variance (CV_{lpdt}) is caused directly by inferior labor productivity that can be estimated by:

$$CV_{lpdt} = CV_{lpd} - CV_{lstart} \tag{3.29}$$

CV_{lu} occurs when current-period or to-date average unit cost (LU_a) is different from the planned unit cost (LU_s). Equation (3.30) is employed to calculate the unit cost contribution to the labor cost variance.

$$CV_{lu} = LU_s \times Q_s - LU_a \times Q_a \tag{3.30}$$

CV_{lq} occurs when current-period or to-date revised cumulative Q_b is different from the Q_s. Equation (3.31) is employed to calculate the quantity contribution to the labor cost variance.

$$CV_{lq} = (Q_b - Q_s) \times LU_s \tag{3.31}$$

CV_{hr} occurs when current-period or to-date average hourly cost (HR_a) is different from the planned hourly cost (HR_b). Equation (3.32) is employed to calculate the hourly cost contribution to the labor cost variance.

$$CV_{hr} = (HR_b - HR_a) \times Mhrs_b \tag{3.32}$$

CV_{lp} occurs when current-period or to-date average productivity (LP_a) is different from the planned productivity (LP_s). Equation (3.33) is employed to calculate the productivity contribution to the labor cost variance.

$$CV_{lp} = CV_{labor} - (CV_{lq} + CV_{lpd} + CV_{hr}) \tag{3.33}$$

CV_{cn} occurs when current-period or to-date average number of crew (CN_a) is different from the planned number of crew (CN_b). Equation (3.34) is employed to calculate the crew attendance contribution to the labor cost variance.

$$CV_{cn} = (CN_b - CN_a) \times CP_b \tag{3.34}$$

CV_{cp} occurs when current-period or to-date average crew payment rate (CP_r) is different from the CP_b. Equation (3.35) is employed to calculate the crew payment rate contribution to the labor cost variance.

$$CV_{cp} = CV_{hr} - CV_{cn} \tag{3.35}$$

The labor schedule variance is caused by variance of control-object quantity and production whose values are identical to CV_{lq} and CV_{lpd}.

3.7.2 Impact-Cost of Material Indicator

Material is a special resource because its cost will directly contribute to the final product of a project. Material is part of the product. It is not a service like labor and equipment, which provide the service while their cost is converted to the product. According to the proposed causal model in Fig. 3.10, material cost variance (CV_m) can be caused by allocation the variances of control-object production (CV_{mpd}) and material unit cost (CV_{mu}). Material unit cost variance can further be broken down to variances of material usage (CV_{ms}), material price (CV_{mp}), and/or allocation of the variance of control-object quantity (CV_{mq}). Equation (3.36) represents the relations described above.

$$CV_{material} = CV_{mpd} + CV_{mu}$$
$$= CV_{mpd} + CV_{ms} + CV_{mq} + CV_{mp} \quad (3.36)$$

CV_{mpd} occurs when the current-period or to-date revised cumulative Q_a is different from the cumulative Q_b. Equation (3.37) is employed to calculate the production contribution to the material cost variance.

$$CV_{mpd} = (Q_a - Q_b) \times MU_s \quad (3.37)$$

where,

MU_s is the planned material unit cost.

Control-object start-variance and inferior productivity of labor or equipment lead to the production variance, which is reflected here by the indicator of material usage. The start-variance can be estimated in Equation (3.28) by substituting LC_b to MC_b. The production variance can be estimated in Equation (3.29).

CV_{mu} depends upon the change of its unit price, actual material usage and/or control-object quantity. It denotes the difference between MU_s and current-period or to-date average unit cost (MU_a). Equation (3.38) is employed to calculate the unit cost contribution to the material cost variance.

$$CV_{mu} = MU_s \times Q_s - MU_a \times Q_a \quad (3.38)$$

CV_{mq} occurs when cumulative Q_b is different from the cumulative Q_s. Equation (3.39) is employed to calculate the quantity contribution to the material cost variance.

$$CV_{mq} = (Q_b - Q_s) \times MU_s \tag{3.39}$$

CV_{ms} occurs when current-period or to-date cumulative material usage (MQ_a) is greater or less than the planned cumulative usage (MQ_s) that is allocated by PC_s. Equation (3.40) is employed to calculate the usage contribution to the material cost variance.

$$CV_{ms} = (MQ_s - MQ_a) \times MU_s \tag{3.40}$$

CV_{mp} occurs when the actual material purchased price (MP_a) is greater or less than the estimated price (MP_b). It reflects the market price escalation. Equation (3.41) is employed to calculate the price contribution to the material cost variance.

$$CV_{mp} = (MP_b - MP_a) \times MQ_a \tag{3.41}$$

Material schedule variance is caused by control-object quantity variance and/or production variance whose values are identical to CV_{mq} and $CV_{mpd.}$

3.7.3 Impact-Cost of Equipment Indicator

According to the causal model in Fig. 3.11, equipment cost variance (CV_e) of a control-object can be caused by allocation of the variances of control-object production (CV_{epd}) and equipment unit cost (CV_{eu}). Equipment unit cost variance can further be broken down to variances caused by inferior equipment productivity (CV_{ep}), equipment usage rate (CV_{ur}) and/or allocation of the variance of control-object quantity (CV_{eq}). Equation (3.42) represents the relations described above.

$$\begin{aligned} CV_{equipment} &= CV_{epd} + CV_{eu} \\ &= CV_{epd} + CV_{ep} + CV_{ur} + CV_{eq} \end{aligned} \tag{3.42}$$

CV_{epd} occurs when current-period or to-date cumulative Q_a is different from the cumulative Q_b. Equation (3.43) is employed to calculate the control-object production contribution to equipment cost variance.

$$CV_{epd} = (Q_a - Q_b) \times EU_s \tag{3.43}$$

where,

EU_s is the planned equipment unit cost.

The production variance can be caused by control-object start-variance and inferior productivity of equipment. The start-variance can be estimated in Equation (3.28) by substituting LC_b to EC_b. The production variance can be estimated in Equation (3.29).

CV_{eu} occurs when current-period or to-date average unit cost (EU_a) is greater or less than the planned unit cost (EU_s). Equation (3.44) is employed to calculate the unit cost contribution to the equipment cost variance.

$$CV_{eu} = EU_s \times Q_s - EU_a \times Q_a \tag{3.44}$$

CV_{eq} occurs when cumulative Q_b is different from the cumulative Q_s. Equation (3.45) is employed to calculate the quantity contribution to equipment cost variance.

$$CV_{eq} = (Q_b - Q_s) \times EU_s \tag{3.45}$$

CV_{ep} occurs when current-period or to-date average productivity (EP_a) is greater or less than the planned productivity (EP_b). Equation (3.46) is employed to calculate the productivity contribution to the equipment cost variance.

$$CV_{ep} = CV_{equipment} - (CV_{eq} + CV_{epd} + CV_{ur}) \tag{3.46}$$

CV_{ur} occurs when current-period or to-date average usage rate (UR_a) is greater or less than the budgeted usage rate (UR_b) that is defined by PC_b. Equation (3.47) is employed to calculate the usage rate contribution to the equipment cost variance.

$$CV_{ur} = (UR_b - UR_a) \times Whrs_b \tag{3.47}$$

The schedule variance is caused by control-object quantity and/or equipment production whose values are identical to CV_{eq} and CV_{epd}.

3.7.4 Impact-Cost of Sub-Contractor Indicator

According to the causal model in Fig. 3.12, sub-contractor cost variance of a control-object can be broken down to variances caused by sub-contractor quantity, unit cost, and/or sub-contractor's production. Sub-contractor unit cost variance can further be broken down to variances caused by sub-contractor's productivity and hourly cost. The variances caused by sub-contractor indicators can be defined and estimated by Equations (3.42 ~ 3.47).

The schedule variances caused by sub-contractor's quantity and/or productivity are identical to cost variances caused by sub-contractor quantity and production.

3.8 Multi-Level Evaluation Criteria

In order to control a project effectively, a multi-level evaluation criterion is developed as shown in Fig. 3.13. At the project and control-object levels, only cost and schedule variances are taken into consideration. The cost variance (CV) and schedule variances are defined in Equations 2.1 and 2.2. The percentage cost variance (CV%) is defined as a ratio of the cost variance (CV) to the budgeted cost of work performed (BCWP) (Equation 3.48). The percentage schedule variance (SV%) is defined as a ratio of the schedule variance (SV) to the budgeted cost of work performed (BCWP) (Equation 3.49). If the absolute values of CV, SV, and/or percentage variances calculated at the project or control-object levels are less than or equal to the user defined threshold values, the performance at the project or control-object levels, being considered, is deemed acceptable. Otherwise, the performance is deemed unacceptable, trigging performance evaluation at the resource level in order to detect possible cause(s) behind that unacceptable performance.

$$CV\% = \frac{CV}{BCWP} = \frac{BCWP - ACWP}{BCWP} \tag{3.48}$$

$$SV\% = \frac{SV}{BCWP} = \frac{BCWP - BCWS}{BCWP} \tag{3.49}$$

At the resource level, cost and schedule variances of each resource are evaluated respectively. Here also, if the absolute values of CV, SV and/or percentage variances do not exceed the predefined threshold values, the performance of the resource, being considered, is deemed acceptable. Otherwise, the indicators' values will be progressively assessed according the applicable causal model, such as those shown in Figs. 3.9 to 3.12. The calculated ratios of the indicators provide a criterion to diagnose possible sources of the variance experienced in each case. If the ratio of a performance indicator (i.e. the actual versus budgeted values) is equal to one, the performance of that indicator is deemed favorable; if the ratio of a performance indicator is greater than one (in control-object quantity, crew payment, and crew attendance, for example) or less than one (in control-object production and labor productivity, for example), the performance of that indicator is deemed unacceptable and will accordingly be highlighted.

Evaluation Criteria

- **Project and Control-object Levels**

  1. ***|Cost Variance|≤Threshold***
  2. ***|Schedule Variance|≤Threshold***

- **Resource Level**

  1. ***|Cost Variance|≤Threshold***
  2. ***|Schedule Variance|≤Threshold***
  3. ***Indicator's Ratio<>1***

Figure 3. 13 Multi-Level Evaluation Criteria

The cost and schedule variances evaluation criteria used in the developed IT/CC system can be found in Table 3.7. |CV| and |SV| mean absolute values of CV and SV. For example, in the case of $PC_a<100$, $|CV|$ > Threshold, and $|SV| \leq$ Threshold, the cost performance is unacceptable, but that of the schedule performance is acceptable. The threshold value used in Table 3.7 can be either absolute or relative, or both. The threshold values of SV can either be represented in date or in dollars. If it is denoted in date the SV can be calculated in Equation (3.11). Otherwise SV can be computed in Equation (2.2).

Table 3. 5 Cost and Schedule Variances Evaluation Criteria

Evaluation Criteria			Description
$PC_a=100$	$\lvert CV \rvert$ > Threshold	SV=0	Cost performance is unacceptable, no comments on schedule
	$\lvert CV \rvert$ < Threshold		Cost performance is acceptable, no comments on schedule
$PC_a<100$	$\lvert CV \rvert$ > Threshold	$\lvert SV \rvert$ > Threshold	Cost performance is unacceptable, schedule performance is unacceptable
		$\lvert SV \rvert \le$ Threshold	Cost performance is unacceptable, schedule performance is acceptable
	$\lvert CV \rvert$ = Threshold	$\lvert SV \rvert$ > Threshold	Cost performance is acceptable, schedule performance is unacceptable
		$\lvert SV \rvert \le$ Threshold	Cost performance is acceptable, schedule performance is acceptable
	$\lvert CV \rvert$ < Threshold	$\lvert SV \rvert$ > Threshold	Cost performance is acceptable, schedule performance is unacceptable
		$\lvert SV \rvert \le$ Threshold	Cost performance is acceptable, schedule performance is acceptable
$PC_a=100$	$CV \ge 0$, $CPI \ge 1$	$SV = 0$, $SPI = 1$	Cost is under run, no comments on schedule
	$CV < 0$, $CPI < 1$		Cost is overrun, no comments on schedule
$PC_a<100$	$CV \ge 0$, $CPI \ge 1$	$SV \ge 0$, $SPI \ge 1$	Cost is under run, schedule is advanced
		$SV < 0$, $SPI < 1$	Cost is under run, schedule is delayed
	$CV < 0$, $CPI < 1$	$SV \ge 0$, $SPI \ge 1$	Cost is overrun, schedule is advanced
		$SV < 0$, $SPI < 1$	Cost is overrun, schedule is delayed

The labor performance indicator evaluation criteria used in the developed IT/CC system can be found in Table 3.6. According to the labor causal model, the diagnostic procedure starts by evaluating the indicators of control-object production and labor unit cost. If the indicator of labor unit cost is highlighted, then the indicators of control-object quantity, labor unit productivity and labor hourly cost are evaluated respectively. For example, if the labor hourly cost is highlighted, then, the indicators of crew payment and crew attendance will be further evaluated. When no further indicators could be examined, the current one is called the terminal indicator. Control-object production, control-object quantity, labor unit productivity, crew payment, and crew attendance are all possible terminal indicators for labor cost performance. The impact-costs caused by those terminal indicators are estimated by the equations described in Section 3.7. Then the problem-source factors that associate with the indicators need further exploration. For example, if the control-object quantity ratio is greater than one, a change order might be one possible source of the problem. According to the developed causal models, the schedule variance could only be caused by the indicators of control-object quantity and production, therefore the reasoning procedure of schedule variance for each individual resource are all the same. The evaluation criteria for material, equipment and sub-contractor used in the developed IT/CC system can be found in Tables 3.7, 3.9 and 3.8, respectively. A similar diagnostic process is developed for material, equipment, and sub-contractors.

Table 3. 6 Labor Performance Indicator Evaluation Criteria

Labor indicator	Indicator ratio	Criteria	Description
Control-Object Production	$\frac{Q_a}{Q_b}$	>1	Ahead of schedule, no problem
		=1	On schedule, no problem
		<1	Delay, check of problem
Control-Object Quantity	$\frac{Q_b}{Q_s}$	≠1	Quantity change or Change order
		=1	As planned, no problem
Unit Cost	$\frac{LC_a \times Q_b}{LC_b \times Q_a}$	>1	Cost overrun, check of problem
		=1	As planned, no problem
		<1	Cost underrun, no problem
Unit Productivity	$\frac{Q_a \times Mhrs_b}{Q_b \times Mhrs_a}$	>1	High productivity, check of problem
		=1	As planned, no problem
		<1	Low productivity, check of problem
Hourly cost	$\frac{LC_a \times Mhrs_b}{LC_b \times Mhrs_a}$	>1	Hourly cost increased, check of problem
		=1	As planned, no problem
		<1	Hourly cost decreased, check of problem
Crew Payment	$\frac{LC_a \times N_b \times n}{LC_b \times \sum_{i=1}^{n} N_i}$	>1	Actual crew payment increased
		=1	As planned, no problem
		<1	Actual crew payment decreased
Crew Attendance	$\frac{\sum_{i=1}^{n} N_i}{N_b \times n}$	>1	Actual crew number increased
		=1	As planned, no problem
		<1	Actual crew number decreased

Table 3. 7 Material Performance Indicator Evaluation Criteria

Material indicator	Indicator ratio	Criteria	Description
Unit Cost	$\frac{MC_a \times MQ_b}{MC_b \times MQ_a}$	>1	Cost overrun, check of problem
		=1	As planned, no problem
		<1	Cost under run, no problem
Usage rate	$\frac{MQ_a}{MQ_b}$	>1	High usage rate, check of problem
		=1	As planned, no problem
		<1	Low usage rate, check of problem
Material price	$\frac{MP_a}{MP_b}$	>1	Market price increased
		=1	As planned, no problem
		<1	Market price decreased

Table 3. 8 Sub-Contractor Performance Indicator Evaluation Criteria

Sub-contractor indicator	Indicator ratio	Criteria	Description
Sub-contractor Production	$\frac{Q_{sa}}{Q_{sb}}$	>1	Ahead of schedule, no problem
		1	On schedule, no problem
		<1	Delay, check of problem
Sub-contractor Quantity	$\frac{Q_{sb}}{Q_{ss}}$	$\neq 1$	Quantity change or Change order
		1	As planned, no problem
Unit Cost	$\frac{SC_a \times Q_{sb}}{SC_b \times Q_{sa}}$	>1	Cost overrun, check of problem
		1	As planned, no problem
		<1	Cost under run, no problem
Unit Productivity	$\frac{Q_{sa} \times SWhrs_b}{Q_{sb} \times SWhrs_a}$	>1	High productivity, check of problem
		1	As planned, no problem
		<1	Low productivity, check of problem
Hourly cost	$\frac{SC_a \times SWhrs_b}{SC_b \times SWhrs_a}$	>1	Hourly cost increased, check of problem
		1	As planned, no problem
		<1	Hourly cost decreased, check of problem

Table 3. 9 Equipment Performance Indicator Evaluation Criteria

Equipment indicator	Indicator ratio	Criteria	Description
Unit Cost	$\frac{EC_a \times Q_b}{EC_b \times Q_a}$	>1	Cost overrun, check of problem
		=1	As planned, no problem
		<1	Cost under run, no problem
Unit Productivity	$\frac{Q_a \times Whrs_b}{Q_b \times Whrs_a}$	>1	High productivity, check of problem
		=1	As planned, no problem
		<1	Low productivity, check of problem
Usage Rate	$\frac{EC_a \times Whrs_b}{EC_b \times Whrs_a}$	>1	Usage cost increased, check of problem
		=1	As planned, no problem
		<1	Usage cost decreased, check of problem

3.9 Summary

An object-based model is proposed based on object-oriented modeling. Each control element is represented as a control-object with its associated resources of labor, material, equipment, and sub-contractors. A control-object has its budget and actual cost and schedule values for evaluation. It also has relationships to other control-objects and user-defined threshold values for unacceptable performance of time and cost. A project is an aggregation of control-objects. The user can define the control-object in his/her own way, no matter which project breakdown method (PBS or WBS) is used. Project performance can be evaluated at three levels: the project level, control-object level, and resource level, according to the proposed evaluation criteria. The earned value method is employed in the assessment of cost and schedule variances. In order to detect the reason(s) behind the identified variances, eighteen indicators are chosen to represent the resource performance of labor, material, equipment, and/or sub-contractors. These indicators serve as sensors to detect the problem sources for an unacceptable performance. The variances caused by the indicators establish the corresponding causal models. Four causal models are established to breakdown the identified variances to the highlighted indicator. The possible problem-source factors associated with terminal indicators are identified according to the results of an Internet-based questionnaire survey. A set of equations is developed to estimate the impact-cost for each terminal indicator. These impact-costs form the linkage strength between the performance indicators and the cost and schedule variances. The terminal indicator will be further analyzed in Chapter 4 to determine the factors that cause the variances and suggest corresponding corrective actions accordingly.

Chapter 4

PROPOSED REASONING PROCESS

4.1 General

In this chapter, a fuzzy reasoning process that assists members of project teams in performing integrated time and cost control for construction projects is presented. The process utilizes an object-based model to represent the data structure of a project. A set of resource performance indicators and a factor indicator serve as sensors to detect problem-sources behind unacceptable performance. Problem-source factors and possible corrective actions were identified, making use of the literature and of Internet-based questionnaire surveys. Casual links between earned-value-based variances, performance indicators, problem-source factors, and corrective actions are established. The degree of linkage strength is expressed using fuzzy set theory. Reasons behind unacceptable performance are determined using fuzzy composition and union operations. Possible corrective actions are suggested based on the identified reasons. Three levels of reasoning reports can be generated, at individual resource, control-object and project levels.

4.2 Proposed Methodology

The developed reasoning process starts from the resource level. It focuses on individual resources within each control-object in the project being considered. As shown in Fig. 4.1, the process has a three-tier structure that comprises presentation, middle and data tiers. The presentation-tier provides interfaces to allow users to interact with the developed reasoning process. The data-tier houses two databases, namely “Factor” and “Reason”, for reasoning purpose. The middle-tier provides the major functions of reasoning. It includes the components of variances, indicators, factors, actions, and causal links. The variances (v_i) are produced by cost and schedule performance. They are quantified using the earned-value method. The indicators (s_j) are terminal resource performance indicators, designed to detect problematic areas that give rise to unacceptable performance, which may emanate from labor, material, equipment, and/or sub-contractors as discussed in Section 3.6. Additional factor indicators are also considered in the reasoning process. The factors (f_k) represent possible problem-source factors used to explain the reasons behind unacceptable performance as discussed in Section 3.5 and shown in Table 3.4. The actions (a_m) represent possible corrective actions to improve the status of these variances. Causal links among earned-value-based variances, performance indicators, problem-source factors, and corrective actions are identified by an Internet-based questionnaire survey. The degrees of linkage strength on those causal relations are expressed using fuzzy binary relations. The linkage strengths between variances and performance indicators are determined based on the estimated impact-cost discussed in Section 3.7. However, it is very difficult to define the linkage strengths between the performance indicators and problem-source factors as well as corrective actions in a set of standard formulas. Therefore, user-specified linkage strengths are considered. The factor database is developed to store all the identified factors and actions for reasoning purposes. The reason database is developed to store the user-specified linkage strengths during the reasoning process.

4.2.1 Resource Level Reasoning

The reasoning process starts at the resource level, upon finding that the calculated cost and/or schedule variances of an individual resource to be unacceptable. Then, the values of the terminal indicators associated with that resource and/or factor indicator are evaluated. If the value of any such indicators is found unacceptable, this indicator is accordingly be highlighted. The highlighted indicators are used as input indicators in the reasoning process. The linkage strengths between the detected variances and the highlighted indicators are determined based on the estimated impact-cost. The linkage strengths for other indicators are set to zero. Subsequently, problem-source factors that have causal links with the highlighted indicators are retrieved from the factor database. In case a factor is associated with two or more indicators, that factor can only appear once. It means that the same factor is assumed to have the same linkage strength with its associated indicators. Users, then, are involved in establishing the linkage strengths between the factors and the highlighted indicators using a scale from 0 to 10 according to his/her own judgment and experience. A fuzzy binary relation operation such as composition operation is then invoked to infer the output-factors behind the detected unacceptable performance. For convenience, the factors are reported in a descending order; capturing problem-sources behind the detected cost and/or schedule variances. Similarly, corrective actions that have causal links with each identified factor are retrieved from the factor database. In case an action is associated with two or more factors, that action can only appear once. It means that the same action is assumed to have the same linkage strength with its associated factors. Again, the users need to rate the linkage strengths between the detected factors and the generated actions according to his/her own judgment and experience. A fuzzy composition operation is then applied to generate the output-actions. The generated corrective actions are reported and ranked the users. The resource level reasoning process is designed to support daily and cumulative to-date analysis. The analysis can also be produced on weekly, monthly, and/or yearly basis. Daily performance data are used to generate the reasoning reports for that day; the accumulated data from the starting date to the reporting date are used to generate the to-date reasoning reports; the weekly, monthly, and/or yearly reasoning reports are generated using fuzzy union operations of the daily reasoning results.

4.2.2 Reasoning at Control-Object and Project Levels

Similarly, the reasoning process at the control-object level starts upon finding the performance of the control-object unacceptable. The problem-source factors and corrective actions are generated by aggregating those obtained earlier from the reasoning process conducted at the resource level. The aggregation accounts for the relative weight of each resource within the control-object being considered.

The relative weight is defined as $W_r = C_r / C_{object}$, where W_r is the weight for an individual resource; C_r is the budgeted cost for an individual resource; C_{object} is the budgeted total cost for the control-object. Then, fuzzy union operations are utilized to aggregate the problem-source factors and corrective actions. The output problem-source factors and corrective actions resulting from the reasoning process are ranked based on their relative weights. A similar process is implemented for the reasoning process at the project level. The following will discuss the reasoning components in detail.

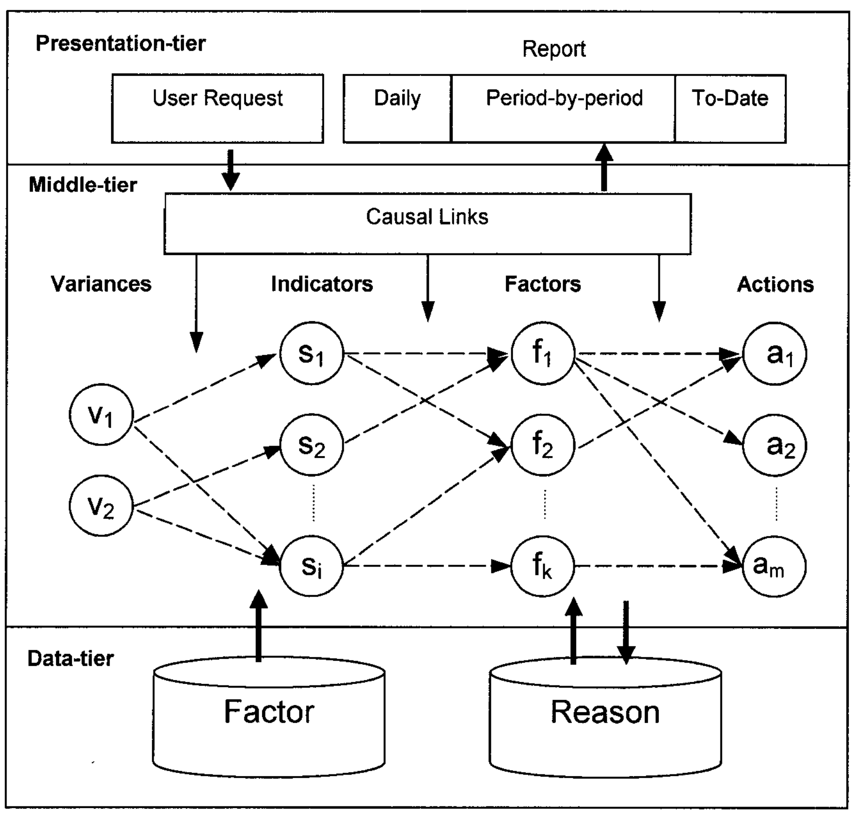


Figure 4. 1 The Proposed Reasoning Process

4.3 Possible Corrective Actions

Generic corrective actions associated with problem-source factors, likely to be encountered in various types of construction projects, were initially extracted from the literature (Diekmann and Kim 1992, Yates 1993, Alkass et al. 1993, Russell 1993, Russell and Fayek 1994, Assaf et al. 1995, Fayek et al. 1998, Hsieh 1998, Mulholdland and Christian 1999, O'Brien and Fischer 2000, Suraji et. al. 2001). They were then augmented by additional actions obtained through web-based questionnaire and 10 structured interviews with project managers; 4 located in Ottawa and 6 in Los Angeles. These corrective actions may not correspond on a one-to-one basis to the problem-source factors identified in Table 3.4, but are intended to encompass a number of problem-source factors. To maintain compatibility with the classifications of the problem-source factors, the corrective actions are classified into *Action* classes of *ESActions* (environment and site conditions), *MgmActions* (management), *CActions* (contract), *LActions* (labor), *MActions* (material), *EActions* (equipment), and *SActions* (sub-contractors). For example, the *ESActions* class represents the actions related to the problem-sources of environment and site conditions, such as "Re-examine construction site layout". The *MgmActions* class represents problem-sources related to management. The *CFactors* class represents the actions related to the problem-sources of contract. Also, the *LActions*, *MActions*, *EActions*, and *SActions* classes represent actions that are directly related to the problem-source factors of labor, material, equipment, and sub-contractors, respectively.

Table 4. 1 Possible Corrective Actions

Category	Code	Corrective actions (attributes)
ESActions (environment and site conditions)	1.1	Provide a protected environment to prevent loss of productivity
	1.2	Stop the work to prevent loss of productivity
	1.3	Re-examine construction site layout
	1.4	Re-examine safety facilities and program
	1.5	Use multiple shifts
	1.6	Use extra support or shoring to alleviate poor ground conditions
	1.7	Improve worksite conditions
	1.8	Conduct site soil investigation
CActions (Management)	2.1	Improve design/construction coordination
	2.2	Allocate extra resources
	2.3	Request a project time extension
	2.4	Consider alternative materials
	2.5	Request compensation
	2.6	Consider revising project baseline
MgmActions (contract)	3.1	Re-examine the planned cost and/or duration
	3.2	Re-schedule the remaining work
	3.3	Re-examine the work plan
	3.4	Re-examine the instructions of construction crews
	3.5	Improve supervision of work
	3.6	Use more equipment and less labor intensive construction methods
	3.7	Use alternative construction method
	3.8	Use a rover crew (over and above the regular work force)
	3.9	Increase work time for current labor and/or equipment
	3.10	Consider training program
LActions (labor)	4.1	Re-examine crew balance or mix
	4.2	Re-allocate skilled labor from a buffer or non-critical work
	4.3	Consider financial incentive and/or other motivational programs
	4.4	Consider additional skilled labor force
	4.5	Re-examine management of labor relations and safeties
	4.6	Consider conducting analysis labor productivity (work sampling, etc)
MActions (material)	5.1	Track and control expedite processes to avoid material shortage/wastage
	5.2	Improve material handling and/or storage management
	5.3	Re-schedule work to hours with less traffic
EActions (equipment)	6.1	Improve equipment maintenance system
	6.2	Use skilled operator
	6.3	Optimize equipment selection
	6.4	Re-allocate tools/equipment from a buffer or non-critical work
	6.5	Purchase or rent backup tools/equipment
	6.6	Consider conducting analysis equipment productivity
SActions (sub-contractors)	7.1	Improve sub-contractor coordination
	7.2	Consider timely processing of interim payments
	7.3	Improve sub-contractor management
	7.4	Use alternate shifts for interfering sub-contractor
	7.5	Consider conducting analysis of sub-contractor's productivity

Based on this classification, possible corrective actions for poor labor can be generated by aggregating those generated in the *LActions*, *MgmActions*, *ESActions*, and *CActions* classes according to their respective, causal links, which will be described later; those for poor material can be generated by aggregating those generated in the *MActions*, *MgmActions*, *ESActions*, and *CActions* classes; those for poor equipment can be generated by aggregating those generated in the EActions, *MgmActions*, *ESActions*, and *CActions* classes; Sub-contractor corrective actions correspond to the *SActions* class. The attributes of the defined seven classes can be found in Table 4.1. These attributes encompass identified possible corrective actions related to the problem-source factors discussed in Section 3.5. Further analysis is needed to determine the causal links between the attributes of those corrective *Action* classes and the attributes of the *Factor* classes.

4.4 Causal Links

In order to define the causal links between the terminal indicators and factor indicator, the attributes of the *Factor* classes, and the attributes of the *Action* classes, another Internet-based questionnaire survey was carried out (see Appendix 2). The survey targeted experienced project managers and researchers to establish the generic associations that exist between the factors and indicators on one hand, and the actions and factors on the other. The survey was sent to specific web communities, for example, cnbr-l@yahoogroups.com. Also, it was sent to an email list composed of a number of construction companies. The survey was conducted in February 2003. Fifty responses were received--from China, Canada, the USA, the UK, and Australia. The respondents were in the field of education/research, and practitioners in construction management. A survey database was designed to collect all the respondent results. Based-on the statistic results of the survey, the attributes of the *Factor* classes that are associated with the indicators and the attributes of the *Action* classes associated with the attributes of the *Factor* classes are classified and arranged as shown in Tables 4.2 to 4.6. Many-to-many relationships are employed in mapping the causal links. This means that one indicator may be affected by many problem-source factors, and one problem-source factor may impact many indicators. Similar relationships exist between the problem-source factors and the corrective actions as shown in Tables 4.2 to 4.6.

4.5 Fuzzy Relations

In order to provide a universal interpreter in support of the developed project control system, the causal links between variances, indicators, factors, and actions are described using fuzzy binary relations. A fuzzy binary relation can be expressed by a matrix. The elements of the matrix represent the degrees of linkage strength for each link between two sets of data. Fuzzy relations allow for partial memberships, as opposed to the crisp binary relation, which allow only for either the presence or absence of an association (Klir and Yuan 1995).

If V_r is the subset of cost and schedule variances for the r resource as described in Equation (4.1), and if S_r is the subset of the performance indicators that denotes the indicators' set for the r^{th} resource as described in Equation (4.2), then their relationships can be represented by the matrix of X_r (v_{ri}, s_{rj}) as shown in Equation (4.3) (Klir and Yuan 1995). The matrix describes the binary relation between the variances and the indicators called the X_r (V_r, S_r) relation. Similarly, the binary relation between performance indicator set S_r for r^{th} resource and the corresponding factors' subset F_r (defined in Equation 4.4) can be represented by matrix Y_r (S_r, F_r) as shown in Equation (4.5). Also, the binary relation between factor set F_r and the corresponding actions' subset A_r (defined in Equation 4.6) can be represented by matrix Z_r (F_r, A_r) as shown in Equation (4.7). The elements of the matrixes X_r, Y_r, and Z_r represent the degrees of the linkage strength between the two sets they represent.

$$V_r = \{v_{r1}, \cdots, v_{ri}\}, \qquad r = 1 \quad to \quad 4 \tag{4.1}$$

where,

r = type of resources, which values can be 1 to 4,

v_i = cost variance and schedule variances respectively, i = 1 to 2.

$$S_r = \{s_1, \cdots, s_j\}, \qquad r = 1 \quad to \quad 4 \tag{4.2}$$

where,

s_j = resource performance indicators, j=1, …, 4 or 5.

$$X_r(V_r, S_r) = \begin{pmatrix} (v_{r1}, s_{r1}) & \cdots & (v_{r1}, s_{rj}) \\ \vdots & \vdots & \vdots \\ (v_{ri}, s_{r1}) & \cdots & (v_{ri}, s_{rj}) \end{pmatrix}, \qquad r = 1 \text{ to } 4, \tag{4.3}$$

where,

the elements of X_r (v_{ri}, s_{rj}) represent the degrees of the linkage strength between the variances and indicators, and each lies between 0.0 to 1.0.

$$F_r = \{f_1, \cdots, f_k\}, \qquad r = 1 \quad to \quad 4 \tag{4.4}$$

where,

f_k = problem-source factors displayed in Table 3.4, k= 1 to 39.

$$Y_r(S_r, F_r) = \begin{pmatrix} (s_{r1}, f_{r1}) & \cdots & (s_{r1}, f_{rk}) \\ \vdots & \vdots & \vdots \\ (s_{rj}, f_{r1}) & \cdots & (s_{rj}, f_{rk}) \end{pmatrix}, \qquad r = 1 \text{ to } 4, \tag{4.5}$$

where,

the elements of Y_r (s_{rj}, f_{rk}) represent the degrees of the linkage strength between the indicators and problem-source factors, and each lies between 0.0 to 1.0.

$$A_r = \{a_1, \cdots, a_m\}, \qquad r = 1 \quad to \quad 4 \tag{4.6}$$

where,

a_m = corrective actions displayed in Table 4.1, m=1 to 44.

$$Z_r(F_r, A_r) = \begin{pmatrix} (f_{r1}, a_{r1}) & \cdots & (f_{r1}, a_{rm}) \\ \vdots & \vdots & \vdots \\ (f_{rk}, a_{r1}) & \cdots & (f_{rk}, a_{rm}) \end{pmatrix}, \qquad r = 1\, to\, 4, \tag{4.7}$$

where,

the elements of Z_r (f_{rk}, a_{rm}) represent the degrees of the linkage strength between the problem-source factors and corrective actions, and each lies between 0.0 to 1.0.

The composition of the set (X_r) that represents the relation between variances and indicators and the set (Y_r) that represents the relation between indicators and factors into a single set (P_r) that represents the relation between the variances and factors can be carried out as follows:

$$P_r(V_r, F_r) = X_r(v_{ri}, s_{rj}) \circ Y_r(s_{rj}, f_{rk}), \qquad i = 1 \quad to \quad 4 \tag{4.8}$$

where,

the elements of P_r (V_r, F_r) represent the degrees of the linkage strength between the variances and problem-source factors, and each lies between 0.0 to 1.0.

Table 4. 2 Control-Object Relations

<table>
<tr><td colspan="5">Control-Object</td></tr>
<tr><td rowspan="2">Indicators</td><td colspan="2">Problem-source Factors</td><td colspan="2">Corrective Actions</td></tr>
<tr><td>Category</td><td>Factors</td><td>Actions</td><td>Category</td></tr>
<tr><td rowspan="3">Production</td><td>MgmFactors</td><td>3.9</td><td>3.2</td><td>MgmActions</td></tr>
<tr><td>LFactors</td><td>4.8</td><td>4.6</td><td>LActions</td></tr>
<tr><td>EFactors</td><td>6.5</td><td>6.6</td><td>EActions</td></tr>
<tr><td rowspan="6">Quantity</td><td rowspan="6">CFactors</td><td>2.2</td><td>2.1</td><td>CActions</td></tr>
<tr><td rowspan="5">2.3</td><td>2.2</td><td rowspan="2">CActions</td></tr>
<tr><td>2.3</td></tr>
<tr><td>3.2</td><td rowspan="3">MgmActions</td></tr>
<tr><td>3.8</td></tr>
<tr><td>3.9</td></tr>
</table>

Table 4. 3 Labor Relations

Labor				
Indicators	Problem-source Factors		Corrective Actions	
	Category	Factors	Actions	Category
Productivity	*ESFactors*	1.1	1.1	*ESActions*
			1.2	
			2.3	*CActions*
			3.2	*MgmActions*
		1.3	1.7	*ESActions*
		1.5	3.7	*MgmActions*
		1.6	1.3	*ESActions*
			1.5	
	MgmFactors	3.1	3.3	*MgmActions*
		3.2	3.4	*MgmActions*
		3.3	3.5	*MgmActions*
		3.4	3.6	*MgmActions*
			3.7	
		3.6	5.1	*MActions*
			5.2	
			5.3	
			6.4	*EActions*
			6.5	
		3.7	2.1	*CActions*
		3.8	1.4	*ESActions*
	CFactors	2.1	2.3	*CActions*
			2.4	
			2.6	
			3.1	*MgmActions*
			3.2	
	LFactors	4.2	4.3	*LActions*
			4.4	
			4.5	
			3.5	*MgmActions*
		4.3	4.5	*LActions*
			3.10	*MgmActions*
		4.7	4.5	*LActions*
Crew Payment	*CFactors*	2.4	3.4	*MgmActions*
			3.5	
			3.10	
	MgmFactors	3.5	3.9	*MgmActions*
	LFactors	4.5	4.4	*LActions*
		4.8	4.6	*LActions*
	EFactors	6.5	6.6	*EActions*
Crew Attendance	*LFactors*	4.1	3.6	*MgmActions*
			3.9	
			3.10	
			4.1	*LActions*
			4.2	
			4.4	
		4.4	4.1	*LActions*
		4.5	Same as factor 4.5 above	
		4.6	3.2	*MgmActions*

Table 4. 4 Material Relations

Material				
Indicators	Problem-source Factors		Corrective Actions	
	Category	Factors	Actions	Category
Material quantity	*CFactors*	2.2	Same as factor 2.2 in Table 4.3	
		2.3	Same as factor 2.3 in Table 4.3	
Usage	*CFactors*	2.1	Same as factor 2.1 in Table 4.2	
		2.4	Same as factor 2.4 in Table 4.2	
	LFactors	4.8	Same as factor 4.8 in Table 4.2	
	EFactors	6.5	Same as factor 6.5 in Table 4.2	
	MFactors	5.1	3.5	*MgmActions*
			5.1	*MActions*
		5.2	5.2	*MActions*
		5.3	5.2	*MActions*
			5.3	
Price	*ESFactors*	1.2	2.4	*CActions*
			2.5	
	MFactors	5.4	2.4	*CActions*

Table 4. 5 Equipment Relations

Equipment				
Indicators	Problem-source Factors		Corrective Actions	
	Category	Factors	Actions	Category
Unit Productivity	*ESFactors*	1.1	Same as factor 1.1 in Table 4.2	
		1.4	1.6	*ESActions*
			1.8	
	CFactors	2.1	Same as factor 2.1 in Table 4.2	
	MgmFactors	3.6	Same as factor 3.6 in Table 4.2	
	EFactors	6.1	6.2	*EActions*
Usage	*EFactors*	6.2	6.3	*EActions*
		6.3	6.2	*EActions*
		6.4	6.1	*EActions*
			6.5	

Table 4. 6 Sub-Contractor Relations

Sub-contractor				
Indicators	Problem-source Factors		Corrective Actions	
	Category	Factors	Actions	Category
Production	*MgmFactors*	3.9	Same as factor 3.9 in Table 4.3	
	Sub-contractor	7.3	7.3	*SActions*
			7.4	
			7.5	
Quantity	*CFactors*	2.3	Same as factor 2.3 in Table 4.3	
Productivity	*LFactors*	4.8	Same as factor 4.8 in Table 4.2	
	EFactors	6.5	Same as factor 6.5 in Table 4.3	
	SFactors	7.1	7.1	*SActions*
		7.2	7.2	*SActions*
Hourly Rate	*CFactors*	2.4	Same as factor 2.4 in Table 4.2	
	MgmFactors	3.5	Same as factor 3.5 in Table 4.2	
	LFactors	4.5	Same as factor 4.5 in Table 4.2	
		4.8	Same as factor 4.8 in Table 4.3	
	EFactors	6.5	Same as factor 6.5 in Table 4.2	

Similarly, the set (C_r) that represents the corrective actions can be generated as follows:

$$C_r(V_r, A_r) = P_r(V_r, F_r) \circ Z_r(F_r, A_i) = [X_r(v_{ri}, s_{rj}) \circ Y_r(s_{rj}, f_{rk})] \circ Z_r(f_{rk}, a_{rm}) \quad (4.9)$$

where,

the elements of C_r (V_r, A_r) represent the degrees of the linkage strength between the variances and corrective actions, and each lies between 0.0 to 1.0.

To perform the operations in Equations (4.8) and (4.9) above, two methods for composition of fuzzy relations are utilized (Klir and Folger 1988): the maximum-minimum (max-min) and the cumulative-minimum (cum-min). The two methods are described in Equations (4.10) and (4.11), respectively. For given fuzzy relations X_r (V_r, S_r) and Y_r (S_r, F_r), the max-min and cum-min compositions of X_r (V_r, S_r) and Y_r (S_r, F_r) can be expressed as (Klir and Folger 1988):

$$P_r(V_r, F_r) = [X \circ Y](V_r, F_r) = \max_{s_{rj} \in S_r} \min[X_r(v_{ri}, s_{rj}), Y_i(s_{rj}, f_{rk})] \quad (4.10)$$

$$P_r(V_r, F_r) = [X \circ Y](V_r, F_r) = \underset{s_{rj} \in S_r}{cum} \min[X_r(v_{ri}, s_{rj}), Y_r(s_{rj}, f_{rk})] \quad (4.11)$$

where,

all $v_{ri} \in V_r$, and all $f_{rk} \in F_r$, and the elements of matrix (P_r) represent the degree of linkage strength between the variances and the problem-source factors.

Equation (4.10) determines the most likely solution based on the strongest linkage strength. Equation (4.11), on the other hand, accumulates the linkage strength for the same indicator when determining the output value. The results of these two composition operations are compared in the numerical example.

The generated linkage strength between the factors and variances, using Equations (4.10) and (4.11), is then ranked to identify the most significant factor(s) behind the detected unacceptable performance using Equation (4.12). A similar computation is also used to rank the recommended corrective action(s).

$$PS_{in} = \frac{P(v_{ri}, f_{rn})}{\sum_{j=1}^{k} P(v_{ri}, f_{rj})} \times 100 \tag{4.12}$$

where,

PS_{in} = the percentage strength of n^{th} factor for v_i variance.

Once the problem-source factor(s) and corrective action(s) for all the resources within a control-object are obtained, fuzzy union operation can then be applied to infer the most significant factor(s) and the most suitable corrective action(s) for that control-object. Fuzzy union or logical OR operation of two fuzzy sets is defined by taking the maximum of membership values at each point across their common domains (Cox 1995).

$$\mu_{A \cup B}(x) = Max[P_A(V, F), P_B(V, F)] \tag{4.13}$$

where,

$P_A(V, F)$ and $P_B(V, F)$ relations describe their linkage strengths between variances and problem-source factors for resources A and B, in a given control-object, respectively.

4.6 Linkage Strength

The linkage strength reflects the degree of membership expressed in matrix X_r, Y_r and Z_r of Equations (4.3), (4.5) and (5.7), respectively. The elements of X_r (V_r, S_r) relation are determined based on the estimated impact-cost. For example, crew attendance is one of the labor performance indicators. If it is highlighted, the impact-cost for this indicator is estimated as the difference between the planned and actual crew cost. As an element of a fuzzy set, the linkage strength should have values in a range from 0 to 1 to represent the degree of the membership. Therefore, the calculated impact-costs are normalized to form the linkage strengths between the detected variances and the highlighted terminal indicators. A set of rules is applied when normalizing the impact-costs associated with the highlighted indicators. Rule 1: if the impact-cost of labor crew attendance is positive, and if the impact-cost of the crew payment is negative, and if their absolute values are equal, then the impact-cost of crew attendance is considered. In this case, the crew attendance variation is the only cause of the crew payment increase; rule 2: if the impact-cost of labor productivity is positive and the impact-cost of control-object production is negative, the impact-cost of labor productivity is considered. In this case, the lower labor productivity is identified as the reason for the poor production. A similar rule applies for equipment productivity.

The linkage strength between the indicators and the factors, as well as the actions, also needs to be determined. There are many ways to generate the linkage strength: interviewing with site personnel is one way, a questionnaire survey is another, where quantitative data is not available. No matter which method is used, the application of a generic set of values is not suitable for reasoning about performance. Therefore, user-defined linkage strength in a range of 0 (not significant) to 10 (most significant) is considered in the proposed reasoning process. The range will be converted into 0.0 to 1.0 in the computational process. In addition, two rules are set when determining the linkage strength between the indicators and the factors. Rule 3: If the control-object has the attribute of weather sensitivity, and if the actual weather recorded is bad, then the linkage strength corresponding to the weather aspect is set to 1.0; rule 4: If the control-object has the attribute of site congestion sensitivity, and if the actual site situation recorded is congested, the linkage strength corresponding to this aspect is set to 1.0. The "Reason" database houses the user defined linkage strengths at resource level. It should be noted that the assumption of equal linkage strength does not inhibit the representation of an indicator-factor relationship as well as a factor-action relationship. This is because the linkage strength between the variance-indicator relationship assigns other weights for indicators and these weights will separate the same problem-source factors or corrective actions through fuzzy binary relation operation. Also, the reasoning results are the accumulation of all the obtained weights for the same problem-source factors and corrective actions as described in Section 7.3.3.2.

4.7 Summary

A reasoning process that supports integrated project time and cost control has been presented. It is extensions of the developed causal models discussed in Section 3.6. The proposed reasoning process provides diagnosis of reported project variances employing thirteen terminal resource performance indicators and one factor indicator. A set of generic form of problem-source factors and corrective actions has been established. Fuzzy binary relation is utilized to describe causal links between these indicators, factors, and actions. Fuzzy composition operation is used to infer the reasoning at the resource level. The reasoning at the control-object is generated using fuzzy union operation of its resource level reasoning results. Similarly, the reasoning at project level is generated using fuzzy union operation of the reasoning results of all in-progress control-objects. The proposed reasoning process provides a tool to assist members of project teams in identifying reasons behind unacceptable performance and in suggesting corrective actions, accordingly. The implementations of the developed reasoning processes are discussed in Section 7.2.2.

Chapter 5

PROPOSED FORECASTING METHOD

5.1 General

In this chapter, a fuzzy forecasting method that supports project time and cost control in the developed object-based project model is presented. It is based on the principle of GMP type reasoning. Thirteen terminal resource performance indicators are utilized as input parameters to predict cost at completion and at interim future horizons for an individual resource. Two terminal resource performance indicators are utilized for duration forecasting of a control-object. A set of fuzzy if-then rules is used to infer the future values of the cost and duration. Three levels of forecasting reports can be generated, at individual resource, control-object, and project levels.

5.2 Fuzzy Forecasting Method

The developed forecasting method employs hierarchical process that starts at the resource level. It focuses on individual resources within each control-object in the project being considered. As shown in Fig. 5.1, the method has a three-tier structure that comprises presentation, middle and data tiers. The middle-tier houses the major functions of the developed forecasting method. It includes the components of 1) input variables' fuzzification using membership functions (MBFs), 2) knowledge-based rules used in the developed fuzzy inference process, and 3) defuzzification of output variables, and self-learning adjustment.

The input variables are essentially terminal resource performance indicators discussed in Section 3.5.3. According to the corresponding causal model discussed in Section 3.4.3, those terminal indicators are classified into input variables of cost and duration, respectively as shown in Table 5.1. The indicators provide ratios of actual against budgeted values, which are then fuzzified using MBFs to determine their degrees of membership to the corresponding linguistic terms. A set of fuzzy rules has been developed to assist in forecasting project cost and duration. Fuzzy inference is a heuristic process that activates applicable rules. The degrees of membership for each input variable determine the firing strength of its applicable rules. The output of the inference process is converted to a crisp value using a defuzzification method. A self-learning adjustment method is developed to continuously improve the accuracy of forecasting by making use of the difference between the previously predicted and the actual values at current reporting date. In this respect, the construction process for each control-object is divided into ten work progress periods corresponding to 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% completion.

Forecasting at resource level predicts only cost (C_r) at completion and at future interim horizons for each type of resources. It employs the method described above and 13 indicators to form the 17 input variables (S_i) listed in Table 5.1. The resource level forecasting method is designed to support daily and cumulative to-date analysis as well as weekly, monthly, and/or yearly.

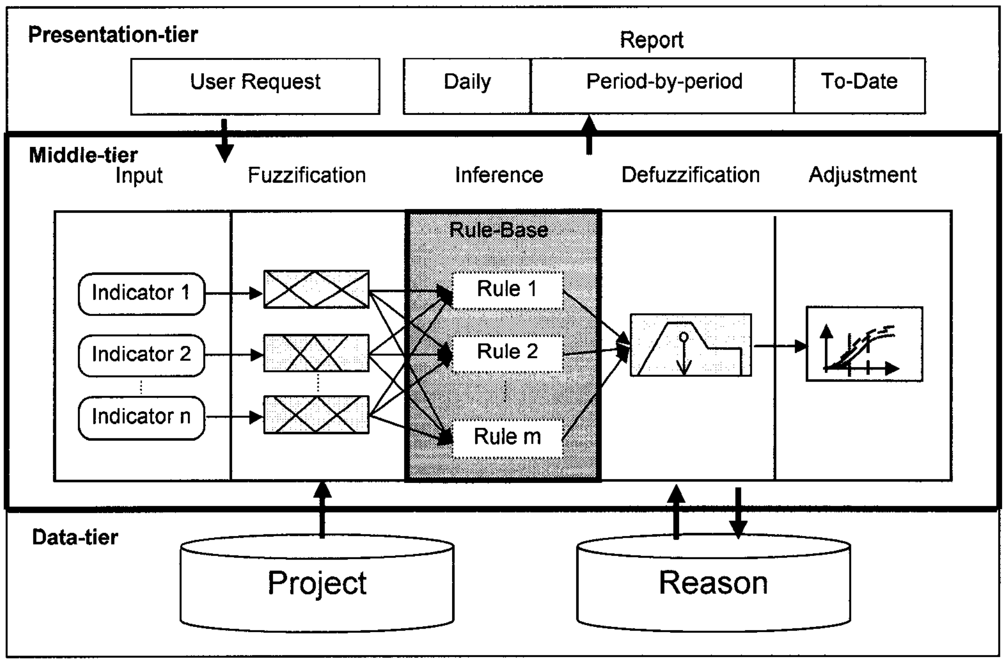


Figure 5. 1 The Proposed Forecasting Method

Forecasting at control-object level predicts not only cost (C_o), but also duration at completion (D_o) and at future horizons for a specified control-object. Cost forecasting at control-object level is performed by aggregating the cost forecasting results obtained for the resources associated with each control-object. Duration forecasting at control-object level is performed using the two input variables as listed at the bottom of Table 5.1 and the process described earlier for cost forecasting at the resource level. Forecasting at project level predicts cost (C_p) and duration at completion (D_p) and at user-specified future horizons. Cost forecasting at the project level is based on the summation of the cost forecasting results of all ongoing control-objects along with the summation of the actual costs of all accomplished control-objects. Duration forecasting at project-level, however, is the summation of the forecasted durations for the ongoing control-objects as well as those of the accomplished control-objects on the critical path.

Table 5. 1The Forecasting Variables and Their Properties

Name	Inputs for Cost	Linguistic Terms	Numerical Measure
Labor	(1) Quantity	*Decreased, Planned, Increased*	Ratio
	(2) Production	*Decreased, Planned, Increased*	Ratio
	(3) Productivity	*Decreased, Planned, Increased*	Ratio
	(4) Crew Attendance	*Decreased, Planned, Increased*	Ratio
	(5) Crew Payment	*Decreased, Planned, Increased*	Ratio
Material	(1) Quantity	*Decreased, Planned, Increased*	Ratio
	(2) Production	*Decreased, Planned, Increased*	Ratio
	(6) Usage	*Decreased, Planned, Increased*	Ratio
	(7) Unit Price	*Decreased, Planned, Increased*	Ratio
Equipment	(1) Quantity	*Decreased, Planned, Increased*	Ratio
	(2) Production	*Decreased, Planned, Increased*	Ratio
	(8) Productivity	*Decreased, Planned, Increased*	Ratio
	(9) Usage Rate	*Decreased, Planned, Increased*	Ratio
Sub-contractor	(10) Quantity	*Decreased, Planned, Increased*	Ratio
	(11) Production	*Decreased, Planned, Increased*	Ratio
	(12) Productivity	*Decreased, Planned, Increased*	Ratio
	(13) Hourly cost	*Decreased, Planned, Increased*	Ratio
Cost	**Output Cost**	*Underrun, Planned, Overrun*	Ratio
Name	**Inputs for duration**	**Linguistic Terms**	**Numerical Measure**
Control-Object	(1) Quantity	*Decreased, Planned, Increased*	Ratio
	(2) Production	*Decreased, Planned, Increased*	Ratio
Duration	**Output Duration**	*Decreased, Planned, Increased*	Ratio

Users can also specify, based on their own judgment and experience, percentage of improvement or deteriorate for indicators, signifying whether the performance of each indicator will improvement or deteriorate as ±10%, ±25%, ±50%, ±75%, or ±100%. The default settings of percentage of deteriorate /improvement for each indicator is 1.0, indicating that current performance is expected to continue unchanged in the future. The user specified percentage of improvement/deteriorate modifies the value of the indicator. Therefore, it will change the firing strength of applicable rules for that indicator. Detailed description of the proposed forecasting method is given below.

5.3 Fuzzification

Fuzzification is a method of converting a crisp value to degrees of membership of its associated linguistic terms using suitable MBFs. Three linguistic terms such as *Decreased*, *Planned*, and *Increased* are used to describe input and output variables as listed in Table 5.1. A linguistic term can take various shapes of MBFs. Although the transition from member to nonmember status could be linear or nonlinear, linear representations such as trapezoidal and triangular MBFs are commonly used. The values of the MBFs, range from 0.0 to 1.0 to define different degrees of membership and accordingly the degrees to which the variable fits the linguistic classifications being considered.

5.4 Membership Functions

MBFs can be developed using different methods such as: heuristics (based on knowledge extracted from interviews or questionnaire survey) and statistics, making use of available data. Heuristic-based methods (Dubois and Prade 1980, Cox 1999, Fayek and Zhuo 2001) are commonly used and they clearly have the advantage in absence of quantitative data. In the proposed model, however, a statistic-based method (Dubois and Prade 1980, Cox 1999, Boussabaine and Elhag 1999) is used to capture the characteristics of the project performance. It makes use of the accumulated daily performance data at each reporting period from project commencement to completion. The advantage of statistically based MBFs is that they directly capture the physical properties of the set (Boussabaine and Elhag 1999). In this respect, triangular and trapezoidal fuzzy numbers are utilized in the developed forecasting method. They are constructed using the mean (m), and the standard deviation (σ) associate with the variable being considered. The MBFs associated with "as planned", "underrun", and "overrun" conditions are referred to here as "*Planned*", "*Increased*", and "*Decreased*", respectively. These membership functions can be expressed as:

$$\mu(x) = \left| \frac{m-x}{2\sigma} \right| \qquad m-2\sigma \le x \le m \qquad (5.1)$$

$$\mu(x) = 1 \qquad 0 \le x < m-2\sigma \qquad (5.2)$$

for the *Decreased* status:

$$\mu(x) = \left| \frac{x-m+2\sigma}{2\sigma} \right| \qquad m-2\sigma \le x \le m \qquad (5.3)$$

$$\mu(x) = \left| \frac{m+2\sigma-x}{2\sigma} \right| \qquad m < x \le m+2\sigma \qquad (5.4)$$

for the *Planne*d status:

$$\mu(x) = \left| \frac{x-m}{2\sigma} \right| \qquad m < x \le m+2\sigma \qquad (5.5)$$

$$\mu(x) = 1 \qquad m+2\sigma x < x \le m+4\sigma \qquad (5.6)$$

for the *Increased* status:

While, there is no precise algorithm for determining the minimum or maximum degree of overlap, experience indicates that the overlap for the mid-point-edge for neighboring fuzzy regions averages somewhere between 25% and 50% of the fuzzy set base (Cox 1999). A high degree of overlap ensures that, when the system is in its optimal state (good performance), any small changes to this state can be detected and handled immediately (Cox 1999). Therefore, (2σ) degree of overlap, which is 50% of the fuzzy set base, is chosen for MBFs of input and output variables in the proposed method. Fig. 5.2 depicts the shape and spread of the $\mu(x)$ obtained in the equations given above in a graphic form.

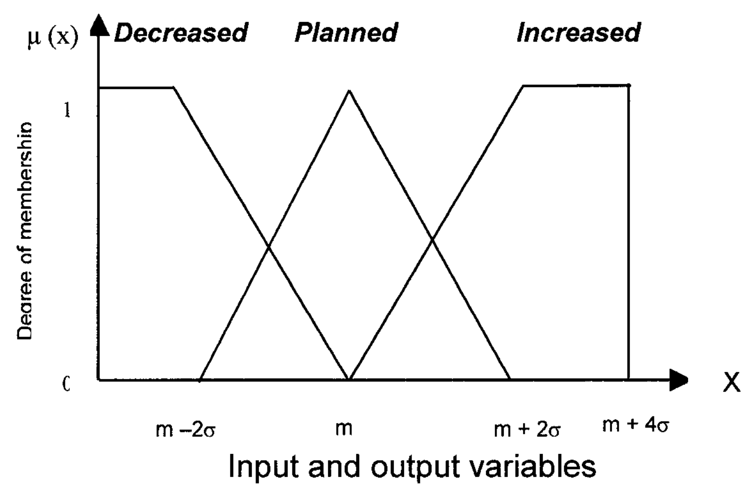


Figure 5. 2 Membership Functions for Input and Output Variables

The horizontal x-axis in Fig. 5.2 represents the input and output variables. Triangular and trapezoidal fuzzy numbers are utilized to describe the status expressed linguistically as *Decreased*, *Planned*, and *Increased*. The fuzziness is increased or decreased by the central point (m) and the range factor (σ). The degree of membership associated occurs at the value of (m-2σ) regarded as *Decreased*, (m) as *Planned*, and (m+2σ) as *Increased*. The boundary of the linguistic term of *Decreased* is defined at x=0. To maintain consistency with the 2σ overlap, the boundary of linguistic term of *Increased* is defined at x=m+4σ. In case a value of an input variable exceeds this boundary, the boundary will extend to this value.

In the developed system, the project baseline is the control reference. The value of input variable is defined as the ratio of the budgeted to the actual values. When the performance of an input variable is as *Planned* or at the start of a project and/or control-object, the statistical established standard deviation (σ) is equal to zero (σ=0). Therefore, default values of standard deviations for each input variable are necessary to allow the developed forecasting method to predict future based on good performance or at the start of a project and/or control-object. To demonstrate the use of the developed method, the labor productivity data reported by Thomas and Završki (1999) are considered to determine its default value of standard deviation. The data include labor productivity of masonry, concrete formwork, and structural steel erection activities, collected from 42 construction projects. The 42 construction projects include 23 masonry, 8 concrete formwork, and 11 structure steel activities. Labor productivity for masonry and formwork were measured by square feet per working hour (ft^2/wh), and for structural steel erection, it was measured by pieces per work hour. The data pertinent to the baseline and final cumulative productivity for the 42 projects can be found in Tables 5.2, 5.3 and 5.4. The baseline productivity is calculated based on the 10% of workdays that have the highest production (output) (Thomas and Završki 1999). The calculated standard deviations of productivity ratios for masonry, concrete formwork, and structural steel erection are 0.273, 0.372, and 0.229, respectively. The standard deviation of productivity ratios of all activities in the 42 projects is 0.279. Due to lack of detailed project performance data, the standard deviation for the input variable of labor productivity is considered equal to the default threshold values for all input variables. As more data from projects become available, the default values of the standard deviations are replaced by those determined statistically. As the work progress, more performance data is accumulated, leading to more accuracy of the values of the standard deviations used for generating the MBFs for input variables.

Table 5. 2 Labor Productivity for Formwork

(1) Project	(2) Baseline productivity (ft/wh)	(3) Cumulative productivity (ft/wh)	(4) Ratio
1	23.256	13.158	1.767
2	5.405	2.717	1.989
3	8.696	6.579	1.322
4	19.231	18.182	1.058
5	25.000	15.385	1.625
6	8.772	7.407	1.184
7	14.286	8.130	1.757
8	9.709	9.804	0.990

Note: (4) = (2)/(3)

Table 5. 3 Labor Productivity for Masonry

(1) Project	(2) Baseline productivity (ft/wh)	(3) Cumulative productivity (ft/wh)	(4) Ratio
1	11.765	10.204	1.153
2	12.500	9.804	1.275
3	10.526	10.870	0.968
4	13.333	9.174	1.453
5	12.500	5.988	2.088
6	12.500	11.765	1.063
7	9.091	7.874	1.155
8	10.526	8.264	1.274
9	5.882	3.390	1.735
10	20.000	14.706	1.360
11	9.524	6.329	1.505
12	13.333	10.204	1.307
13	7.692	6.757	1.138
14	8.696	7.299	1.191
15	5.882	4.219	1.394
16	18.182	13.514	1.345
17	14.286	9.524	1.500
18	12.500	9.709	1.288
19	10.526	7.752	1.358
20	16.667	8.475	1.967
21	10.526	9.434	1.116
22	12.500	8.264	1.513
23	12.500	10.753	1.163

Note: (4) = (2)/(3)

Table 5. 4 Labor Productivity for Structural Steel Erection

(1) Project	(2) Baseline productivity (ft/wh)	(3) Cumulative productivity (ft/wh)	(4) Ratio
1	0.898	0.578	1.553
2	0.650	0.549	1.183
3	0.559	0.330	1.695
4	0.978	0.758	1.292
5	0.525	0.565	0.929
6	0.916	0.735	1.245
7	0.647	0.455	1.423
8	0.804	0.667	1.206
9	0.536	0.327	1.639
10	0.448	0.291	1.543
11	0.914	0.690	1.325

Note: (4) = (2)/(3)

The MBFs for output variables of cost and duration have also been developed using statistical analysis of historical project performance data. Twelve projects performance data were extracted from Zwikael et al. (2000) and utilized for this purpose. The projects were delivered using lump sum contracts and they have relatively low-risk. Therefore, the expenditure rates were relatively stable during construction, and there was a strong incentive not to exceed the planned budget. These projects were completed over a five-year period from 1993 to 1997. Budgeted and actual data were captured and processed using the same information system under the supervision of the same financial control manager. Cost and schedule data for the12 projects are summarized in Table 5.5. The average planned cost was $1.3 million, and the average duration was three years. The majority of the projects ended with cost and schedule overruns. Each project was originally divided into 10 work progress periods corresponding to 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% completions. Therefore, 20 sets of data (10 for actual cost and 10 for actual duration) were used to develop the values of mean and standard deviation for the 10 work progress periods. For each set of data the ratios of cumulative actual versus its total budgeted values were calculated. The obtained values of mean and standard deviation for cost and duration for the 10 work progress periods are presented in Table 5.6. These values are used to establish the MBFs for cost and duration for the 10 work progress periods respectively. Figs. 5.3 and 5.4 are examples of graphic representations of the MBFs for cost and duration at 50% completion, respectively.

Table 5. 5 Project Performance Data (Zwikael et al. 2000)

Project	Planned Cost (K$)	Actual Cost (K$)	Cost Overrun (%)	Planned Duration (months)	Actual Duration (months)	Schedule Overrun (%)
1	898.00	1,212.30	35%	21	24	14%
2	604.80	870.91	44%	32	38	19%
3	322.00	669.76	108%	36	43	19%
4	613.20	772.63	26%	43	47	9%
5	291.20	276.64	-5%	24	24	0%
6	1,524.60	2,439.36	60%	50	59	18%
7	585.20	766.61	31%	46	54	17%
8	1,026.20	1,169.87	14%	29	30	3%
9	2,222.92	2,978.71	34%	45	55	22%
10	6,076.62	6,988.11	15%	44	50	14%
11	352.80	645.62	83%	17	23	35%
12	1,304.80	2,009.39	54%	50	50	0%

Table 5. 6 Values to Establish the MBFs for Cost and Duration

Item		Work progress									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Cost	Mean (m)	0.1416	0.2832	0.4248	0.5663	0.7079	0.8495	0.9911	1.1327	1.2743	1.4158
	SD (σ)	0.0312	0.0624	0.0936	0.1249	0.1561	0.1873	0.2185	0.2497	0.2809	0.3122
Duration	Mean (m)	0.1143	0.2286	0.3429	0.4573	0.5716	0.6859	0.8002	0.9145	1.0288	1.1432
	SD (σ)	0.0101	0.0202	0.0303	0.0405	0.0506	0.0607	0.0708	0.0809	0.0910	0.1011

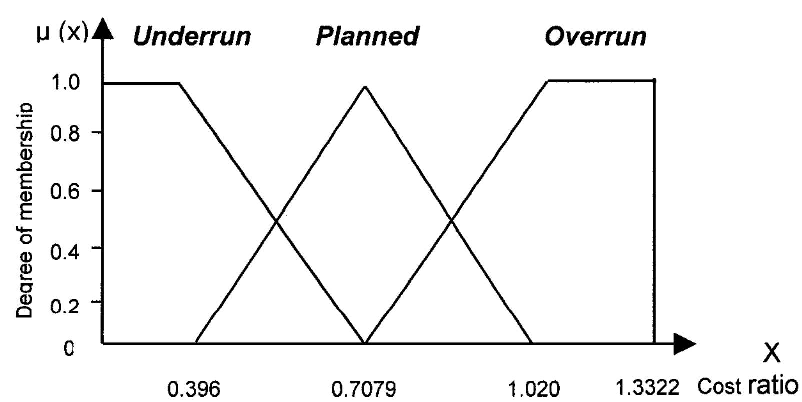


Figure 5. 3 MBFs for Cost at 50% Completion

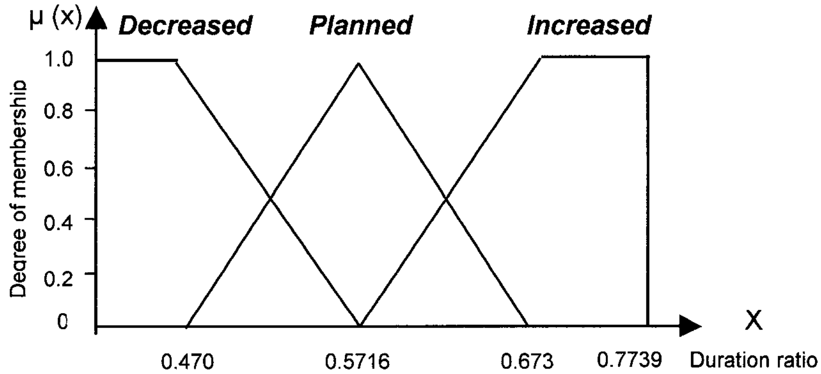


Figure 5. 4 MBFs for Duration at 50% Completion

5.5 Fuzzy Inference

The developed fuzzy inference process identifies the rules that apply to the fuzzified values of input variables and deducts the output linguistic terms that describe the status of cost and duration. The process takes into consideration the possible combinations of input variables, and satisfies the following the following criteria (Guillaume 2001):

COMPLETENESS: For any possible input, at least one rule should be fired to prevent the fuzzy system from getting blocked.

COMPLETENESS: For any possible input, at least one rule should be fired to prevent the fuzzy system from getting blocked.

RULE-BASE SIMPLICITY: The set of rules must be as small as possible. Otherwise, only a few rules can be fired simultaneously, for any input.

SINGLE-RULE READABILITY: The number of conditions implied in the antecedent of a rule should be as simple as possible (i.e., the number of conditions should be in the range of 5 to 9).

CONSISTENCY: The consequents of two or more rules that fire simultaneously should not be contradictory, i.e., they should be semantically close.

An example of cost forecasting for labor involves the use of the five input variables listed in Table 5.1. The combination of all possible situations for the 5 input variables generates a total of 243 (3^5=243) rules. A similar situation applies to input variables of material, equipment, and sub-contractors. Due to the large number of input variables, rules that consider all possible combinations are burdensome and not amenable to computer implementation. In an effort to avoid this problem, input variables are assumed to be independent, accordingly, the rules can take the following simple form:

if X is A **then** Z is C

where, X and Z represent antecedent and consequent elements of a rule.

This significantly reduces the number of rules. For example, the 243 rules referred to above can be reduced to 15 rules as shown in Table 5.7. The rules for the rest of the performance indicators are developed in a similar manner. The complete list of the rules for input variables of labor, material, equipment, and sub-contractor as well as the output variables of cost and duration can be found in Appendix D. A total of 39 rules are developed to support the fuzzy inference process. The fuzzy inference also provides flexibility to add new rules using the defined linguistic variables.

Table 5. 7 Rules Developed for Labor Cost

Quantity	(1) *Decreased* Then *Decreased*	(2) *Planned* Then *Planned*	(3) *Increased* Then *Increase*
Production	(4) *Decreased* Then *Increased*	(5) *Planned* Then *Planned*	(6) Increased Then *Decreased*
Productivity	(7) *Decreased* Then *Increased*	(8) *Planned* Then *Planned*	(9) *Increased* Then *Decreased*
Crew Attendance	(10) *Decreased* Then *Decreased*	(11) *Planned* Then *Planned*	(12) *Increased* Then *Increased*
Crew Payment	(13) *Decreased* Then *Decreased*	(14) *Planned* Then *Planned*	(15) *Increased* Then *Increased*

A single input and output fuzzy inference process can be represented as (Zimmermann 1996):

Rule: **if** X is A **then** Z is C

Observation: X is A'

Conclusion: Z is C'

The above rule can be symbolically represented as A→C. If A and A' are fuzzy subsets of fuzzy set U, C and C' are fuzzy subsets of fuzzy set W, A and C have the membership functions $\mu_A(u)$ and $\mu_C(w)$, respectively, the above single inference process can be expressed as (Zimmermann 1996):

$$C' = A' \circ (A \to C) \tag{5.7}$$

In membership domain, Equation (5.7) can be expressed as:

$$\mu_{C'}(w) = \vee_{u \in U} C(\mu_{A'}(u), \mu_{A \to C}(u, w)) \quad \forall w \in W \tag{5.8}$$

where,

C is a composition operator,

$\mu_{C'}(w)$ is the resultant membership function.

The implied relationship between the two fuzzy sets A and C can be expressed in terms of their Cartesian product using Mamdani's approach (Mamdani and Assilian 1975), i.e.

$$A \rightarrow C = R_{A \times C} \tag{5.9}$$

where,

$$\mu_{R_{A \times B}}(u, w) = \min\{\mu_{A'}(u), \mu_C(w)\} \tag{5.10}$$

If C in Equation (5.8) is taken as min, and $\mu_{A \rightarrow C}$ (u, w) is replaced by Equation (5.10), then Equation (5.8) becomes:

$$\mu_{C'}(w) = \underset{u \in U}{\vee} \min(\mu_{A'}(u), \min(\mu_A(u), \mu_C(w)) \quad \forall w \in W \tag{5.11}$$

If A' is a singleton observation (single value), fuzzy set, and is represented by u_o then Equation (5.11) becomes:

$$\mu_{C'}(w) = \min(\mu_{A'}(u_o), \min(\mu_A(u_o), \mu_C(w)) \quad \forall w \in W \tag{5.12}$$

Since $\mu_{A'}(u_o)$ = 1.0 for a singleton fuzzy set, then Equation (5.12) can be simplified as:

$$\mu_{C'}(w) = \min(\mu_A(u_o), \mu_C(w)) \quad \forall w \in W \tag{5.13}$$

Therefore, the inference results can be obtained by applying Equation (5.14). The center of sums (COS) defuzzification method (Zimmermann 1996) is used to directly convert all of the resulting fuzzy sets obtained from above inference process into a single value. This method takes into account the changes of all involved indicators. The other defuzzification methods such as the center of area (COA) (Zimmermann 1996) and the mean of maximum (MOM) (Lee 1990) methods convert only one fuzzy set into a single crisp value. These methods takes into account the significant change of an indicator. The COS method is, therefore, adopted in view of its ability to reflect any change of an indicator rather than the COA and the MOM methods which takes only the significant impact of an indicator. The COS method is defined as (Zimmermann 1996):

$$x_{COS} = \frac{\int_X x \sum_r \mu_r(x)dx}{\int_X \sum_r \mu_r(x)dx} \tag{5.14}$$

where,

x_{COS}= the center of sums, and $x \in X$,

r = the number of rules.

The graphic representation of this method is shown in Fig. 5.5. The overlapping areas of the resulting fuzzy set are considered more than once. The algorithm associated with this method has further the advantage of being much faster, saving computational time (Zimmermann 1996).

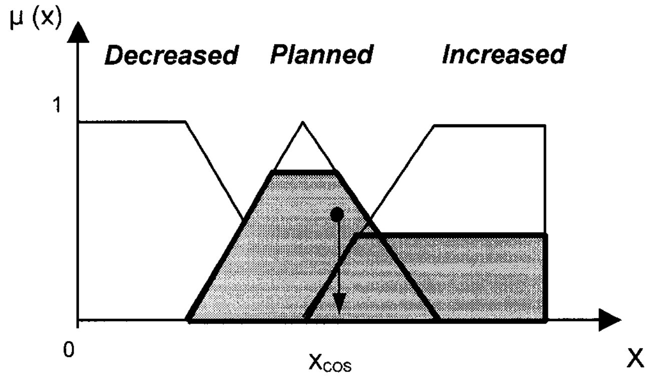


Figure 5. 5 COS Defuzzification

5.6 Self-learning Adjustment

The differences between predicted results and actual occurred values are used to improve the accuracy of the forecasted results. It is assumed that the differences from current reporting date moving forward is increasing with 10% increments for the remaining horizons. Equations (5.15) and (5.16) are developed to adjust the forecasted cost and duration at completion and at interim future horizons based on the dynamically captured difference during construction process, respectively.

$$C_k^{'} = C_k + (1+\alpha_k)(ACWP_i - C_i) \qquad k > i \tag{5.15}$$

where,

$C_k^{'}$ = adjusted cost at the kth future horizon,

C_k= as in $C_k^{'}$, but based on data up to the previous reporting period,

C_i= predicted cost using performance data from the previous reporting period,

i= the i^{th} percentage completion at reporting date,

k=at future horizons, k=1 to10,

α_k= 10 percent increments for k^{th} future horizons measured moving forward from the reporting date, e.g. for i at 30% completion, k=5 (50% completion), α_5 = 50%-30%=0.2,

$ACWP_i$ = actual cost of work performed at the i^{th} percent complete.

$$D_k' = D_k + (1+\alpha_k)(D_i - D_i') \qquad k > i \tag{5.16}$$

where,

D_k' = adjusted duration at k^{th} future horizon,

D_k= as in D_k', but based on data up to the previous reporting period,

D_i' = predicted duration using the data from the previous reporting period,

D_i = actual duration elapsed at the reporting date.

For example, considering a project with the status depicted in Fig. 5.6, i.e. at 40% of project completion, $ACWP_4$ is \$900, $BCWP_4$ (budgeted cost of work performed) is \$380, the cost variance at the reporting date (CV_4) is CV_4=$BCWP_4$-$ACWP_4$=\$380-\$900=-\$520. The predicted cost C_4 using the data of the previous period at this reporting date is \$1300. Therefore, the cost variance based on C_4 is CV'=$BCWP_4$-C_4=\$380-\$1300= -\$920. Thus, the cost difference Δ_c =CV' (forecasting)-CV_4 (actual) =-\$920+\$520=-\$400. The Δ_c can also be represented as $ACWP_4$-C_4 in Equation (5.15). If the predicted cost at completion C_{10} is \$2750, the application of Equation (5.15) yields an adjusted cost at completion C_{10}' of \$2110. Here, k=10, α_{10}=100%-40%=0.60.

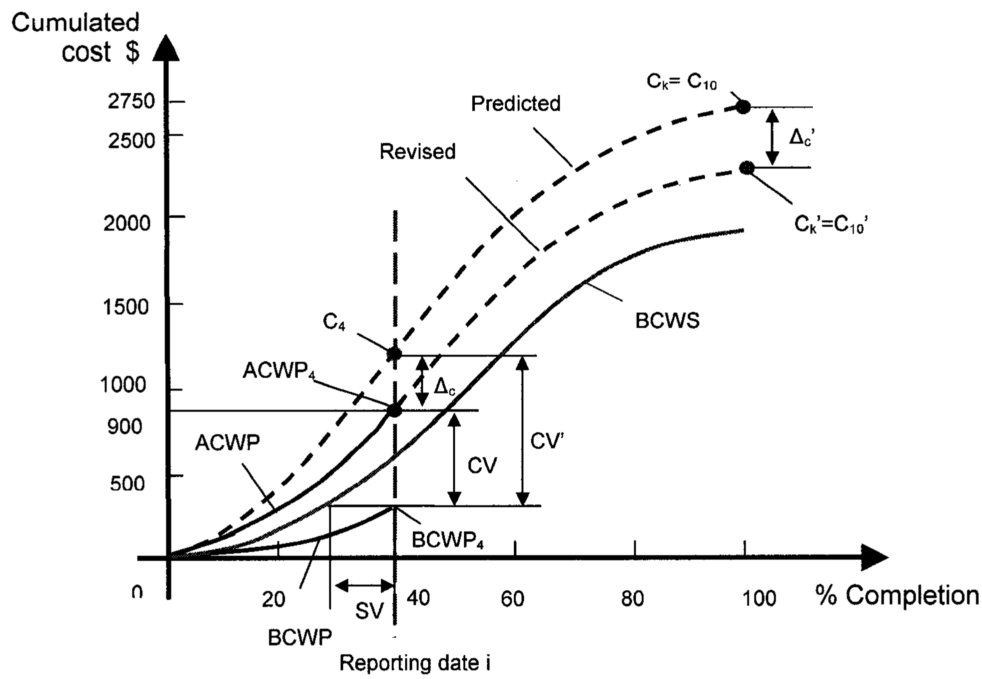


Figure 5. 6 Predicted and Actual S Curves

5.7 Summary

The forecasting method is developed using the principle of GMP type reasoning. Fuzzy inference process is utilized to predict future cost and duration not only at completion but also at interim future horizons. Thirteen terminal indicators are employed as input variables for cost prediction. Two terminal indicators are employed for duration forecasting. Three linguistic terms called *Decreased*, *Planned*, and *Increased* represent the scopes of the changes for the input and output variables. The MBFs of the input variables are established using statistical analysis of the collected daily performance data. A self-learning process is developed to improve the accuracy of the forecasting results. Three levels of forecasting reports are obtained in corresponding to the developed control functions. The module and implementation of the proposed forecasting method are discussed in Sections 6.4.5 and 7.2.3. The use and capabilities of the developed prototype forecasting system is demonstrated using a numerical example in Section 7.3.3.3. The comparison of the proposed method with the earned-value based methods is discussed in Section 7.3.3.4.

WEB-BASED SYSTEM DESIGN

6.1 General

In this Chapter, an integrated web-based time and cost control system (IT/CC) that is designed to assist project managers and contractors to track and control their construction site activities through the Internet is explained. The IT/CC system provides a tracking function for the evaluation of in-progress project performance as well as the control functions to allow for an explanation of the reasons for poor performance, a recommendation for corrective actions, and a prediction of the time and cost at future interim horizons and at completion. It also provides for the function of data storage including the budget and schedule data, the actual progress of the project, the factors and actions involved in the reasoning process, the user specified values for reasoning and forecasting, as well as other particulars of the case, and the history data about the previous projects. In order to develop the system, it is necessary to describe the desired requirements for the system, the necessary functionality, the needed resources, and the components of the system as follows:

6.2 System Requirements

In the area of software engineering, the development of software is based on software requirements. After the implementation is completed, the system must be validated against the requirements. A list of system requirements is formulated to guide the development of the proposed IT/CC system. This list describes the necessary components of that system and presents the necessary characteristics that should be manifested in the course of system development. The requirements of the IT/CC system are as follows:

1. A hierarchical representation of projects: as discussed in Section 3.2, projects are composed of many control-objects. These control-objects themselves are composed of many resources (e.g. labor, material, equipment, and/or sub-contractors). Therefore, the IT/CC system must be able, with control-objects, to represent the hierarchical structure of the project and the project's resource components, which can be retrieved and reused individually.

2. Representation of control-objects relationships: the hierarchical breakdown of the project into control-objects results in the loss of relations among control-objects except for their relationship to the common parent i.e. the project. This decomposition cannot represent the construction sequence among control-objects. Therefore, the IT/CC system must provide a way to represent the relations among different control-objects in order to account for the effect of schedule variance.

3. Storage project data: project data can be categorized into budget data (planned and scheduled data) and actual data. Budget data are recorded at

project commencement. The actual data, which are in-progress project performance data, are recorded on a daily or weekly basis. The IT/CC system should be able to record the project budget data as well as the actual data.

4. Data reusing and sharing: in a project domain, many control-objects have a repetitive nature. One uses the same attributes to describe their features. Moreover, some of the values are used for more than one control-object. Thus, the IT/CC system should be able to support the reusing of attributes and to support the sharing of attribute values among different control-objects, thereby facilitating efficient data input. The Internet-based system already allows overall data reusing and sharing among team members.

5. Versatile computation and evaluation: the system computes the cost and schedule variances at each control level. Also, there is a versatile evaluation operation of performance indicators as well as of CV and SV according to the predefined criteria. Thus, the IT/CC system should offer versatile techniques for computing and evaluating CV and SV at different control levels and for evaluating performance indicators at resource level.

6. Versatile membership function measures: the system measures the membership functions of input variables (terminal indicators) as the statistic analysis operation of the project-budgeted and actual data. Hence, the IT/CC

system should offer versatile techniques for measuring the membership functions for different terminal indicators.

7. Representation of Knowledge: knowledge is represented by rules. Each rule has its fire strength when invoked. The fire strength is the estimated impact-cost for each terminal indicator in the developed system. Therefore, the IT/CC system should support the representation of knowledge and calculate the estimated impact-cost for each terminal indicator.

8. Fuzzy computation: fuzzy binary relation operation, fuzzy set operations, fuzzy inference, and defuzzification techniques are used to explain the reason(s) for poor performance and to forecast the cost and duration at future interim horizons and at completion. Therefore, the IT/CC system should support the above-mentioned fuzzy set and fuzzy logic operations.

9. Accumulation of project performance data: project performance data is very useful for new project cost estimating and bidding processes. It also serves as a reference for planning and scheduling of future projects. Also, the data from control-objects, which have a repetitive nature, are utilized to develop standard templates for domain-specific works. Thus, the IT/CC system should keep all the project-performed data as history data and the repetitive works' data as case data for future reference.

10. Data derivation: the IT/CC system should allow the derivation of new data items from stored ones. This capability eliminates data duplication (redundancy) that may often lead to inconsistency problems (Hannus et al. 1995). For instance, the planned and actual indicator values of a resource should not be stored because they can be derived from its budgeted and actual data.

11. Input and output (I/O) ability: the I/O function is very important for effective project control. The IT/CC system has to handle data and report the results in an efficient way. It should use every possible advantage offered by the Internet.

12. Multi-user access: the IT/CC system should be multi-user prototype software that allows different users to access the system simultaneously.

13. Modularity: the IT/CC system should be structured in modules, each of which should then be broken down into separate sub-modules according to their functionality. This modularity guarantees manageable modifications on specific modules (Rivard et al. 1998; Hannus et al. 1995). For example, budgeted data input should be designed in a module different from actual data input. This facilitates a quick and safe operation without affecting other system components.

14. Compatibility: as an end-user, an Internet-based system does not suffer from the software incompatibility present in other applications. Any computer that has

a web browser such as Netscape Navigator and Internet Explorer can access and implement such a system. Only a server-side operating system faces this problem. In order to be compatible with most of the servers, a popular server operating system should be chosen for the IT/CC system development.

15. Versatility: the IT/CC system should be able to handle different types of project data. Also, it should be able to represent projects with various hierarchical breakdown structures.

16. Extensibility: the design of the IT/CC system has to be flexible enough to allow the extensibility of the system in the future to meet various requirements.

6.3 System Functionalities

System functionality is the way a system would behave. It is documented in a use-case diagram. This diagram illustrates the system's intended functions, surroundings, boundaries, and internal and external relationships (Quatrani 2002). The use-case diagram for the IT/CC system is presented in Fig. 6.1. It includes the components of actors as well as those of the use-case model, the system boundary, the use-case communication, and the use-case relationships.

ACTORS are not part of the system. They represent anyone (person) or anything (external system) that interacts with the system (Quatrani 2002). In Fig. 6.1, an actor is represented as a stickman. Actors in the IT/CC system are:

general managers, managers, site managers, and staff. General managers are responsible for the control of several projects. They consult the system to obtain, for several projects, information regarding performance evaluation, reasoning, and forecasting. Managers are responsible for the control of one single project. They update project-budgeted data and consult the system to obtain project and control-object information concerning performance evaluation, reasoning, and forecasting. Site managers are responsible for the control of multi-control-objects and their resources. They update the control-object data and consult the system to obtain the control-object information regarding resource performance evaluation, reasoning, and forecasting. Staffs are responsible for maintaining the system performance. They update databases and set up usernames and passwords for system users.

USE-CASE MODEL describes the dialogues between the system and its actors and represents the functionality provided by the system (Larman 1998). A use-case is represented as an oval (See Fig. 6.1). In the IT/CC system, the defined use cases are as follows:

1. *Evaluating-Project*: this use-case is designed to represent performance evaluation for several projects. General managers activate this use-case when evaluating project performance and generate reports for different projects.

2. *Evaluating-Object*: this use-case is designed to represent performance evaluation of multi-control-object for one project. Managers activate this use-case when evaluating one project and/or multi-control-objects performance to generate the performance reports.

3. *Evaluating-Resource*: this use-case is designed to represent the performance evaluation for resources of labor, material, equipment, and sub-contractors. Site managers activate this use-case when evaluating multi-control-object and/or one control-object performance.

4. *Reasoning-Project*: this use-case is designed to represent the project reasoning process. General managers can activate this use-case to get the project level reasoning report.

5. *Reasoning-Object*: this use-case is designed to represent the control-object reasoning process. Managers can activate this use-case to get the control-object reasoning report.

6. *Reasoning-Resource*: this use-case is designed to represent the resource reasoning process for labor, material, equipment, and sub-contractor. Site managers can activate this use-case to get each individual resource reasoning report.

7. *Forecasting-Project*: this use-case is designed to represent the project level forecasting. General managers can activate this use-case to get the project forecasting report.

8. *Forecasting-Object*: this use-case is designed to represent the control-object level forecasting. Managers can activate this use-case to get the control-object forecasting report.

9. *Forecasting-Resource*: this use-case is designed to represent the resource level forecasting for labor, material, equipment, and sub-contractor. Site managers can activate this use-case to get each individual resource forecasting report.

10. *Maintaining-System*: this use-case is designed to represent system maintenance. Staffs activate this use-case to maintain the consistency of the system and to improve its performance.

11. *Validating-User*: this use-case is designed to check the validation and the compliance of the username and the password to the selected actor. When the user logs into the system, this use-case is activated.

SYSTEM BOUNDARY identifies the system's responsibilities by determining what is internal versus external to the system (Larmen 1998). It separates the control system from the external actors. The system boundary is shown as a rectangle shape in Fig 6.1.

USE-CASE COMMUNICATION is the connections between actors and use-cases. There is only one type of communication that may exist between an actor and a use-case. The navigation direction represents the one who is initiating this communication.

USE-CASE RELATIONSHIP identifies other use-cases to which the use-case is related. In a usage-centered design, there are three types of relationships that may exist between use-cases (Constantine and Lockwood 2001): "Inclusion," "Specialization," and "Extension." "Inclusion" relationship describes a single use-case that is included (by reference) within or used by another use-case; the "Specialization" relationship describes a single use-case that is a specialized variant of another more general case; the "Extension" relationship describes a single use-case that extends to another by introducing alternative or exceptional processes. Only the "Inclusion" relationship is considered in the IT/CC system. The *Evaluating Object* use-case, for example, includes the functionality of the *Evaluating Resource* use-case.

A use-case diagram is a collection of actors, use-cases, and their communications as shown in Fig.6.1.

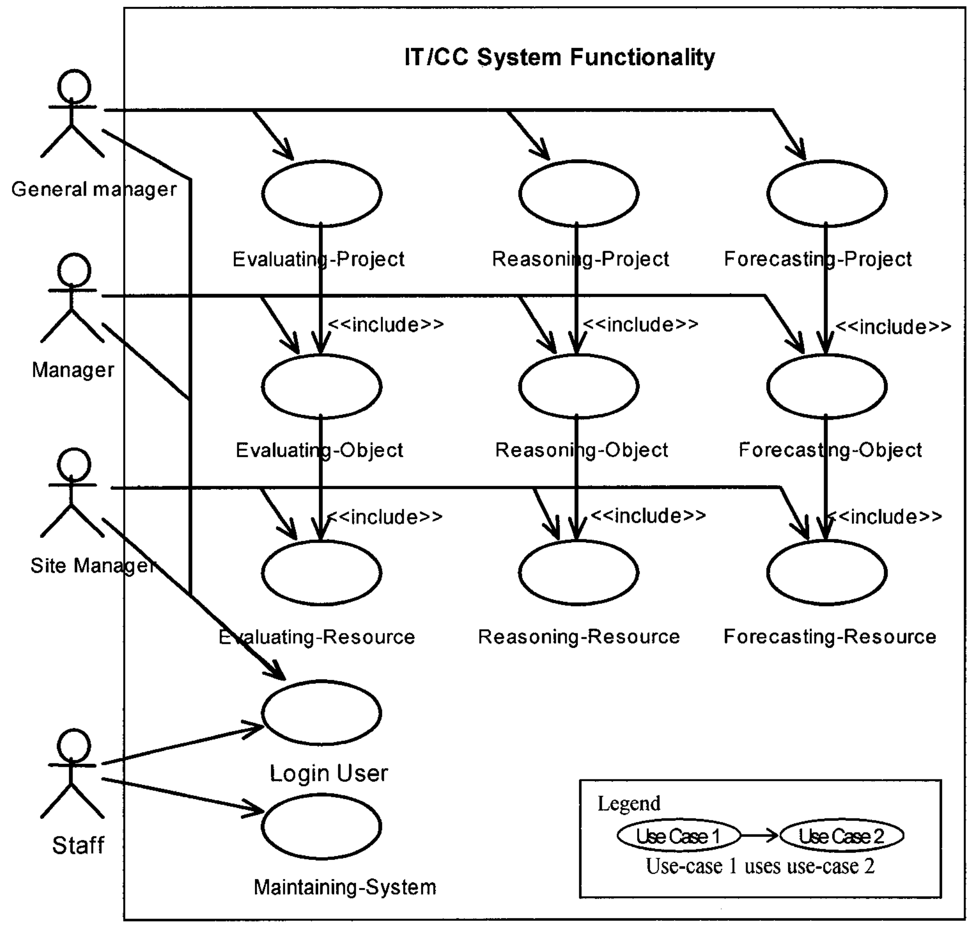


Figure 6. 1 Use-Case Diagram of IT/CC System

6.4 System Resources

System resources are the architecture and platform through which the system is designed to function in a way to meets its requirements. The choice of these resources is a crucial step in the successful development of a system. System requirements play an important role in the selection of the appropriate resources. In the proposed IT/CC system, two main resources have to be selected: the architecture of the Internet-based system and the system platforms including the web server to host the developed system and the web-based Database Management System (DBMS). The choice of each of these resources is described in the following subsections.

6.4.1 Web-based System Architecture

A typical application that interacts with a user usually consists of three elements: presentation, application logic, and data. Presentation focuses on interacting with the user. Application logic performs calculations and determines the flow of the application execution. Data elements manage information that must persist across sessions or be shared between the users.

The most often used web-based systems are two-tier and three-tier client/server architectures. Here, a client is defined as a requester of services and a server is defined as the provider of services. With two-tier client/server (Standard client/server) architecture, the user system interface is usually located in the user's computer and the database management services are usually in a web server that is a more powerful machine that services many clients (Sadoski 1997). Two-tier client/server architecture groups presentation and application logic components on the client computer. It provides data sharing through the Internet connection. Information processing is split between the user interface in the client computer and the database management in the web server. The web server provides data storage procedures and triggers the database when necessary. It is a good structure for a distributed computing network. The advantage of this configuration is that the data is centralized. The centralization of data benefits the organization by sharing data, providing consistency in accessing data, and reducing data duplication and maintenance. However, it does have a number of limitations, such as poor scalability, poor maintainability, poor reusability, and poor network performance. Scalability is the term used to describe the ease with which a system or component can be modified to fit the problem area. For two-tier architecture, when the number of users exceeds 100, performance begins to deteriorate (Sadoski 1997). The system proposed by Abdelsayed and Navon (1999), and Villeneuve and Fayek (2003) are example applications developed with two-tier architecture.

A three-tier client/server architecture (also referred to as multi-tier architecture) has emerged to overcome the limitations of two-tier architecture. The structure of three-tier client/server architecture is shown in Fig. 6.2. It involves the presentation-tier, the application logic/middle-tier, and the data tier. Adjacent tiers are connected through the Internet. By contrast with two-tier architecture, a middle tier was added between the user interface in the client computer and the database in the web server. The presentation-tier components manage user interaction and request services. The event handler embedded in the user interface responds to the user's request and triggers the middle-tier data processing components. The middle-tier components perform queuing, executing, and requesting to the database. ODBC (Open Database Connectivity) connects the data processing component with the Database to facilitate data entry and retrieval. The three-tier client/server architecture separates presentation, application logic/middle-tier, and data elements. Therefore, the system design becomes more flexible because the users can call on server side components when needed to complete a request, and the components in the server side can call on other components to improve code reuse. The major data processing runs on the middle-tier server. The independence of a middle-tier from presentation and data tiers offers numerous benefits including:

Multi-language support: system components can be developed using different programming languages when needed.

- Centralized components: components are centralized for easy development, maintenance, and deployment.
- Efficient data access: the numbers of database connections are minimized since the database faces the components only in the middle-tier.
- Improved security: the middle-tier components can be secured centrally using a common infrastructure. Access can be granted or denied on a component-by-component basis. The database is hidden from the client.

- Simplified access to external resources: access to external resources, for example, to other applications or databases, is simplified. A gateway server becomes another component that is used by the application.

Taking the above into consideration, a three-tier client-server architecture is chosen for the IT/CC system development.

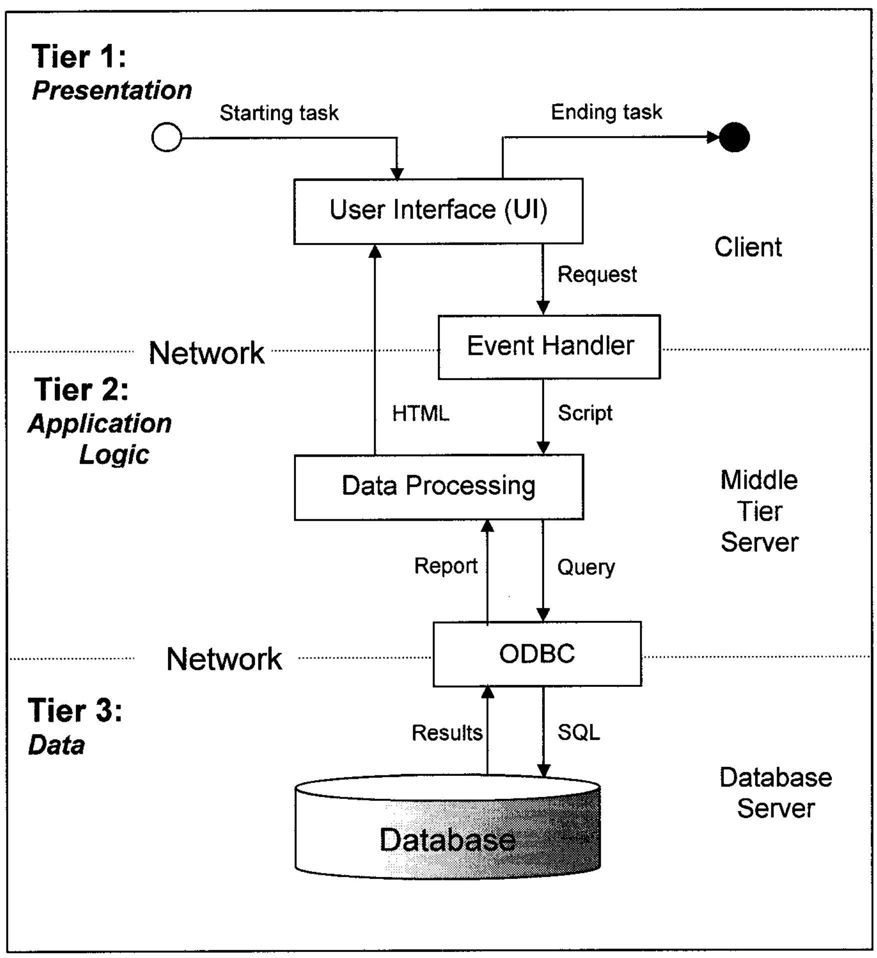


Figure 6. 2 Architecture of Three-Tier Client/Server System

6.4.2 System Platform

The system platform includes the computer operating system, the Database Management Systems (DBMS), and the computer hardware. Since the Windows operation system is widely used, it is chosen as the web server operation system. Windows 95/98 has a weak security feature. Windows NT and Windows 2000 server series are chosen for the IT/CC system implementation. The Microsoft Internet Information Server (IIS 5.0) is utilized to host the web server. The IT/CC system is coded using Hypertext Markup Language (HTML), Java Applet, JavaScript, VBScript, and Active Server Pages (ASP).

Database Management Systems (DBMS) are essential for the support of project tracking and control functions. A database provides a platform to organize, store and retrieve projects' planned and actual performance data in a logical and efficient manner. The DBMS queries the stored project data from the database using SQL (structured query language) to generate different management reports for control purposes.

The application of DBMS for project control has been explored by a number of researchers. Abudayyeh (1991, 1993) developed a DBMS to support automated cost and schedule control function. He used the work package model described in Section 2.2.1 to represent the project data. His system, however, only provides the earned-value based progress reports, which track the cost and schedule variances. It cannot provide the control functions of diagnosing the reason(s) behind unacceptable variances and suggesting corrective action(s) accordingly. To overcome those limitations, DBMS in conjunction with a knowledge-based expert system has been used for the project control. Diekmann and Al-tabtabai (1992) present a knowledge-based approach for project control. In their system, a single form is used to store data pertinent to individual work packages. Their control functions focus on an individual work packages. Fayek et al. (1998) proposed a prototype rule-based expert system to improve project control. Two forms of data, one related to activities, the other related to project, are defined to map the data structure of a project. The developed system can be implemented at project, supervisor and activity levels. Moselhi et al. (2002, 2004) proposed a web-based system for project control of control-objects. An object-based model described in Section 3.2 is proposed to integrate the project data in supporting of the project control functions. Project control can be implemented at project, control-object and resource levels. In summary, the developed systems only evaluate the performance of individual controlled units, for example a work package, and provide control functions for that unit. None of these systems, however, are web-based except those proposed by Moselhi et al. (2002, 2004). They neither support performance control of project on remote sites nor provide the ability to share information. In order to facilitate the development of the Internet-based database management system for project control, a database structure have to be determined.

Two types of database structures are available for selection. They are an object-oriented database and a relational database. An object-oriented database represents data and data inter-relations using pre-defined structures. Relational databases allow data modeling using simple structures (tables) without having to predefine the data inter-relations. Such relational databases are widely used and less expensive. Therefore, Microsoft Access 2000 has been chosen a database for the proposed IT/CC system.

The IT/CC system should perform all of its proposed functions efficiently on the following hardware and software platforms:

Server side:

- Minimum hard disk space: 500MB;
- Minimum RAM: 256 MB;
- A personal computer (PC) with CPU of Intel Pentium 1800 MHz or higher;
- Operating System: Microsoft Windows NT 4.0 or 2000 series;
- DBMS: Microsoft Access 2000.

Client side:

- Minimum hard disk space: 100 MB;
- Minimum RAM: 64 MB;

- A personal computer (PC) with CPU of Intel Pentium 800 MHz or higher;
- Operating System: Microsoft Windows 98, NT 4.0 or 2000;
- Minimum modem connection rate: 5600 bps;
- Web Browser: Netscape Communicator 4.5 or Microsoft Internet Explorer 4.0 or higher.

6.5 System Components

The proposed IT/CC system has a three-tier client/server architecture. Fig. 6.3 illustrates the layout of the proposed IT/CC system and its data flow. The components of the system can be divided into seven modules: user interfaces, input/edit, evaluation, forecasting, reasoning, reporting, and databases as shown in Fig. 6.4. The user interfaces are modules within the presentation-tier, which handles the system communication with the user. The databases are modules of the data-tier, which hides all the supported system data for security purposes and separates the data from the system software for data re-use purposes. The rest belongs to the application logic/middle-tier, which implements the IT/CC system by class interactions. Each time a function of the system is activated, the corresponding classes are initialized and the needed data are set. The arrow lines in Fig. 6.3 represent the data flow. The dashed arrow lines in Fig. 6.4 represent the dependency of these modules. UML is utilized in the designing of the system modules. The structures, attributes, and operations of these modules are introduced as follows.

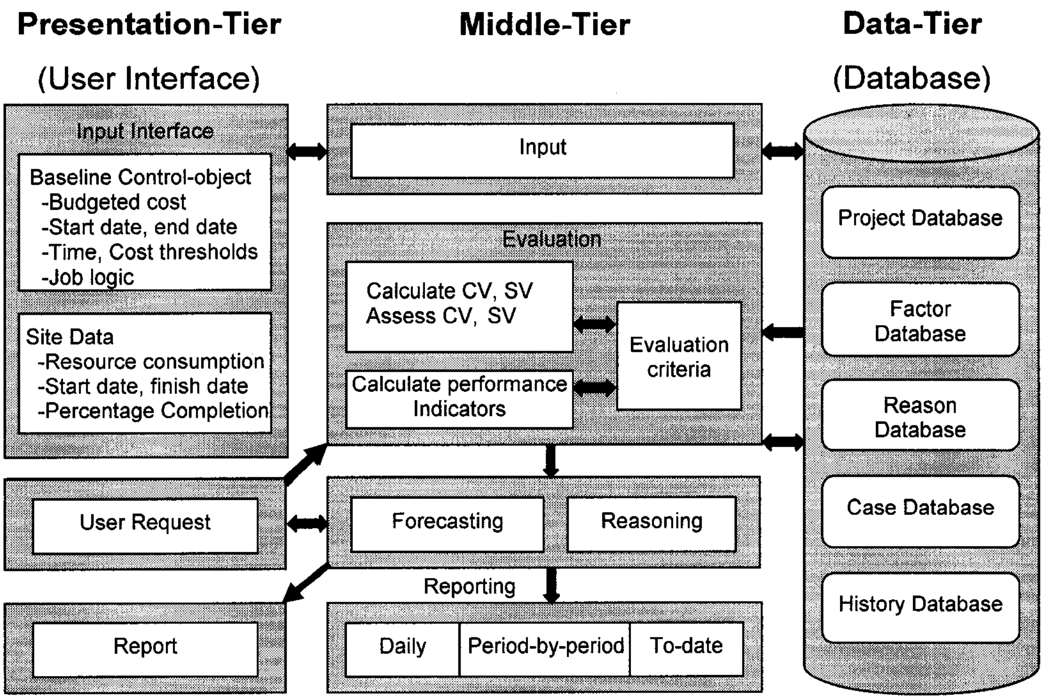


Figure 6. 3 The IT/CC System Layout

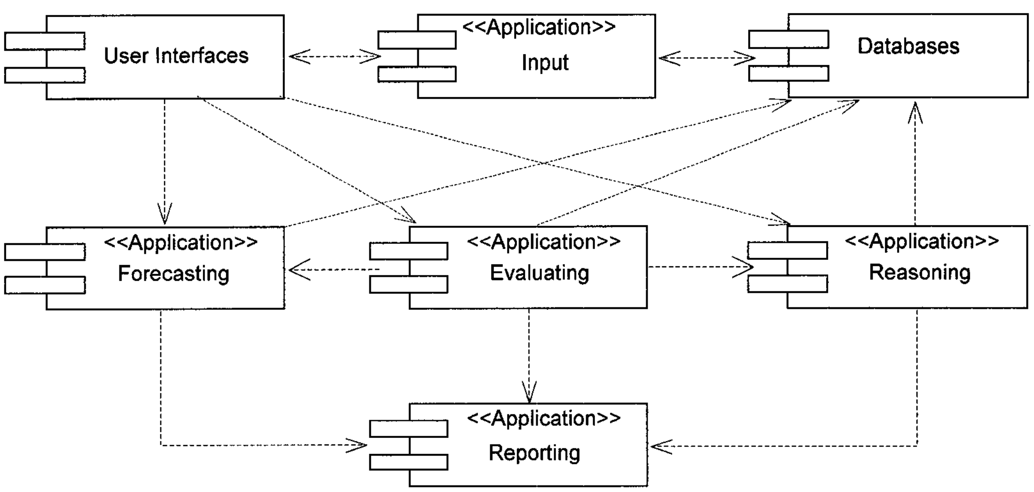


Figure 6. 4 The IT/CC System Components

6.5.1 User Interface (UI)

The UI provides the viewing/input window to allow users to interact with the system through the web pages using an Internet browser. The users can log into the system through the UI. They may modify their passwords, place a request to control the project performance, send reports to the project's team members, and insert, update, delete, and view different types of project reports.

Five windows are developed in the IT/CC system as the user interfaces: the login, the general manager, the manager, the site manager, and the staff windows. The class diagram of the UI along with the attributes and operations can be found in Appendix D. The attributes of the classes are the parameters needed to execute the operations. The operations of the classes execute the tasks described as follows.

LOGIN WINDOW is a main window for execution of the IT/CC system program as shown in Fig. 6.5. It provides an interface that allows the users, namely, the general manager, manager, site manager, and staff, access to the IT/CC system. A valid username and password is needed in order to log into the system.

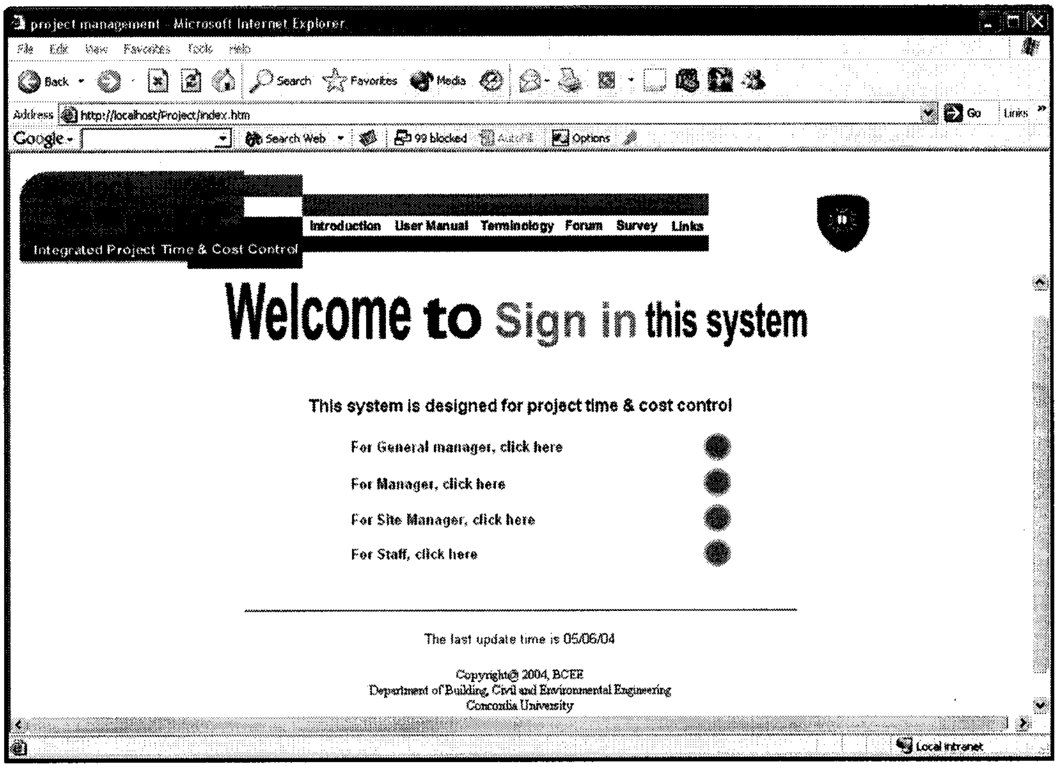


Figure 6. 5 The Main Window

GENERAL MANAGER WINDOW is designed to control one and/or several projects. After successful login as a general manager, a project level control window appears as shown in Fig. 6.6. The users can choose the functions listed on the left side of the menu to perform the following tasks:

- Evaluate the performance of one project and/or more projects; generate the performance evaluation, the reasoning, and the forecasting reports;
- View planned data of the projects, the control-objects, and their resources respectively;
- View actual progress data of the projects and the control-objects;
- View general information about the projects;

- Update/View registered system users and assignments of responsibilities for new users;
- View employees general information;
- View the sub-contractors general information;
- Update/View personal information; change personal password.

The general managers have the right to assign the responsibilities for the project and/or the control-objects to the managers.

MANAGER WINDOW is designed to control one-project and/or all control-objects. After successful login as a manager, a control-object level control window appears as shown in Fig. 6.7. The users can choose the functions listed on the left side of the menu to perform the following tasks:

- Evaluate the performance of a project and its control-objects; generate the performance evaluation, the reasoning, and the forecasting reports;
- Update/View planned data of the control-objects and their resources;
- View actual data of the control-objects and their resources;
- Update/View the control-object predecessors;
- View registered system users and the assignments of responsibilities;
- Update/View personal information; change personal password.

The managers may update the planned data of the projects. They also have the right to assign the responsibilities for the control-objects to the site managers.

SITE MANAGER WINDOW is designed to control all and/or several control-objects. After successful login as a site manager, a resource level control window appears as shown in Fig. 6.8. The users can choose the functions listed on the left side of the menu to perform the following tasks:

- Evaluate the performance of all and/or several control-objects and their resources; generate the performance evaluation, the reasoning, and the forecasting reports;
- View planned data of the control-objects and their resources;
- Input/Update/View actual performed data of the control-objects and their resources;
- Update/View general information of labor;
- Update/View personal information; Change personal password.

Site managers may input and update the actual performance data into the system.

STAFF WINDOW is designed to maintain the system's performance and input project-budgeted data to the system. After successful login as a staff member, an administration window appears as shown in Fig. 6.9. The users can choose the functions listed on the left side of the menu to perform the following tasks:

- Input/Update/View planned data of all control-objects and their resources;
- Input/Update/View the predecessors for each control-object;
- Input/Update/View labor information;
- Input/Update/View material information;
- Input/Update/View equipment information;
- Input/View labor information;
- Input/Update/View sub-contractors information;
- Input/Update/View project general information;
- Input/Update/View craft information;
- Maintain system users;
- Input/Update/View personal information; Change personal password;
- Move case data to case database;
- Move project data to historical database.

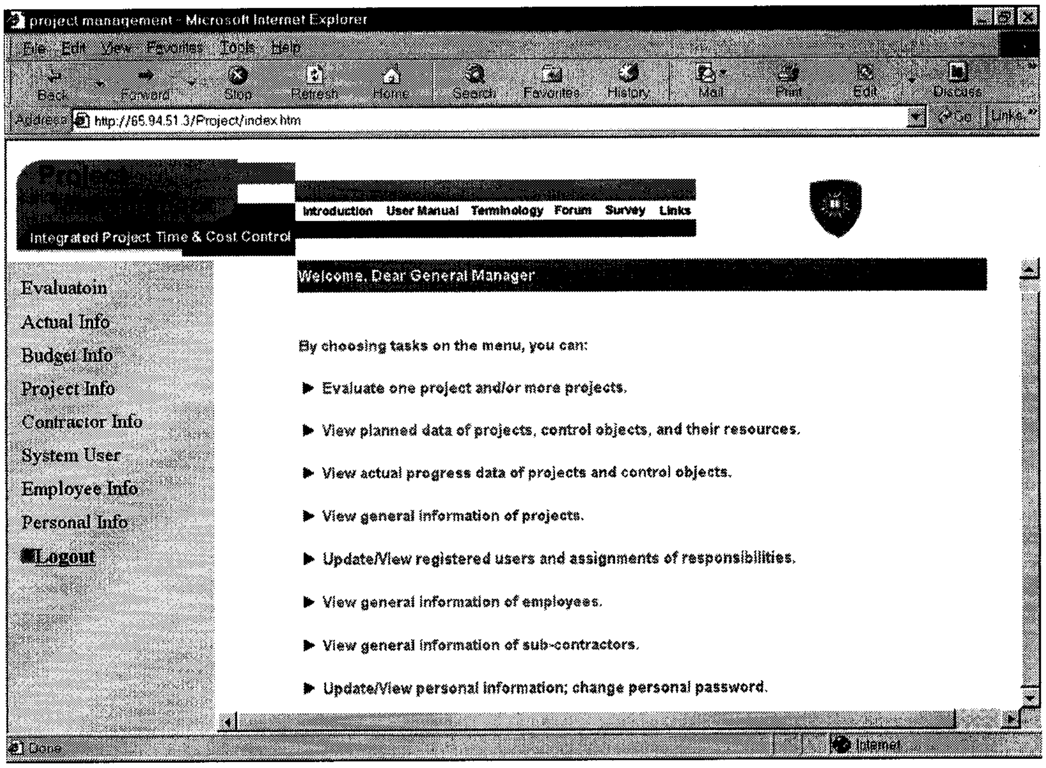


Figure 6. 6 General Manager Window

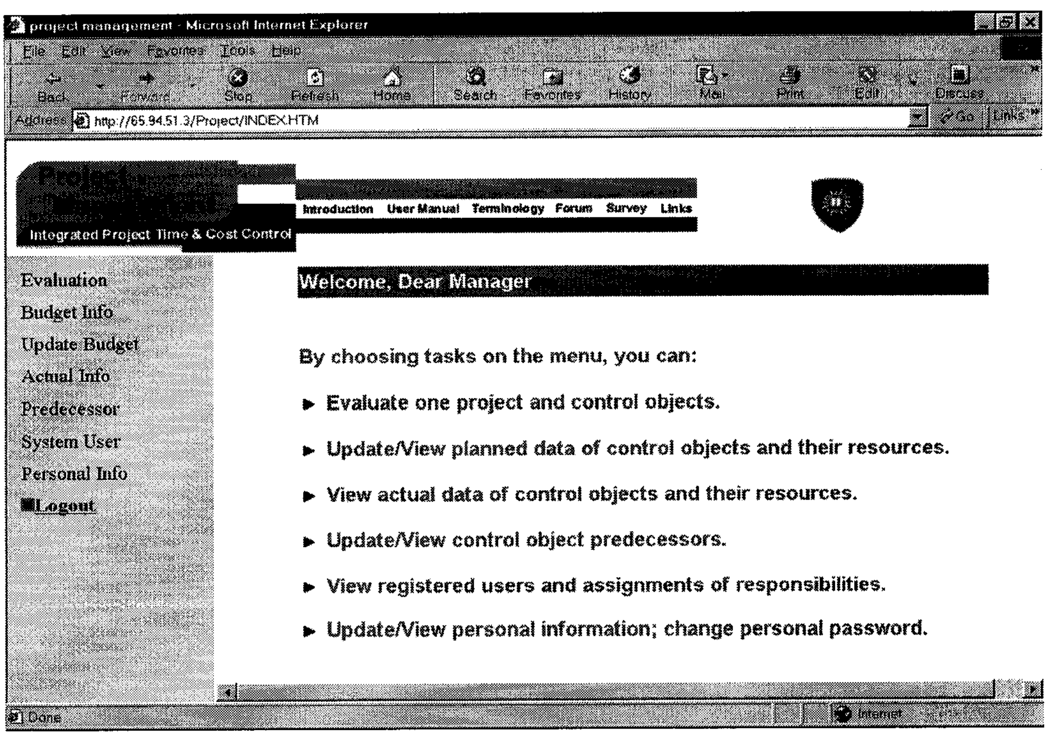


Figure 6. 7 Manager Window

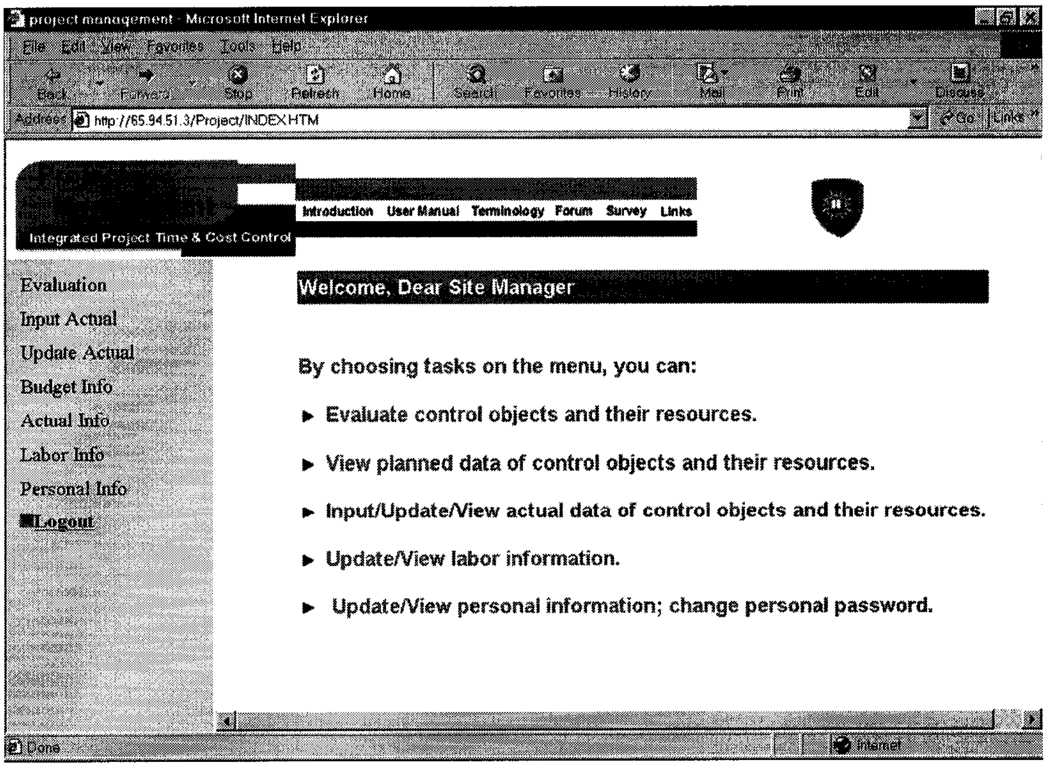


Figure 6. 8 Site Manager Window

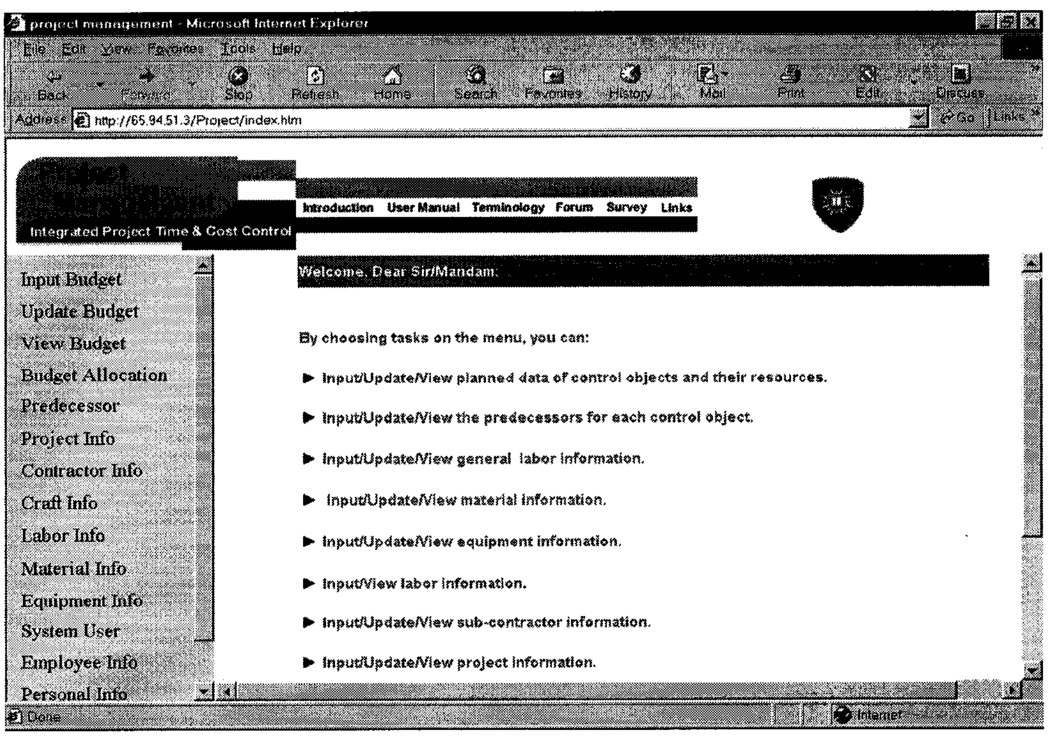


Figure 6. 9 Staff Window

6.5.2 Input Module

This module is used to facilitate data entry and editing. JavaScript, VBScript, and HTML were used to design a set of web-forms for different input, browsing, and editing purposes. A total of 60 specially designed input and edit forms have been developed to support the process of populating the databases. Samples of developed forms can be found in Appendix E. These web-forms serve as the interfaces of the input module. The input module is formed by the operations of the entity classes. As mentioned in Sections 3.2, 3.5, and 4.3, forty-two entity classes are defined in the IT/CC system. They occupy three databases: the project, factor, and reason databases. These databases house project-budgeted and progress data as well as the other necessary data related to users, sub-contractors, labor, material, equipment, predecessors of control-objects, and the assignments of management responsibilities. Each entity class has its corresponding forms for data entry and editing. It also has the operations of data inserting, updating, deleting, and viewing. The attributes of each entity class are described in Sections 3.4.1, 3.5, and 4.3. The object class diagram along with the attributes and operations can be found in Appendix D. To input, update, and/or delete data, the users can trigger the input module using a web form residing in the presentation-tier. Figure 6.10 depicts a sample of web-forms for entering the budgeted data of a control-object. Fig. 6.11 depicts a sample of web-forms for inserting, updating, and/or deleting data. These web-forms are designed to provide simple and user-friendly interfaces.

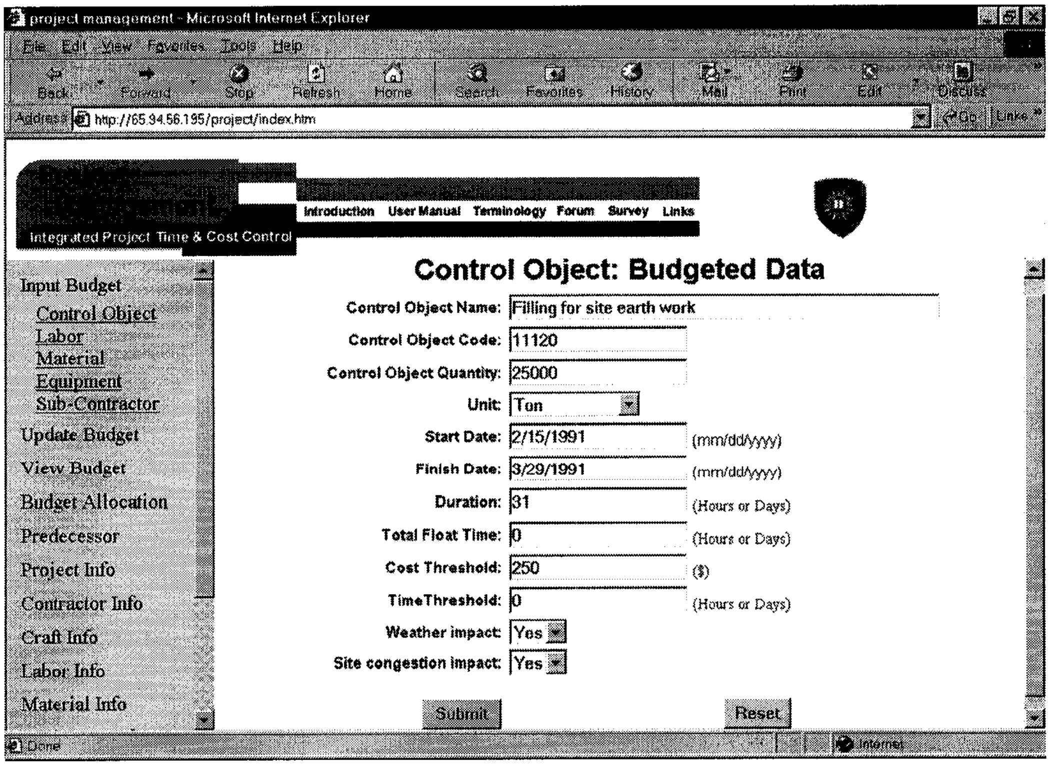


Figure 6. 10 Control-Object Budgeted Data Entry Form

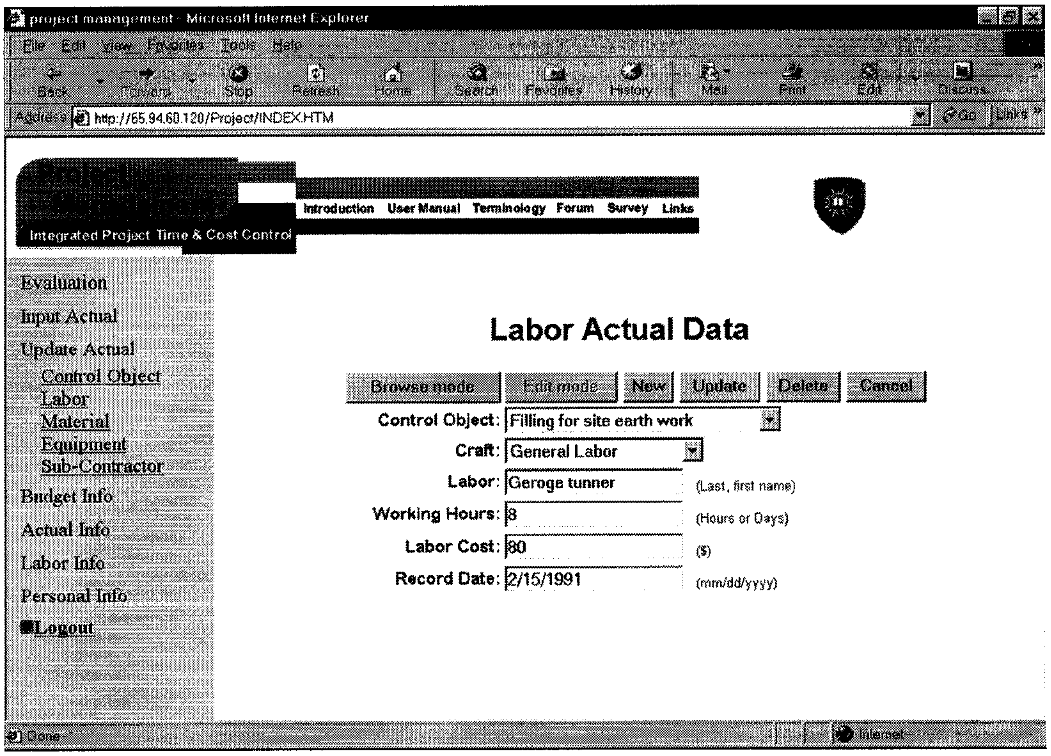


Figure 6. 11 Labor Actual Data Entry Form

6.5.3 Evaluation Module

The evaluation module is the major component of the IT/CC system. It is designed to identify the cost and schedule variances for project control. Performance evaluation can start at project, control-object, and/or resource levels according to user requests. Performance evaluation at project and control-object levels includes the calculation of CV and SV for the project and the control-object being considered. Resource level evaluation includes the calculation of CV, SV, and the ratios of the resource performance indicators. Different reports are generated to support the three levels of project control.

The evaluation module comprises six components which are represented by classes: project evaluation (*PEvaluation*), control-object evaluation (*OEvaluation*), and four classes of resources of labor, material, equipment, and sub-contractor evaluations (*LEvaluation*, *EEvaluation*, *MEvaluation*, and *SEvaluation*). In addition to these six classes, five utility classes, namely the indicators of labor, material, equipment, sub-contractors, and control-object classes (*LIndicator*, *MIndicator*, *EIndicator*, *SIndicator*, and *OIndicator*), calculate the ratio of the indicators and estimate the impact-cost for each terminal indicator. The class diagram of this hierarchy structure module along with the attributes and operations is shwon in Fig. 6.12. The *LEvaluation* class, for example, abstracts the role of labor performance evaluation. It has nine operations such as, GetEvaluation(), CalEV(), IsGreat(), GetImpact(), GetReason(), GetForecast(), GetCrew(), GetCurve(), and CalCurve(). When the user chooses a time period and a control-object to be evaluated, the *LEvaluation* object is created. The GetEvaluation() operation is activated. A set of messages is sent out to retrieve the planned and performed data from the project database during this period. Then, the CalEV() operation is invoked to calculate the cost and schedule variances based on the obtained data. The IsGreat() operation compares the calculated variances with the user-defined threshold values to determine whether the performance is acceptable or not. If the identified variances are less than or equal to the threshold values, the performance is recognized as acceptable. A favorable report is generated to the user. Otherwise, the GetImpact() operation will be activated by the user to estimate the impact-costs for the highlighted indicators according to the equations defined in Section 3.7. The *Lindicator* and *Oindicator* classes are involved in the computing process. In addition, the GetReason() and GetForecast() operations can also be activated by the user to diagnose the reasons for the variances, to recommend corrective action(s), and to forecast duration and cost at future interim horizons and at completion. The GetCrew() operation gets the list of crew members' names. The GetCurve() operation gets the parameters from the CalCurve() operation to draw the earned value curves. A similar procedure is implemented in the *EEvaluation*, *MEvaluation*, and *SEvaluation* classes.

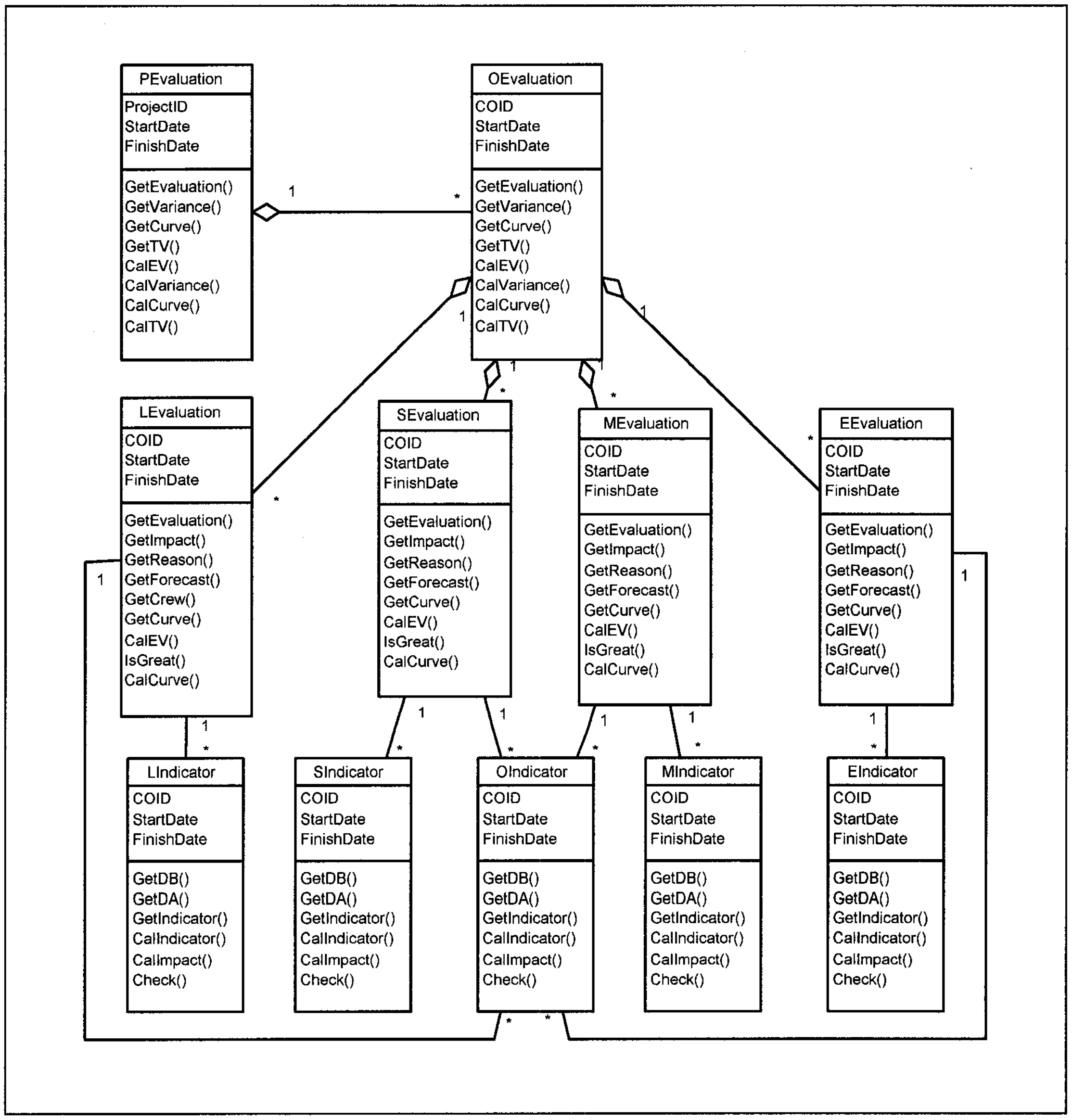


Figure 6. 12 Class Diagram of the Evaluation Component

The *OEvaluation* class abstracts the role of the control-object performance evaluation. It has eight operations such as GetEvaluation(), CalEV(), GetVariance(), CalVariance(), GetTV(), CalTV(), GetCurve(),and CalCurve(). When the manager chooses a time period and a control-object to be evaluated, the *OEvaluation* object is created. The GetEvaluation() operation is activated to summarize its resource level evaluation results by the CalEV() operation. The GetVariance() operation gets the detailed variances for each individual resource from the CalVariance() operation in order to generate the detailed variances report. The GetTV() gets the time variances from the CalTV() operation. The GetCurve() gets the parameters from the CalCurve() operation to draw control-object level earned value curves. A similar procedure is implemented for the *PEvaluation* class, which abstracts the role of project performance evaluation. The performance evaluations at project and control-object levels include the calculation of the earned values of the project and the control-objects being considered. Resource level evaluation includes the calculation of the earned value of individual resource and the ratios of resource performance indicators as discussed in 3.8.

6.5.4 Reasoning Module

The reasoning process is carried out for each individual resource on a daily basis. It includes not only the identification of the reason(s) for unfavorable performance but also the estimation of the impact-cost for terminal indicators. Possible corrective actions, such as "improved design/construction coordination", or "increased work time for current labor", are recommended according to the detected reason(s). Six sub-components, which are represented by different classes, are involved in the reasoning processes: project level reasoning (*PReasoning*), control-object level reasoning (*OReasoning*), and four components of resource level reasoning (*LReasoning*, *EReasoning*, *MReasoning*, and *SReasoning*). The class diagram of this hierarchical structure module along with the attributes and operations can be found in Fig. 6.13. The *LReasoning* class, for example, abstracts the role of labor reasoning. It has five operations such as GetReason(), GetImpact(), GetUser(), CalSource(), and CalAction(). When labor performance is unacceptable, the site manager can invoke the *LReasoning* object. The *GetReason()* operation is then activated. A GetImpact() message is sent to the *LEvaluation* class to get the estimated impact-costs of the terminal indicators on the reporting date. Then, all the problem-source factors associated with the terminal indicators are loaded to the users. The users need to specify the linkage strengths between the indicators and the problem-source factors in a range of 0 to 10. The GetUser() operation holds the user-defined linkage strengths. The values of the linkage strengths are saved in the reason database. The CalSource() operation determines the impact-factors by using a fuzzy binary relation operation and ranks those factors in a descending order. The CalAction() operation recommends the possible corrective action(s) based-on the identified factors by another fuzzy binary relation operation. A similar procedure is implemented in the *EReasoning*, *MReasoning*, and *SReasoning* classes.

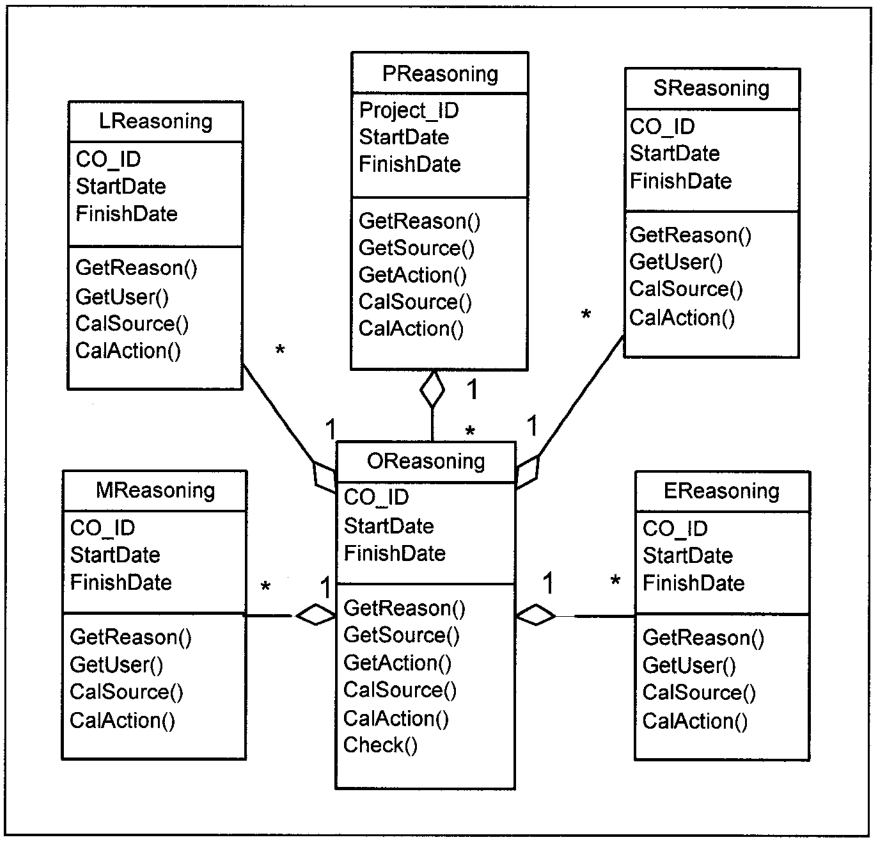


Figure 6. 13 Class Diagram of the Reasoning Component

The *OReasoning* class abstracts the role of control-object performance reasoning. It has six operations such as GetReason(), Check(), GetSource(), CalSource(), GetAction(), and CalAction(). When the control-object performance is unacceptable, the manager or the site manager can create the *OReasoning* object. A GetReason() operation is then activated. Then, the Check() operation is invoked to check the record of the weather situation and site condition of the control-object being evaluated. A GetSource() message is sent out for each type of resources of a control-object to get their resource-level reasoning results. The CalSource() operation aggregates the resource-level reasoning results for a control-object. A similar procedure is implemented for suggesting corrective actions. Similar processes for the *OReasoning* class are implemented for the *PReasoning* class, which abstracts the role of project-level reasoning. Only in-progress project and control-object performances are taken into consideration during the reasoning process. When the evaluated performance is unfavorable, the reasoning module of the IT/CC system can be triggered. The reasoning process starts from the resource level. Control-object reasoning is an aggregation of resource reasoning results. Project level reasoning is an aggregation of control-object reasoning results.

6.5.5 Forecasting Module

The IT/CC system forecasting process starts from the resource level and is set on a daily basis. It comprises six sub-components, which are represented by different classes, such as project level forecasting (*PForecasting*), control-object level forecasting (*OForecasting*), and four components of resource-level forecasting (*LForecasting*, *EForecasting*, *MForecasting*, and *SForecasting*). The class diagram of this hierarchy structure module along with the attributes and operations is shown in Fig. 6.14. The *LForecasting* class, for example, abstracts the role of labor cost forecasting. It has four operations such as GetForecast(), CalMBF(), GetCondition(), and CalPeriod(). The site manager can create a *LForecasting* object. The GetForecast() operation is then activated. A set of messages is sent out to compute the values of the terminal indicators. A CalMBF() operation calibrates the degrees of membership for all input variables based on the MBFs established using statistical analysis of the collected performance data. The users are, then, prompted to specify percentage of deteriorate /improvement for each terminal indicator. The GetCondition() operation holds the user-specified percentage of deteriorate /improvement for the terminal indicators. These values are saved into the reason database for control-object and project-level forecasting purposes. The CalPeriod() operation implements fuzzy inference process, the COS defuzzification method, and the self-learning adjustment method to forecast labor cost at completion and at future interim horizons. A similar procedure is implemented in the *EForecasting*, *MForecasting*, and *SForecasting* classes.

The *OForecasting* class abstracts the role of control-object level forecasting. It has three operations such as GetForecast(), CalPeriod(), and CalDur(). The site manager or the manager can activate the *OForecasting* class. A GetForecast() operation is activated. A set of messages is sent out for all types of resources of a control-object to get their resource level forecasting results. The CalPeriod() operation summarizes the resource-level forecasting results of a control-object at completion and at future interim horizons. The CalDur() operation forecasts duration of a control-object at completion and at future interim horizons in a process similar to labor cost forecasting.

A similar procedure for the *OForecasting* class is implemented for the *PForecasting* class, which abstracts the role of project-level forecasting. Only in-progress project and control-object performances are taken into consideration in the project level forecasting process. At-completion duration and cost are predicted at the project-level forecasting. The forecasting component of the IT/CC system can be invoked by anytime when necessary to predict the project cost and duration at completion and at future interim horizons.

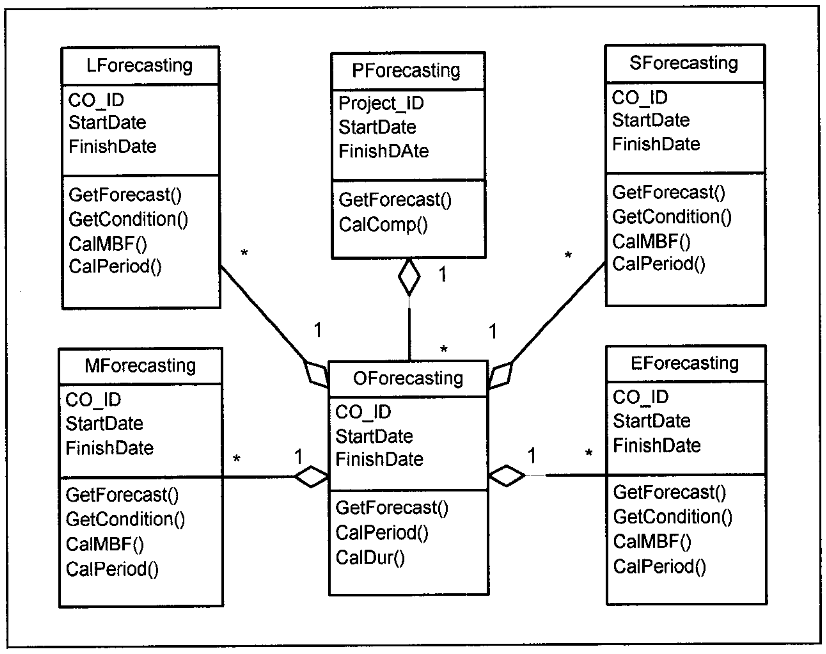


Figure 6. 14 Class Diagram of the Forecasting Component

6.5.6 Reporting Module

This module produces the system output reports. Performance reports can be generated: daily, weekly, monthly, yearly, and/or up to the reporting date. These reports can also be generated to depict progress at all control levels. As such, the system can produce the progress reports at the project (*PReporting*), control-object (*OReporting*), and resource levels (*LReporting*, *EReporting*, *MReporting*, and *SReporting*). The class diagram of this hierarchy structure module along with the attributes and operations is shown in Fig. 6.15.

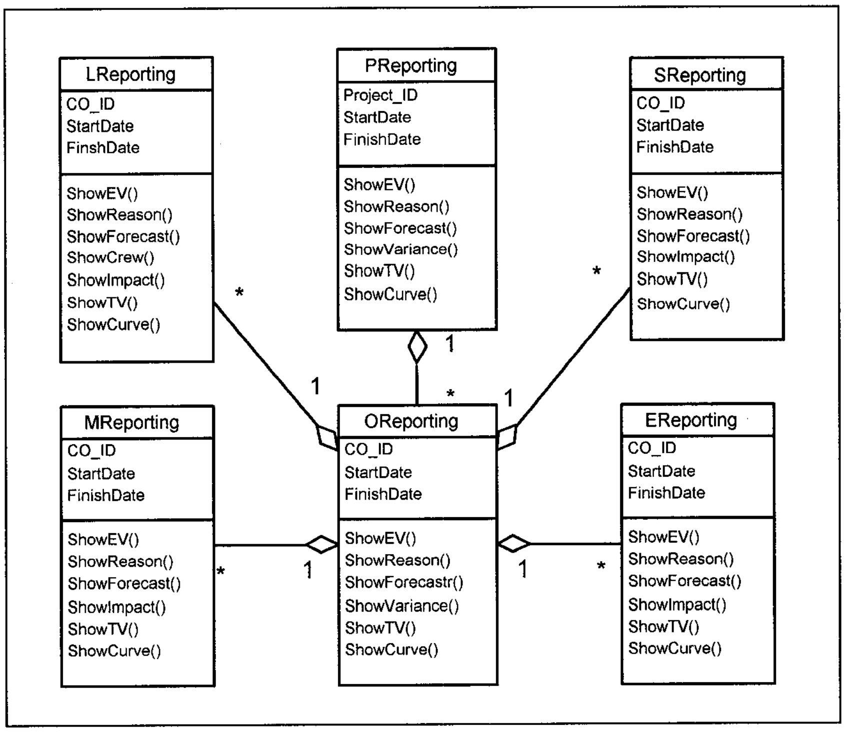


Figure 6. 15 Class Diagram of the Reporting Component

Each reporting class has the function of showing the results of performance evaluation, reasoning, and forecasting. In addition, it also provides the function of showing the schedule status and earned-value curves. At the resource level, the estimated impact-cost for each terminal indicator can be reported. The *LReporting* class can also generate crewmember report for each control-object. All of these reports have a tabular format as well as a graphic format that can be generated in a user-friendly environment. The system provides two ways to view output reports: one is a web page report; the other is a Microsoft Word report, which allows transmission of the performance reports to members of a project team via the e-mail. The Internet-based news board (forum) provides another way for information exchange.

6.5.7 Database

Five relational databases have been developed in the IT/CC system, namely "Project", Factor", "Reason", "Case", and "History" databases. The "Project" database stores planned and actual cost and schedule data for the project being considered. The "Factor" database stores all the resource performance indicators, the problem-source factors, and possible corrective actions. The "Reason" database stores all the user-defined future conditions for forecasting purposes as well as the linkage strengths between the terminal indicators and problem-source factors for reasoning purposes. The "Case" database saves the planned and actual performance data of the control-object, which has a repetitive nature for future reference. Upon project completion, all the information collected in the project database is transferred to the "History" database. All of the databases are set up in the database server. The users from the site and company head offices can access the system simultaneously.

The database design should consider a well-defined scope of work to support tracking and control of individual control units at different levels of reporting. Data structure is essential to the development of an efficient database. It should facilitate the linkages of those individual control units to their respective construction trades. The Entities-Relationship (ER) methodology (Chen 1976) is employed in mapping the project data and in formulating it into above-mentioned databases as shown in Figs. 6.16, 6.20, 6.24, and 6.25. The ER diagram consists of entities, relationships, and attributes. Entities are basic objects with an independent physical or conceptual existence. A binary relationship (i.e. only two entities are related at a time) is used in the designing of the databases. Relationship types involve one-to-one (1:1), one-to-many (1:M), and many-to-many (M: N) relationships. Different types of attributes are used in the development of this database including composite, single-valued, multi-valued, null-valued, and key attributes. Composite attributes form a hierarchy which de-composes a unit into smaller components, each with its own independent meaning, as in a project that is de-composed into control-objects, and control-objects are de-composed into their resources. Single valued attributes are used to identify the names and codes of projects, control-objects, and resources. Multi-valued attributes are used to define the different resources such as cost, working hours, and material quantities. Null valued attributes exist in some cases. It is because of the absence of data, for example, project code. Key attributes are used to distinguish entities. Each entity has a unique identifier called a primary key, where a key can be a single attribute or a combination of several attributes (a composite key). In the developed database, an "auto-number" data type is employed as a primary key for all the entities. The ER diagram serves as a reference for the developer to ensure that all the required data are modeled without any confliction between entities and relationships.

6.5.7.1 Project Database

To keep consistency with the object model proposed in Section 3.2, the "Project" database is modeled conceptually using fifteen entities (12 physical and 3 conceptual) and nineteen relations (see Fig. 6.16). The physical entities represent the *Company*, *Employee*, *User*, *Project*, *ControlObject*, and resources of *Craft*, *Labor*, *Material*, *Equipment*, *SubContractor*, as well as resource *Allocation* and control-object *Progress*. These entities record the internal information of the project being considered such as names of companies, employees, projects, and corresponding budgeted and actual values of labor, material, equipment, and sub-contractors. The *Craft* entity is a newly added entity to describe the types of labor. The *Labor* entity records the personnel labor information. The *Allocation* entity defines the method used in allocation of budgeted data. The *Progress* entity records installed daily quantities. The conceptual entities involve the *Pstatus*, *Status*, and *Predecessor*. The entities record the external information of their respective control-objects. The *Pstatus* records daily site condition including congestion and weather. The *Status* entity records actual start date and finish date of a control-object (assuming that all the resources for a control-object have the same start date and finish date). The *Predecessor* entity defines the relations to other control-objects. A one-to-one relationship exists between *ControlObject-Status* entities and *Employee-User* entities. It means that a control-object can have only one start date and one finish date and one employee can become only one user of the system. A one-to-many relationship exists between the entities of *Company-Employee*, *Company-*

Project, *User-Project*, *User-ControlObject*, *Project-ControlObject*, *Project-PStatus*, *ControlObject-Allocation*, *ControlObject-Predecessor*, *ControlObject-Status*, and *ControlObject-Progress*. This acknowledges that a company can have many employees and projects. A user can control many projects and control-objects. A project may contain many control-objects. A control-object can have many predecessors. Each has its daily status and progress data. A many-to-many relationship exists between the *ControlObject* entity and the resources of *Labor*, *Material*, *Equipment*, and *SubContractor* entities. This means that each control-object has its planned and actual resources and these types of resources can be used by other control-objects. The relationship between *Labor* and *Craft* is designed to record the actual labor cost for that craft. The attributes of the entities and relationships defined for the project database can be found in Appendix F.

The ER diagram can also express the existing dependency of one entity type on another (Chen 1976). For example, the arrow in the relationship of *Project-PStatus* indicates that the existence of the *PStatus* entity depends on the *Project* entity, but the *Project* entity does not rely on the *Pstatus* entity. Therefore, the participation of the *Project* entity is considered partial participation and the participation of the dependent entities is total or full. The *Pstatus, Predecessor*, *Status*, and *Progress* are weak entities because they use the primary key of the *Project* entity as a part of their individual primary key.

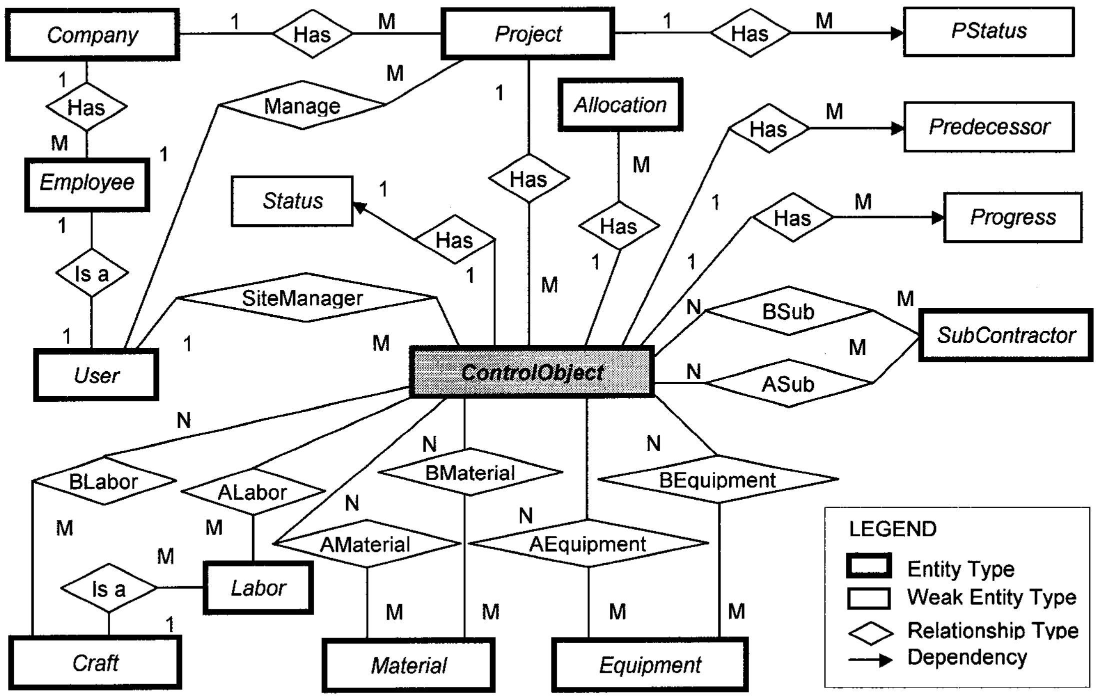


Figure 6. 16 ER Diagram of the "Project" Database

The database as described in the ER diagram shown in Figure 6.16 is implemented using Microsoft Access 2000 environment (see the tables and relationships shown in Figure 6.17). In essence, these tables map the entities, their respective relationships and attributes described above. Fig. 6.18 is the screen snapshot of the "*ControlObject*" table from the "Project" database. The primary key of the table is *CO_ID*. The data type of the primary key is "auto-number", which avoids the redefinition of the key. The detailed list of the attributes for all the defined tables in the "Project" database can be found in Appendix F.

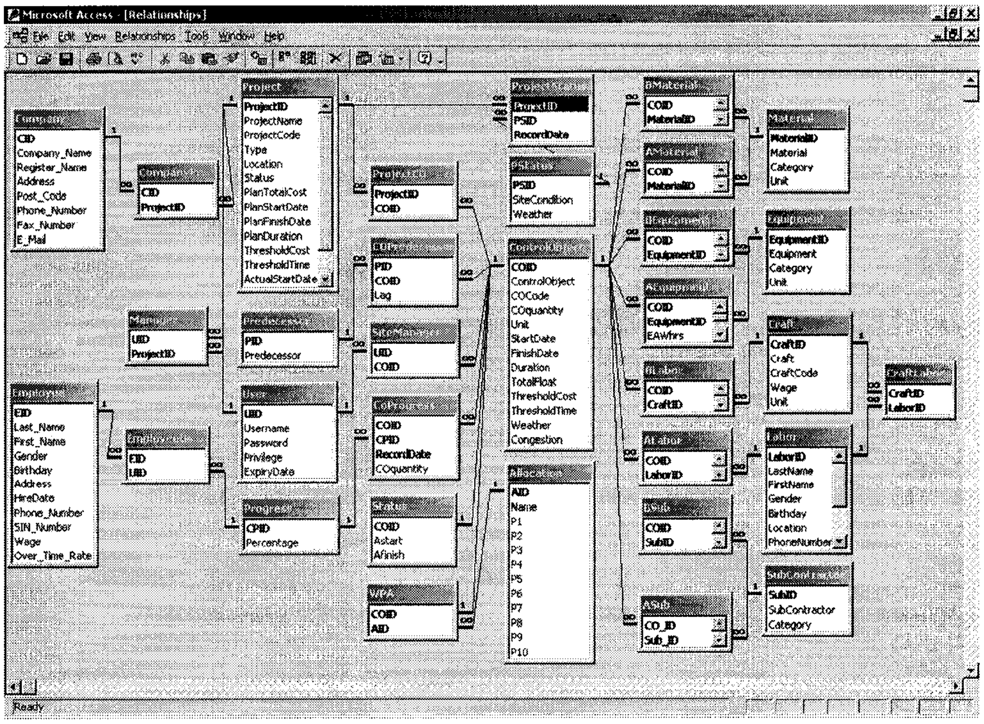


Figure 6. 17 Tables and Relationships of the "Project" Database

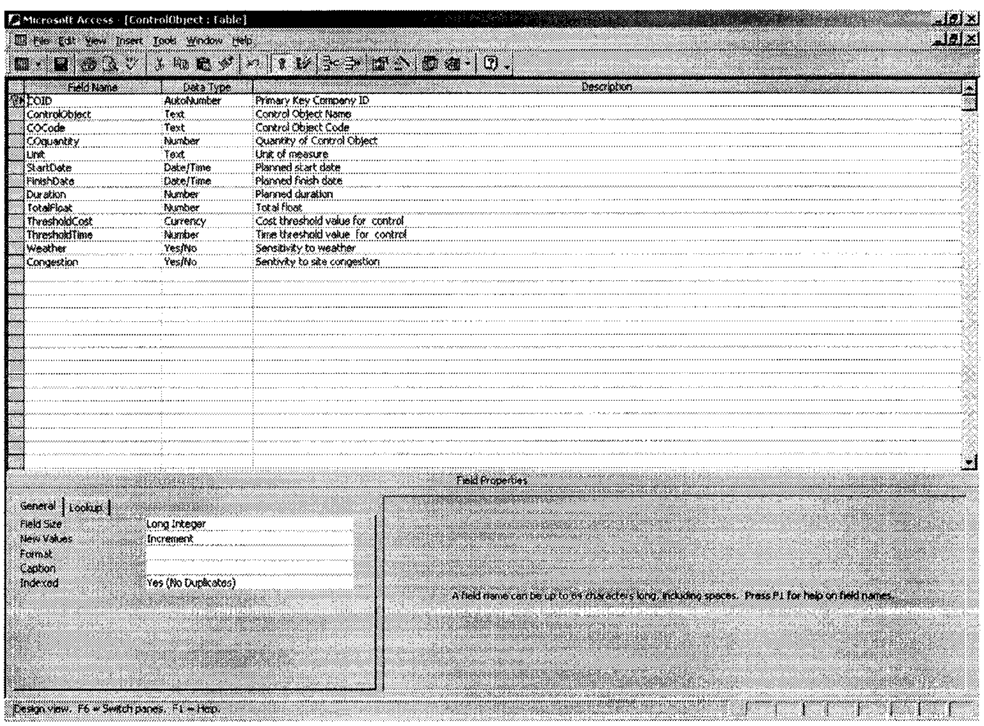


Figure 6. 18 "*ControlObject*" Table from the "Project" Database

6.5.7.2 Factor Database

The "Factor" database stores all the identified problem source factors and corrective actions. There are 7 classes for problem source factors and 7 classes for corrective actions according to the previous discussions in Sections 3.5 and 4.3. Therefore, the E-R diagram of the "Factor" database contains fourteen entity classes as shown in Fig. 6.19. Seventeen relations are established to describe the relationships between the problem source factors and corrective actions according to the discussion in Section 4.4. The attributes of the relations are utilized to store the default values for the reasoning process. Those entities and relations conceptually model the "Factor" database, paving the way for development of the "Factor" database. One-to-many relationships are employed to define all the relationships between these entity classes.

The "Factor" database as described in the ER diagram shown in Figure 6.19 is implemented using Microsoft Access 2000 environment (see the tables and relationships shown in Figure 6.20). Fig. 6.21 is the screen snapshot of the "*MgmFactor*" table from the "Factor" database. The primary key of the table is *MgmFID*. The data type of the primary key is an auto number. The detailed list of the attributes for all the defined tables in the "Factor" database can be found in Appendix F.

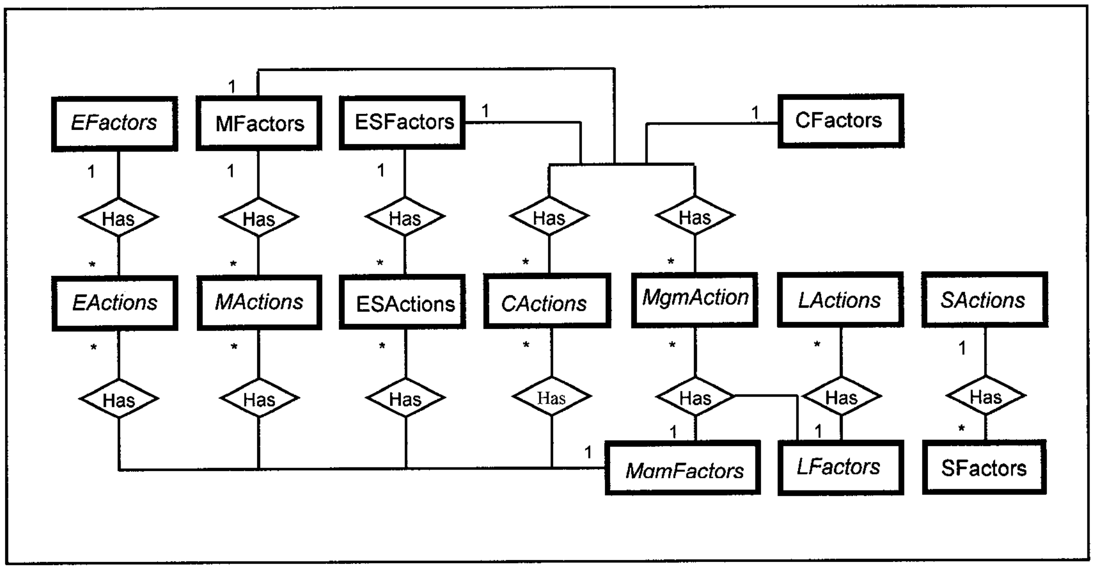


Figure 6. 19 ER Diagram of the "Factor" Database

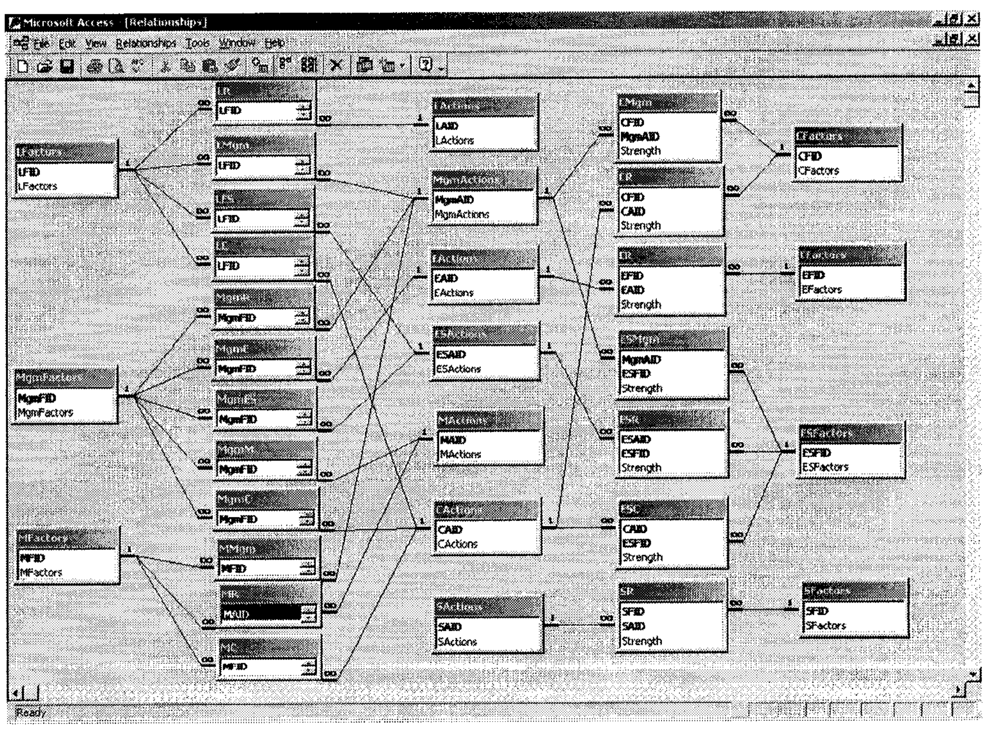


Figure 6. 20 Tables and Relationships of the "Factor" Database

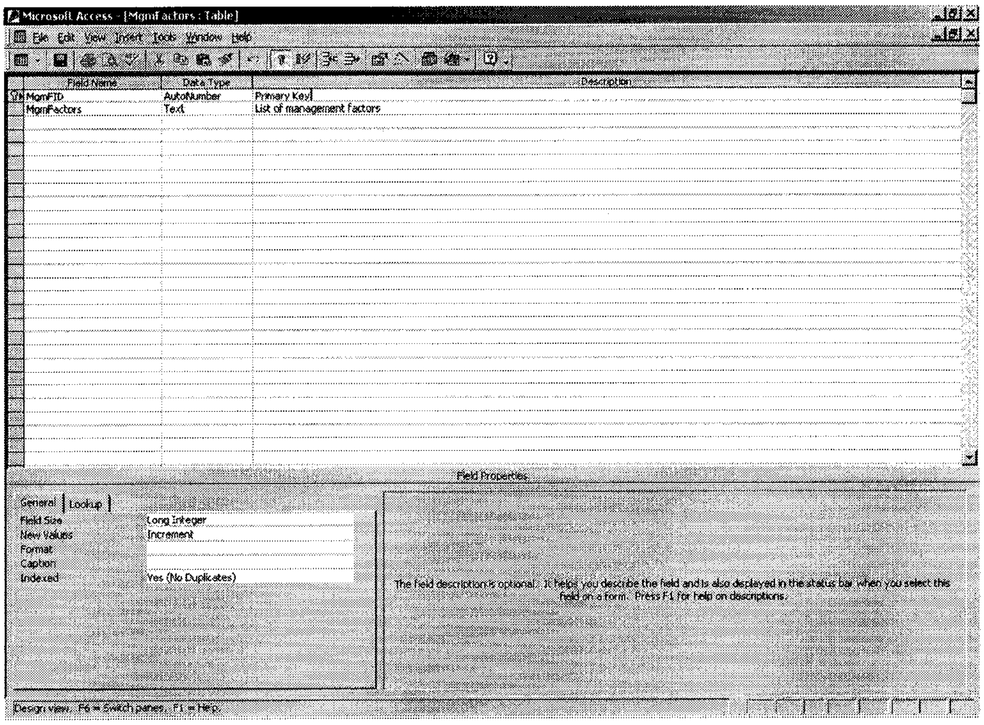


Figure 6. 21 "*MgmFactors*" Table from the "Factor" Database

6.5.7.3 Reason Database

In the reasoning process, the user rated linkage strengths of the problem-source factors for the resources of labor, material, equipment, and sub-contractors are transferred into the reason classes of *LReason*, *MReason*, *EReason*, and *SReason*. The attributes of these classes are the *CO_ID*, and the problem-source factors for each type of resource. Three operations are defined for each of the reason class: *Insert(), Get(),* and *Set(). Insert()* inserts the linkage strengths of the problem-source factors into a database called the reason database. Get() gets the linkage strengths for the problem-source factors by retrieval of the values from the reason database. *Set()* sets up the linkage strengths of the problem-source factors for the reasoning process at control-object and project levels. Similar to the reason classes, action classes of *LAction*, *MActiont*, *EAction*, and *SAction* for resources of labor, material, equipment, and sub-contractors hold the user rated linkage strengths of the corrective actions.

In addition, the forecast classes of *LForecast*, *MForecast*, *Eforecast*, and *SForecast* for the resources of labor, material, equipment, and sub-contractors hold the future indicator trend defined by the user in the forecasting process. The attributes of those classes are the *CO_ID* and the predefined indicators for each type of resource. Similar to the reason classes, three operations are defined for each of the forecast class: *Insert(), Get(),* and Set(). *Insert()* inserts the user defined future improvement/deteroite of the indicators in a range of ±10%, ±25%, ±50%, ±75%, or ±100% to the reason database. It also inserts the predicted time and cost at completion into the reason database. *Get()* gets up the user-specified future trend of the indicators by retrieving the values from the reason database. *Set()* sets the user-specified future trend of the indicators for the forecasting process at control-object and project levels. The above-mentioned eight classes and the control-object class form the object model for the reason database as shown in Fig. 6.22.

One-to-many relationships are employed to define all the relationships between those entity classes. The corresponding E-R diagram of the "Reason" database can be found in Fig. 6.23. It is modeled in eight entities and eight relationships. Fig. 6.24 is the implemented ER diagram of the "Reason" database in Microsoft Access 2000 environment. Fig. 6.25 is the screen snapshot of "*LReason*" table from the "Reason" database. *LRID* is the primary key of the table. The factors of the "*LReason*" table, for example, record all the labor problem-source factors identified in the classes of *ESFactors*, *CfFctors*, *MgmFactors*, and *LFactors* discussed in Section 3.5. The detailed list of the attributes for all the defined tables in the "Reason" database can be found in Appendix F.

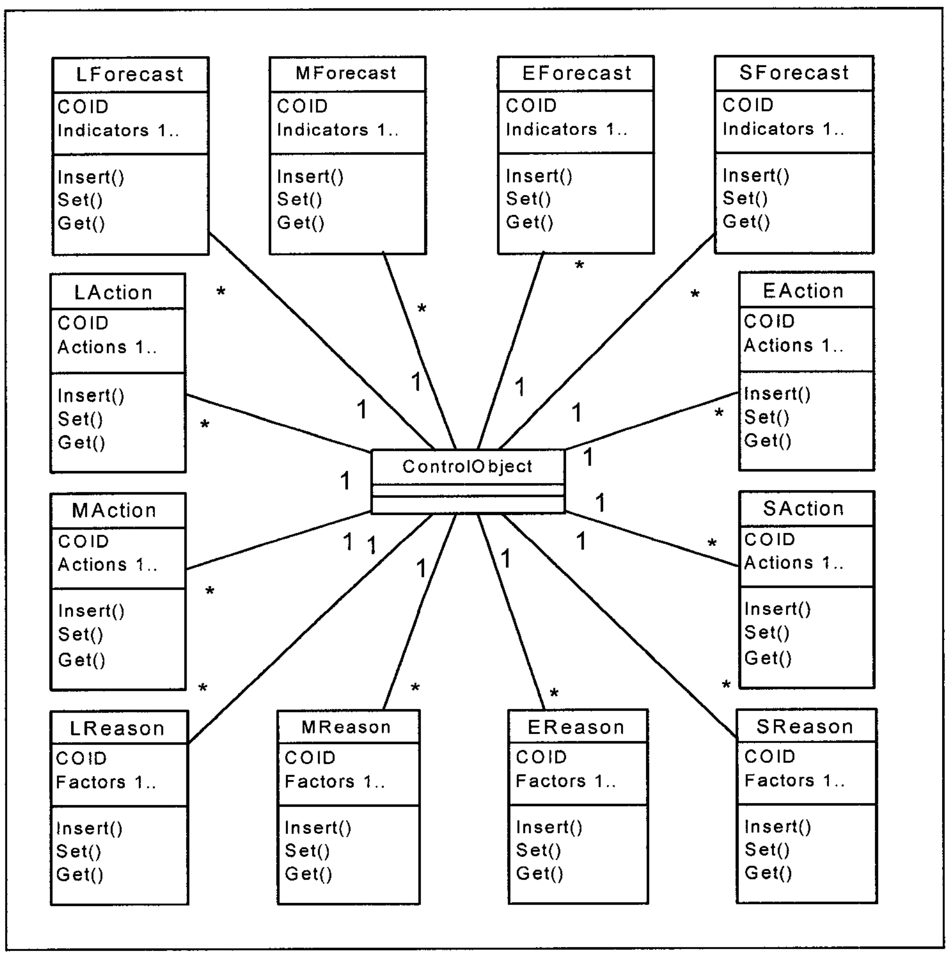


Figure 6. 22 Object Model of the "Reason" Database

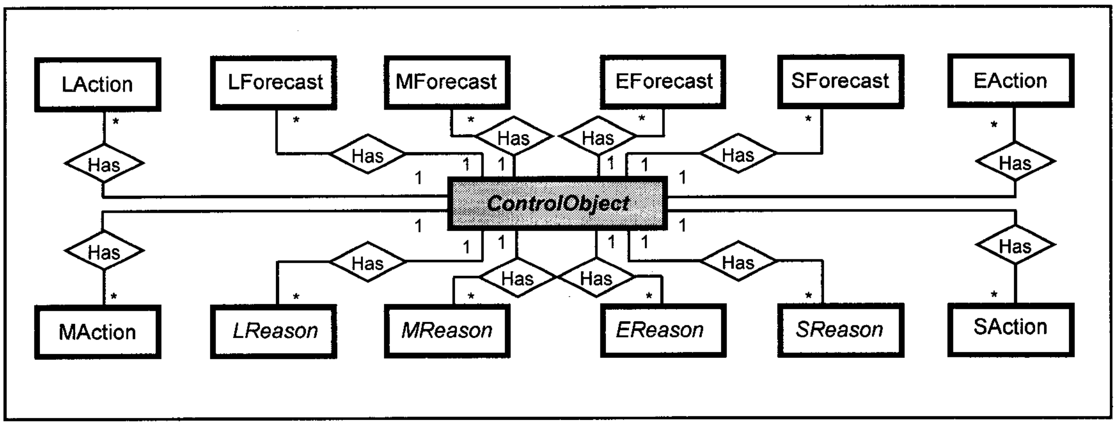


Figure 6. 23 ER Diagram of the "Reason" Database

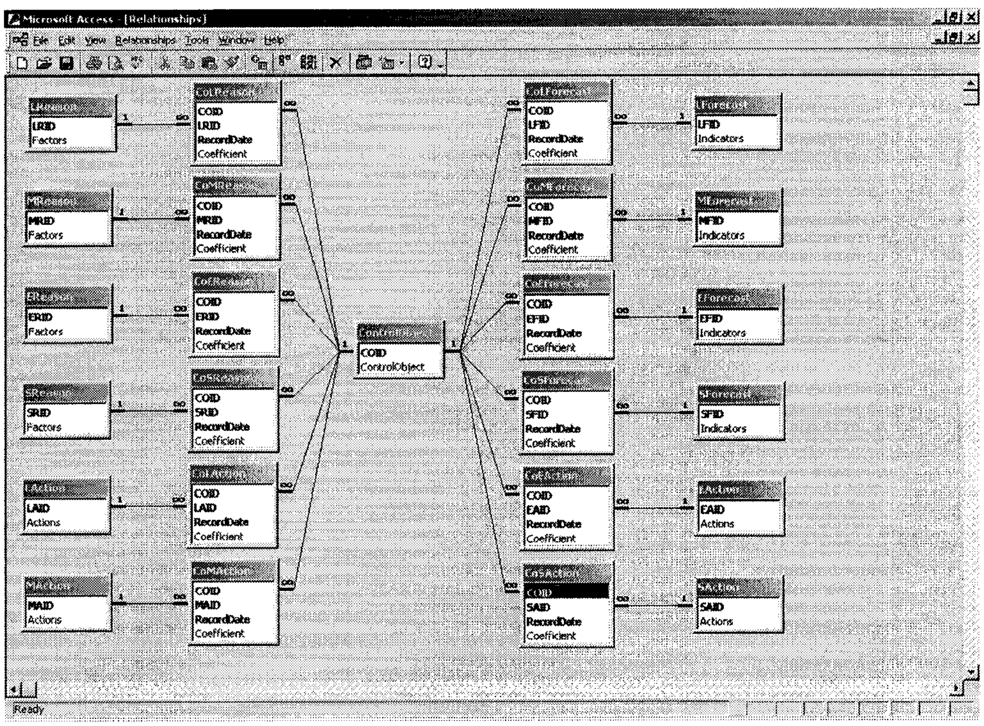


Figure 6. 24 Tables and Relationships of the "Reason" Database.

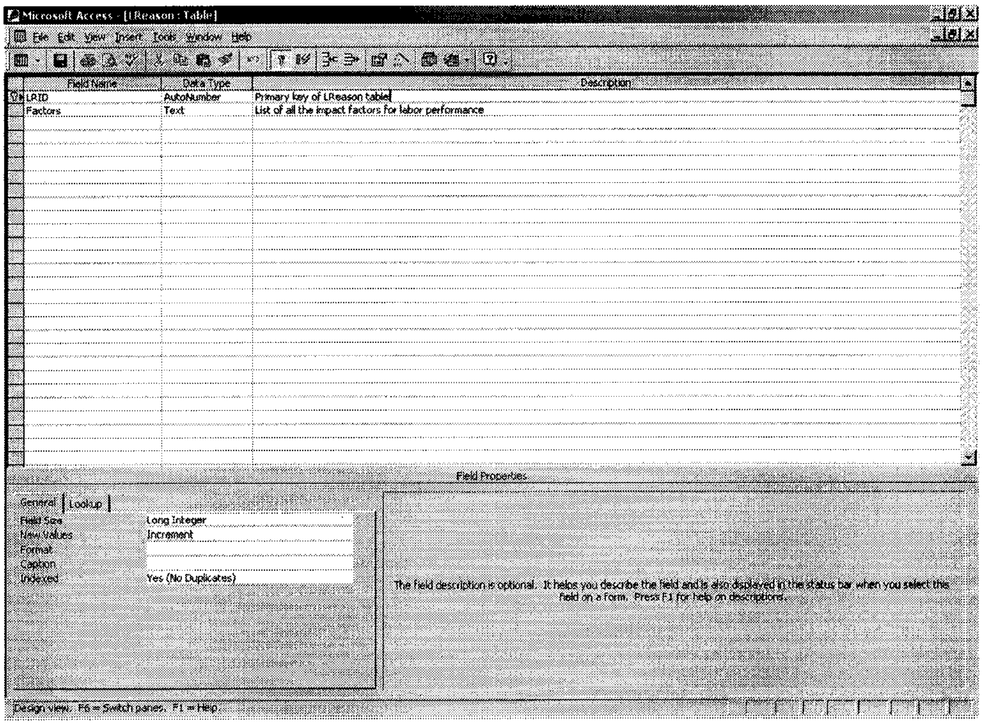


Figure 6. 25 "*LReason*" Table from the "Reason" Database

6.5.7.4 Case Database

The "Case" database includes partial component of the "Project" database and is modeled conceptually using nine entities and eleven relationships as shown in Fig. 6.26. The nine entities include eight that are physical and one that is conceptual. The physical entities represent the *ControlObject*, the resources of *Labor*, *Material*, *Equipment*, *Subcontractor* as well as the resource *Allocation* and the *Progress* of construction. It also includes the *Craft* type. The conceptual entity represents the control-object *Status*. One-to-one, one-to-many and many-to-many relationships are employed to define all the relationships between the entities. The case database as described in the ER diagram shown in Figure 6.26 is implemented using a Microsoft Access 2000 environment (see the tables and relationships shown in Figure 6.27). The detailed list of the attributes for all the defined tables in the "Case" database can be found in Appendix F. The structure of the "History" database is the same as that of the "Project" database.

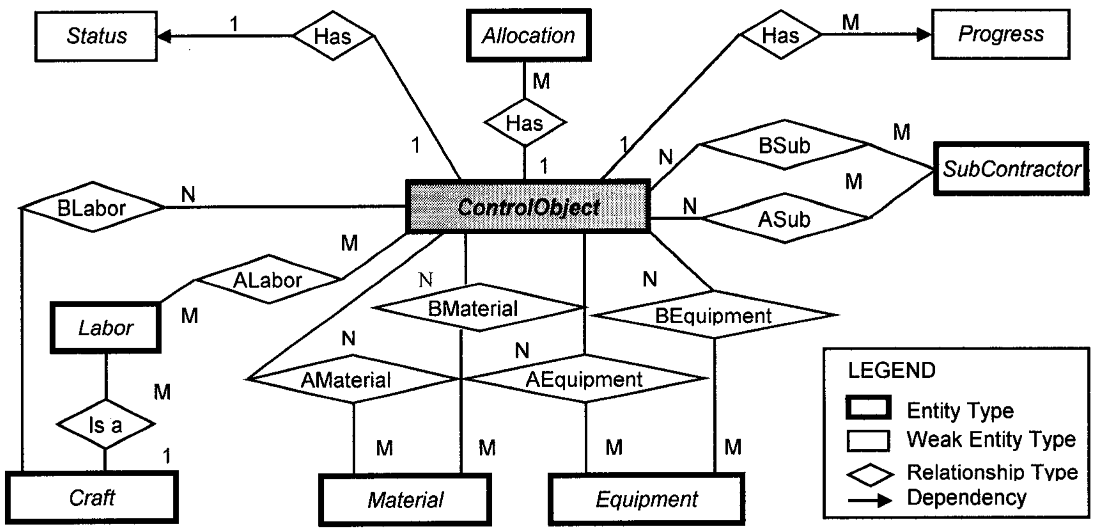


Figure 6. 26 ER Diagram of the "Case" Database

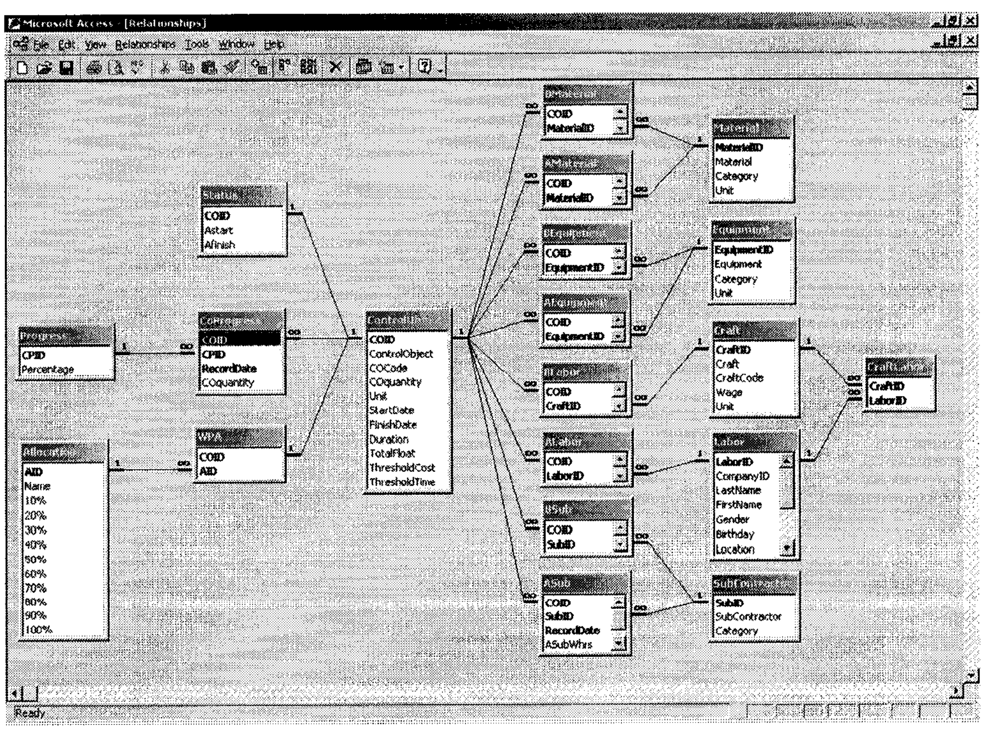


Figure 6. 27 Tables and Relationships of the "Case" Database

6.6 Summary

The structure of the IT/CC system fits well with the Three-Tier Client Server system. The IT/CC system comprises seven major components: user interface, input/editing, evaluation, reasoning, forecasting, reporting, and database. The presentation-tier handles user interfaces that provide system communication with the users; the data-tier encapsulates system data and the middle-tier software implements all the proposed system functions designed in the system components. Four access rights have been assigned to the developed IT/CC system, namely, those of the general manager, manager, site manager, and staff. The input/edit component helps users to input, update, and delete project planned data and actual performance data. The evaluation component executes the user's request to perform the control task at the project, control-object, and/or resource levels. Whenever the variances exceed the predefined threshold values, the reasoning component can be invoked to find the reason(s) for the variances. Then, the forecasting component can also be triggered to predict future cost and duration. The "Project" database is developed to store the project data; the "Factor" database stores the identified problem-source factors and possible corrective actions; the "Reason" database saves the user-specified values such as the linkage strengths, problem-source factors, corrective actions, and the future cost and duration; the "Case" database stores the repetitive control-objects data for future reference; the "History" database stores the previous project data. These databases provide a data sharing environment for all levels of the project control. Object-Oriented concepts are applied to the system design. Class diagrams describe the attributes and operations involved in the system components.

SYSTEM IMPLEMENTATIONS AND VALIDATIONS

7.1 General

This Chapter describes the implementations, the validations, and the uses of the prototype IT/CC system. It aims at demonstrating that the developed models, according to the description of them in previous chapters and after the implementation of them, can achieve their stated objectives. Typical implementation scenarios, represented by developed sequence diagrams, are introduced in this Chapter. A numerical example is utilized to validate the developed methods and to demonstrate the use of the developed prototype.

7.2 Implementations

A Three-Tier Client/Server computer application is developed and coded using Java Applet and Active Server Pages (ASP). The presentation-tier handles the communication between the system and the user. The application logic/middle-tier implements the developed major functions of the IT/CC system such as performance evaluating, reasoning, and forecasting. The data-tier holds the project-related data that support the implementation of the system. The components and processes involved in each developed application are introduced as follow. The implementation scenarios for each use-case are developed and represented by sequence diagrams.

7.2.1 Performance Evaluation

The developed prototype performance evaluating system is the framework of the IT/CC system. It runs on Window NT or Window 2000 series server environment. The structure of the prototype evaluation processes is shown in Fig. 7.1. The presentation-tier includes the components of user interface. The middle-tier includes the developed evaluation module and the reporting module. It houses all the developed evaluation functions. The data-tier stores the "Project", "Case" and "History" databases. The evaluation process can be started at project, control-object and resource levels when users place a request from the presentation-tier. Then, the planned and actual data of the project are retrieved from the project database to calculate the earned-value variables for an individual resource. These variables can be summarized and sent to control-object level by adding the values of the same variables for different types of resources within a control-object. Again, the variables can be summarized and sent to project level by adding the values of the same variables for control-objects within a project. The calculated CV and SV are assessed based on the user-defined threshold values. If the performance is acceptable, a favorable report is generated; otherwise, a poor performance report is generated. If the poor performance is at resource level, the resource performance indicators will be further assessed. The impact-costs of the highlighted indicators are estimated and reported. The evaluation reports can be generated at project, control-object, and resource levels to satisfy different control requirements. Also, the evaluation reports can be produced on a daily, weekly, monthly, yearly, and to-date basis. Daily performance data are used to generate the evaluation reports for that day; the weekly, monthly, and/or yearly evaluation reports are generated based on the performance data during that period; the to-date evaluation reports are generated based on the accumulation of the daily performance data.

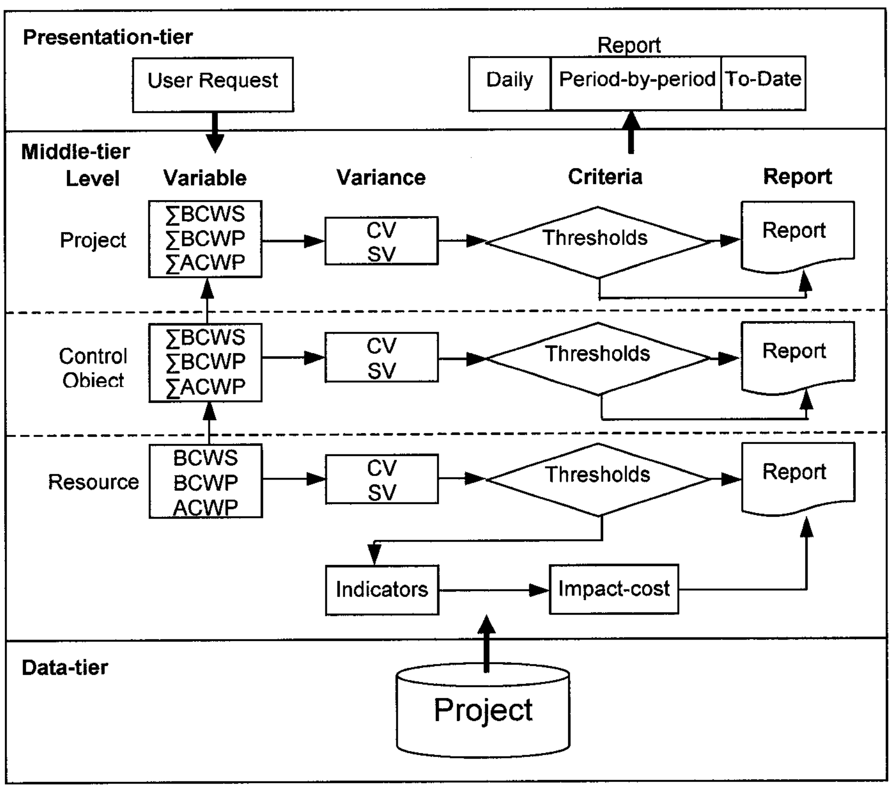


Figure 7. 1 Proposed Evaluation Processes

Sequence diagrams of a use-case are developed as shown in Figs. 7.2, 7.4,7.6 and Appendix E to represent the implementation scenarios of the developed prototype system. A sequence diagram is an interaction diagram that shows how operations are carried out -- what and when messages are sent. It is organized according to implementation time. The time progresses as you go down the page. The objects involved in the operation are listed from the left to the right of the figure according to their accumulated time in the message sequence. Each dotted vertical line is a lifeline, representing the time during which an object exists. Each arrow is a message call. An arrow goes from the sender to the top of the activation bar of the message on the receiver's lifeline. The activation bar represents the duration of execution of the message. Sequence diagrams give dynamic views of a model. They focus on the messages involved in completing a single process and present the mechanism for actions inside the model.

The three-leveled performance evaluations are represented by *Evaluating-Project*, *Evaluating-Object*, and *Evaluating-Resource*, use-cases as described in Section 6.3. An implementation scenario of the *Evaluating-Resource* use-case of labor, for example, is developed and shown in Fig. 7.2. It indicates that the labor performance evaluation starts when the site manager chooses a time period and places a request of evaluation by invoking the GetEvaluation() operation at the site manager window. The GetEvaluation() operation sends a Get() message to the *ControlObject* and the *Progress* classes respectively to get the planned quantity data and actual quantity of the control-object being evaluated. The obtained data are utilized to calculate PCa and PCs of that control-object. Then the *LEvaluation* class sends a Get() message to the *Blabor* and the *Allocation* classes to get the planned labor data and the method of budgeted data allocation for the control-object. The obtained data are utilized to calculate BCWS and BCWP for labor resource. Another Get() message is also sent to the *Alabor* class to get ACWP for labor. A self-call of the CalLEV() operation is issued by the LEvaluation class to calculate labor cost and schedule variances according to the obtained data. Then, the IsGreat() operation is invoked by another self-call to check if the labor performance is acceptable or not. The results are sent to the user interface by the ShowEV() operation in the Reporting class. If the performance is acceptable, there are no any other reports that can be viewed by the user. Otherwise, the user can place a request at the LEvaluation class to invoke the GetImpact() operation. A message of Check() is sent by the LEvaluation class to the LIndicator class to check the status of labor performance indicators. The LIndicator sends a GetD() message to the Blabor and the Alabor classes to get the detailed planned and actually performed data of that control-object. Then, the ratios of labor performance indicators are computed by the CalIndicator() operation declared in the LIndicator class. If the IsEqual() operation result is negative, that indicator is highlighted. The CalImpact() operation is called to estimate the impact-cost of the indicator on the basis of the developed equations discussed in Section 3.5.2.1. The estimated indicator impact-costs are sent to the ShowImpact() operation to generate a variance analysis report for the user. Similar procedures are invoked for the OIndicator class from steps 17 to 20 as shown in Fig. 7.2.

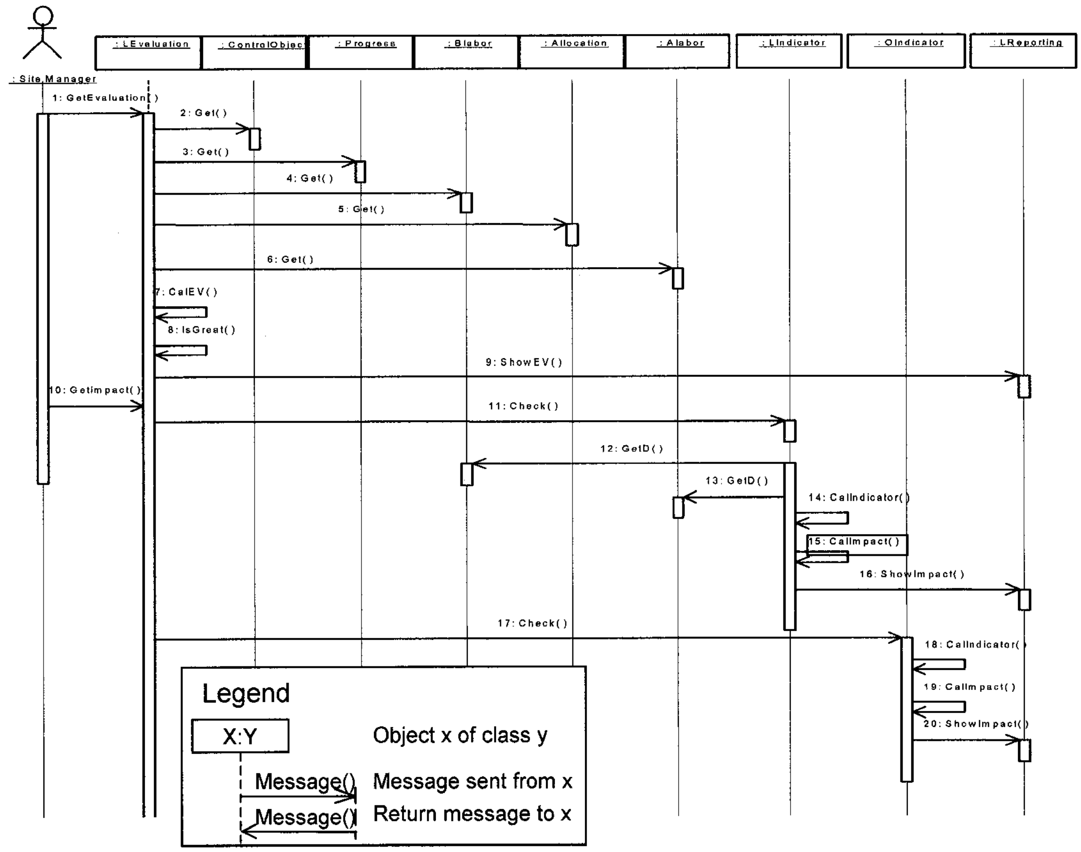


Figure 7. 2 Sequence Diagram for Labor Performance Evaluation

7.2.2 Reasoning

The developed reasoning process has been incorporated into the prototype IT/CC system. It runs on Window NT or 2000 series server environment. The structure of the prototype reasoning process is shown in Fig 7.3. The presentation-tier includes the components of user interface. The middle-tier includes the developed reasoning module and the reporting module. It houses all the developed reasoning functions. The data-tier stores the “Factor” and “Reason” databases. The reasoning process starts from the resource level of an individual control-object when the user places a request. The whole process can be divided into two steps. The first step identifies problem source factors (f_k) according to highlighted indicators (s_i). The second step suggests corrective actions (a_m) based on the determined problem source factors. The user-specified degree of linkage strengths among the highlighted indicators, the problem source factors, as well as the corrective actions are saved into the "Reason" database. Similar steps are implemented for project and control-object levels' reasoning. The control-object level reasoning aggregates the problem source factors and corrective actions identified respectively for all the resources of the control-object using fuzzy union operation. The reasoning reports can be generated at project, control-object, and resource levels to satisfy different control requirements. They can also be produced on a daily, weekly, monthly, yearly, and to-date basis.

The three-leveled reasoning process is represented by *Reasoning-Project, Reasoning-Object,* and *Reasoning-Resource* use-cases as described in Section 6.3. The *Reasoning-Resource* use-case includes the reasoning processes for resources of labor, material, equipment, and sub-contractor, respectively. An example of the implementation scenario for labor reasoning is developed and shown in Fig.7.4. The labor reasoning process starts when the site manager places a request of reasoning by invoking the GetReason() operation of the *LReasoning* class for an individual control-object. The GetReason() operation sends a GetImpact() message to the *LImpact* class to get the estimated indicator impact-costs for a time period. Then, it sends a Get() message to the *LFactors, ESFactors*, *MgmFactors*, and *CFactors* classes to get all possible labor-problem source factors. Then, a Check() operation is sent to the *OReasoning* class to examine the record of the weather situation and site condition in order to determine the linkage strength between highlighted indicators and problem source factors using the default setting of the rules. A Get() message is sent by the *OReasoning* class to the *Pstatus* class to obtain the record of the weather situation and site condition. The GetUser() operation holds the user-specified linkage strengths between the highlighted indicators and the problem source factors. The user-specified values are Set() to the *LReason* class. The *LReason* class issues a self-call that inserts the values into the *Reason* database. The *LEvaluation* class then, issues a self-call of the CalSource() operation to calculate the problem sources for labor performance using fuzzy binary relation operation as defined in Equation (4.11). Similar processes are implemented to recommend corrective actions. A reasoning report is generated by the ShowReason() operation in the *Reporting* class to describe the identified problem source factor(s) and the suggested corrective action(s) for the user.

Taking into account the unique nature of a project, the developed reasoning system has an open architecture that allows users to make use of the developed generic form of reasoning in adopting it to domain-specific reasoning by specifying their own reason(s)/action(s) during the reasoning processes.

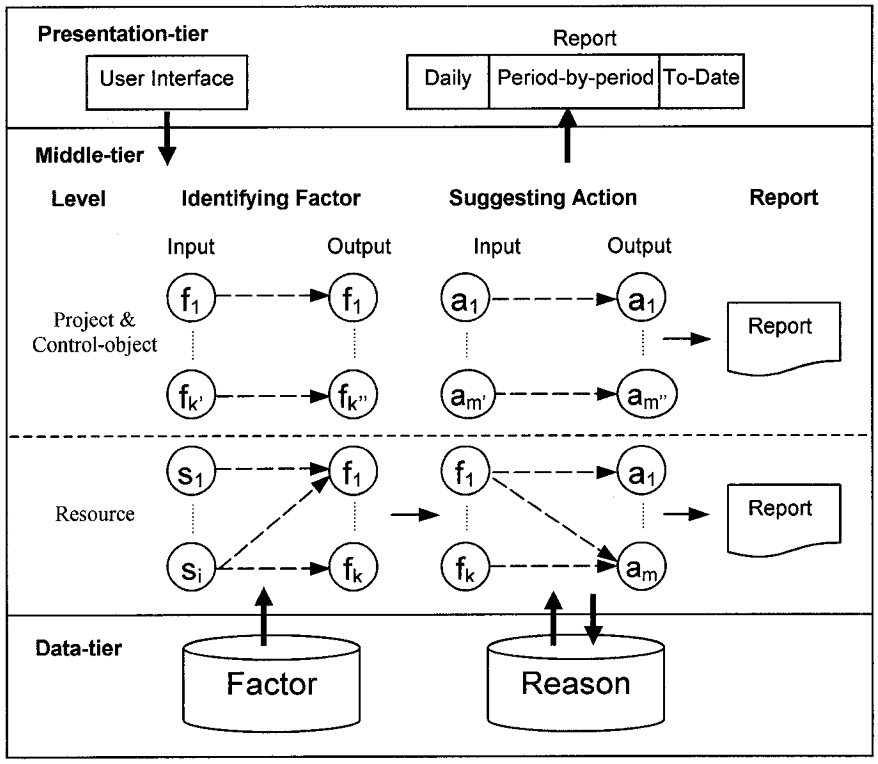


Figure 7. 3 Proposed Reasoning Processes

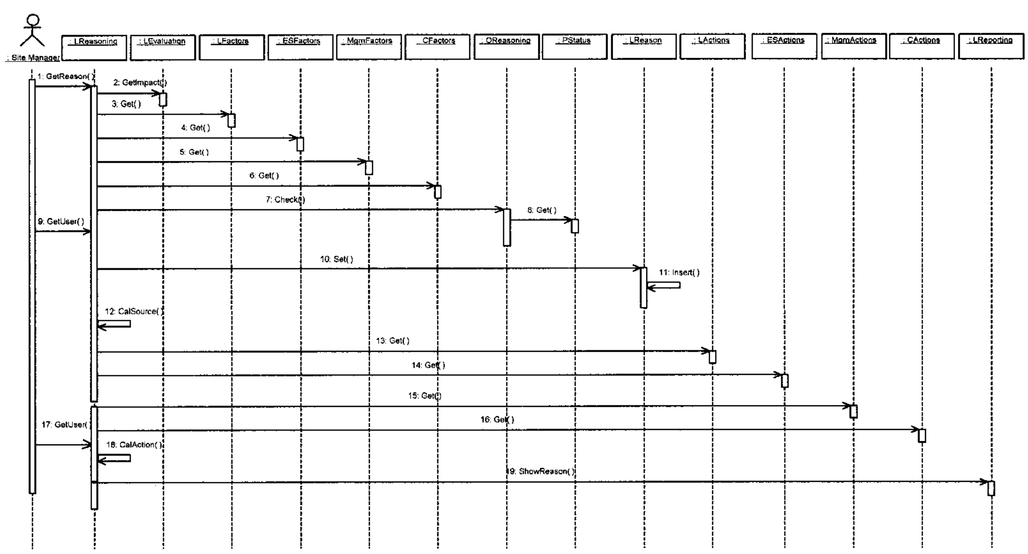


Figure 7. 4 Sequence Diagram of Labor Reasoning

7.2.3 Forecasting

The developed forecasting methods have been incorporated into the prototype IT/CC system. It runs on Window NT or Window 2000 series server environment. The prototype has a Three-Tier Client/Sever architecture as shown in Fig. 7.5, coded using ASP (Active Server Page) and HTML (Hypertext Markup Language). The middle-tier includes the developed forecasting module and the reporting module. It houses all developed forecasting functions. The data-tier stores the "Project" and "Reason" databases, while the presentation-tier focuses on the user interface.

The three-leveled forecasting method is represented by *Forecasting-Project, Forecasting-Object,* and *Forecasting-Resources* use-cases as described in Section 6.4. *Forecasting-Resources* use-case includes the forecasting methods for resources of labor, material, equipment, and sub-contractor, respectively. An example of the implementation scenario for labor cost forecasting is developed and shown in Fig.7.6. The labor cost forecasting method starts when the site manager places a request for forecasting by invoking the GetForecast() operation in the *LForecasting* class. The *LForecasting* class sends a Get() message to the *OIndicator* class to get the values of control-object indicators from the commencement of the work till the evaluation date. The *OIndicator* class sends a Get() message to the *ControlObject*, the *Progress*, and the *Allocation* classes respectively to get the planned and the actual performance data from the commencement of the work till the evaluation date. Then, the *OIndicator* class issues a self-call to calculate the required values of the indicators. Similar methods are implemented for the *LIndicator* class. After all the values of the indicators are obtained, the *LForecasting* class issues a self-call to construct the MBFs for the indicators by undertaking a statistic analysis of the collected performance data. User is prompted to enter percentage of improvement/deteriorate from current value for each indicator. The GetCondition() operation holds the user's input. The CalPeriod() and the CalComp() operations predict labor cost at completion and at the interim future work progress horizons utilizing fuzzy inference process. The obtained forecasting results are carried out to the user by the ShowForecast() operation in the *LReport* class. The implementation scenarios for material, equipment and sub-contractors are similar to that of labor evaluating, reasoning, and forecasting, and can be found in Appendix G.

With consideration of the unique nature of each project, the developed forecasting system has an open architecture that allows users to apply their judgment and use their experience by introducing percentage of "improvement/deteriorate" from current value (i.e. to-date) for each input variable. The developed method also allows users to provide their own input and judgment in forecasting cost and duration. All user-defined values are saved into the "Reason" database later use in forecasting at project and control-object levels. A set of interactive screens has been developed (see Fig. 7.33 and Appendix I) to assist users in performing the functions described above.

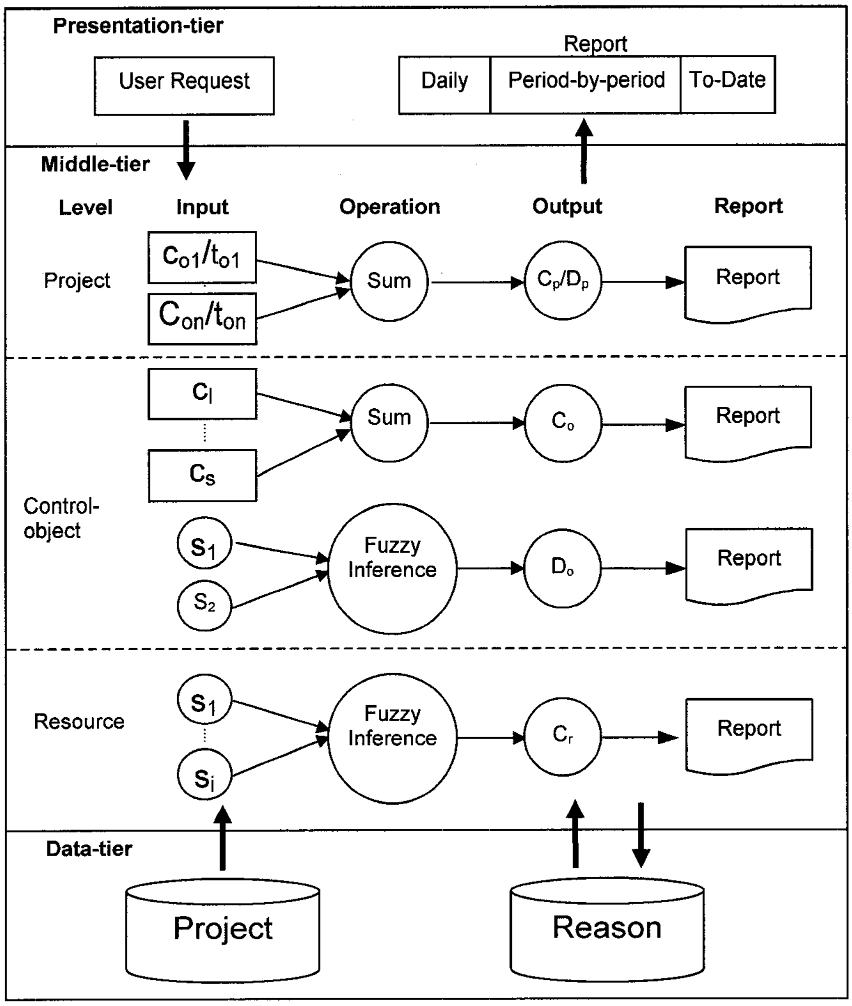


Figure 7. 5 Proposed Forecasting Method

The prototype IT/CC system integrates the developed performance evaluating, reasoning, and forecasting sub-systems. By taking advantage of the Internet, the prototype IT/CC system provides a real-time collaborative environment that allows members of the project team access to tracking construction site performance simultaneously and to taking control functions immediately.

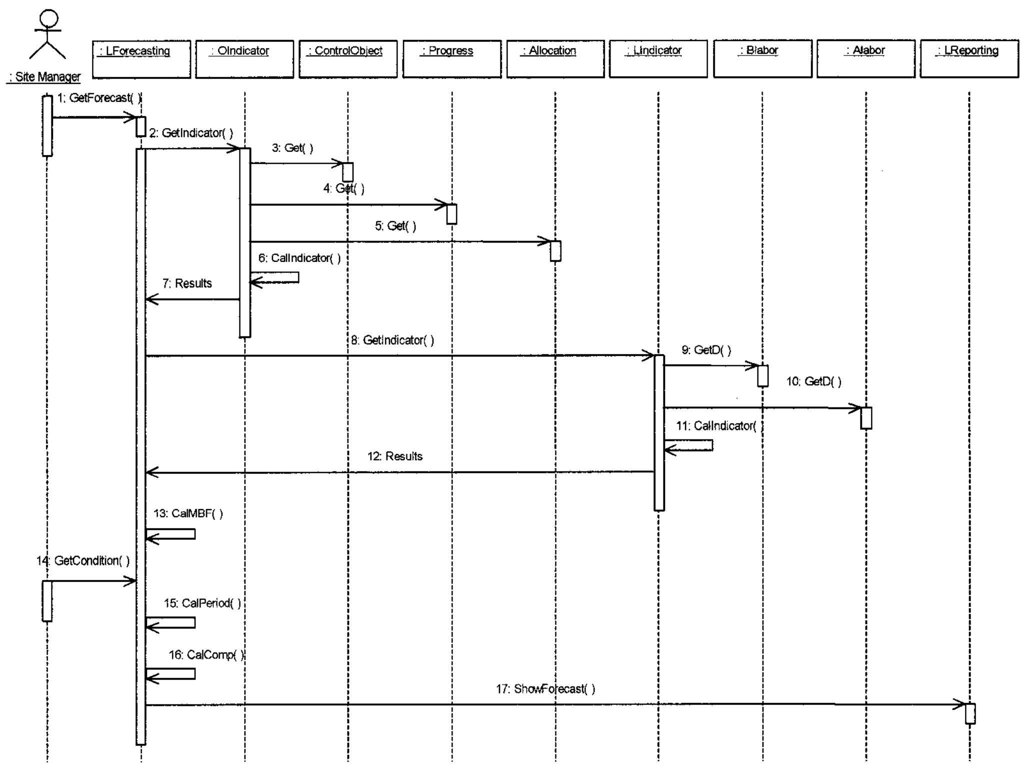


Figure 7. 6 Sequence Diagram of Labor Forecasting

7.3 Validation by Example Application

A numerical example drawn from the literature is worked out to demonstrate the use of the developed IT/CC system and to validate it. The validation process includes the test of the prototype software regarding its code and the functions of the IT/CC system, which are in common practice in most construction firms. It also includes the test of the proposed performance evaluation method, the reasoning processes, and the forecasting method. Detailed descriptions of those validations along with the demonstration of the uses of the system are discussed in the following subsections.

7.3.1 System Validations

Validation is one of the major processes for system development. The objectives of the validations ensure that the developed system conforms to the system requirements and that the system implementation has met the expected functionalities. It also demonstrates that the software appears to be working as stated in the specifications. The data collected through validation can provide an indication of the software's reliability and quality. Usually, a validation process includes two parts: code inspection and module verification.

7.3.1.1 Code Inspection

Code inspection aims to ensure that the developed code satisfies the specified requirement. This includes making sure that the input data are used correctively and the expected output data are presented. All variables and constants are defined properly. There are not any redundant software components. The overall structure or architecture of the code is readily apparent. Any global or shared variables are carefully controlled. Several tools that exist within the development software (Microsoft InterDev) are used in the process. The "debug" tool allows the developer to dynamically follow the program flow step by step to discover any logical error. The "query builder" tool helps the developer build correct data query. The run time error message helps to eliminate any syntax validation that ensures any saved program code is syntactically correct.

7.3.1.2 Module Verification and Validation

The evaluation, forecasting, reasoning, and reporting modules are validated at two different stages:

1. Design Verification

Design Verification is to ensure that the developed modules are in accordance with that described in Chapters 3, 4, 5, and that they satisfy the requirements described in Section 6.1.1. The design verification proceeds in a top-down manner. It includes the following aspects: the design consistency with the functional requirements; the cohesive and logical system architecture or structure; the accuracy and completion of the specification for each function; the completeness and correctness of design; the identification and definition of all external uses of shared data; the conflicting uses of data areas; the corrective decisions logic, algorithm and processing; internal component logic error handling, etc.

2. Integration Validation

Integration Validation is to ensure that components link and functions work together appropriately. It focuses on interactions among components, modules, and sub-systems. The bottom-up strategy will be used to conduct the integration validating. Each individual component, module, and/or subsystem is validated independently. Then, the correctness and effectiveness of functional interactions and compatibility between interfaces are validated. A Microsoft Excel file with the same mathematical equations developed in the modules mentioned in Chapters 3, 4, and 5 is used to verify the computational results produced by the modules.

7.3.2 Data Entry Validations

Entering the project data into the web-based database is a one-time process, which should be as simple as possible for the user and should ensures few errors in the database. During the construction process, the actual cost and work progress are measured by the foreman on a daily basis. These data are entered into the system via web page interfaces and are stored in the web-based project database. Different methods of verification and validations were used in the developed ITC/C system including:

1. Validation by Function

Specially designed JavaScript and/or VBScript functions embedded in the web page interface are used to verify data type, length, and format. Whenever new data are entered, the system automatically checks the data format. If there is a data error or missing data, the system prompts its users with an appropriate message; if, on the other hand, there are no problems with the data, the input modules, which are located in the middle–tier, will be triggered to add, update, or delete the data in the project database. The snapshot of the labor-data entry screen is shown in Fig. 7.7.

2. Validation by Data Type Change

Changing the data type is an effective way for data validation. The resource cost, for example, is entered as text to suit different units. This data type is converted into numerical data before it is stored into the database. If the value of the data is null, it is set to zero. This type of check can also trap human data-entry errors by using a space bar.

3. Validation by Reports

Specially designed queries report the data in table or graphic format to let the user check the entered data in the project database. An example of the planned labor data report is shown in Fig. 7.8; an example of actual labor data is shown in Fig. 7.9. All other planned and actual performance data for a warehouse project can be found in Appendix H. The advanced techniques such as bar coding can reduce the risk of manual data entering error. The incorporation of this technique exceeds the scope of this research and is left for future improvement.

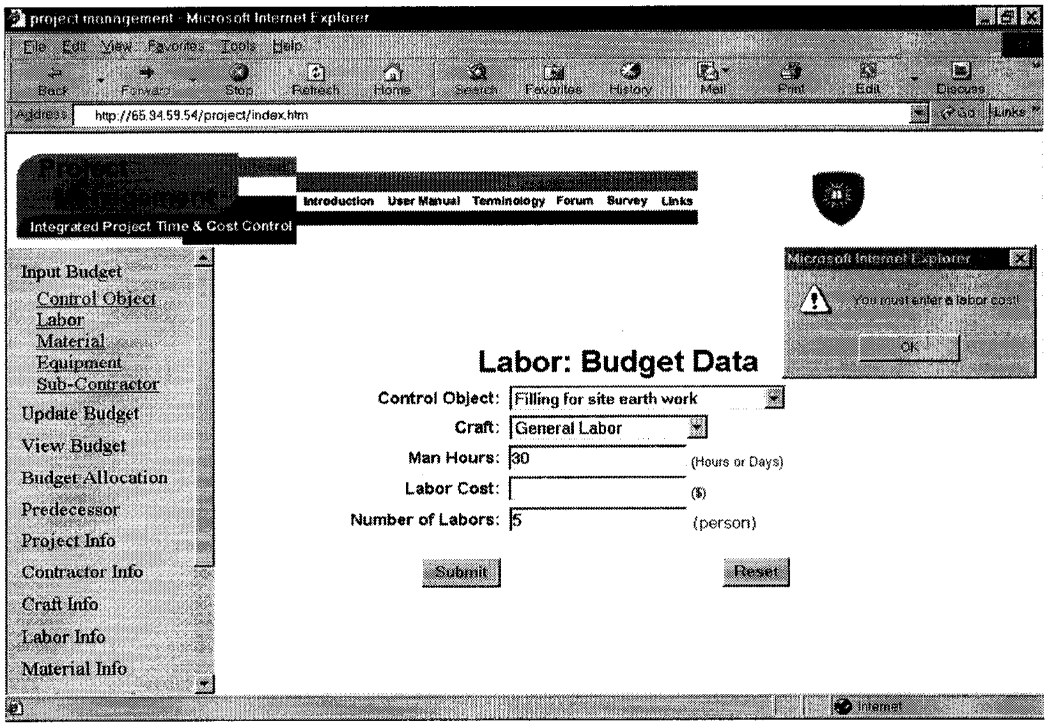


Figure 7. 7 Data Entry Error Check

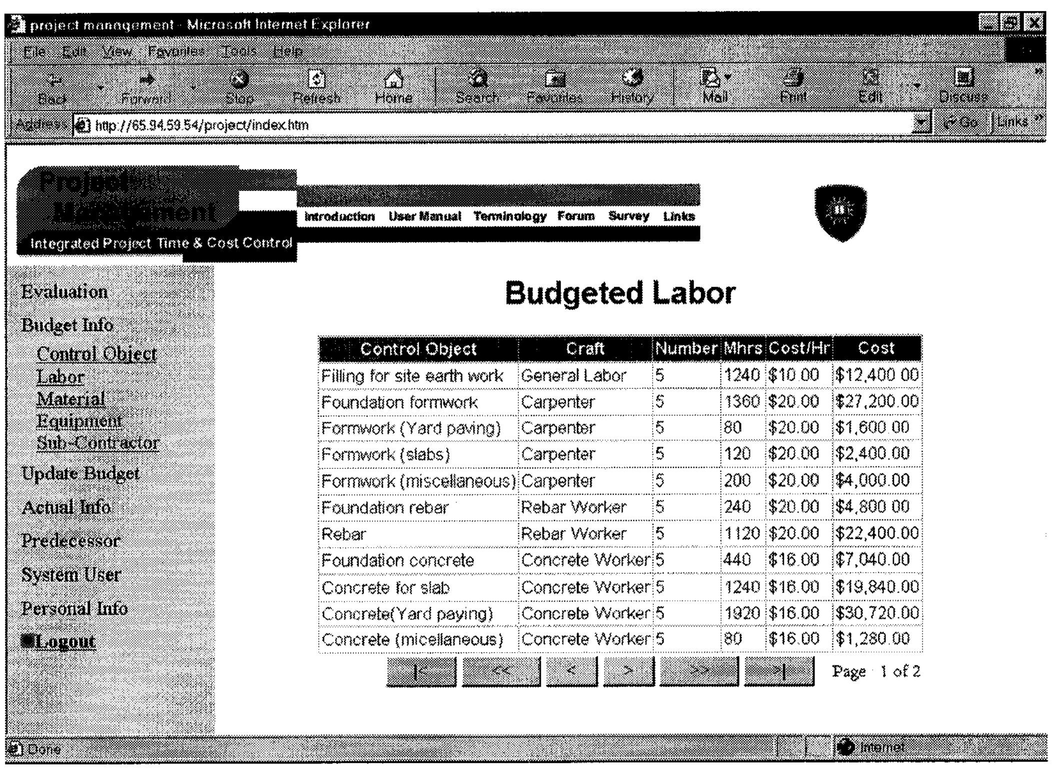


Figure 7. 8 Budgeted Labor Data

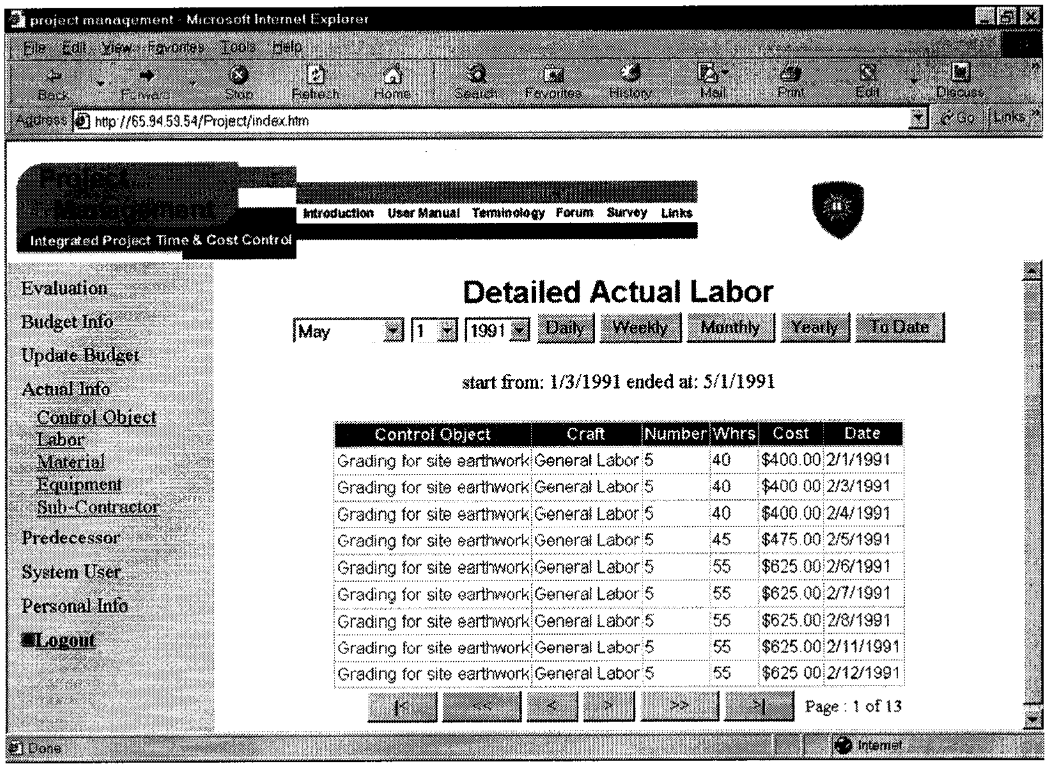


Figure 7. 9 Actual Labor Data

7.3.3 Example: Warehouse Project

A numerical example from the literature (Abudayyeh 1991, 1993) is used to validate the algorithms and functions of the developed IT/CC system. The example is a warehouse project used for storing grocery and nonfood items. The project took approximately a year to complete. It has an area of approximately 150,000 square feet. The project has three major components 1) heavy-duty concrete-paved yard, 2) a ramp slab used as a loading dock, and 3) a base slab constituting the warehouse's storage area covered with a special hardened topping as shown in Fig. 7.10. The structure is formed by double-T precast and prestressed concrete walls, structural steel framing with a metal deck, and a built-up roof.

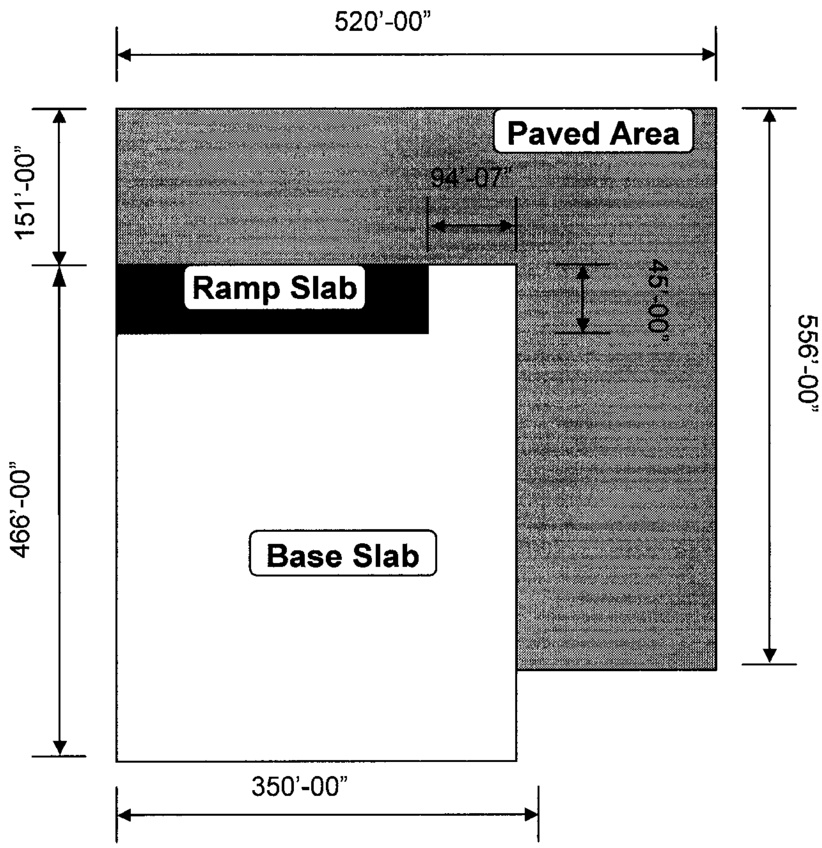


Figure 7. 10 Site Plan of the Warehouse Project

The project has been broken down into twenty-three activities that form the same number of control-objects by using WBS. The project network made by Primavera P3 along with its activity code, control-object code, and duration is shown in Fig. 7.11. The estimation sheet (CII 1988) is used to estimate the planned resource demands for each control-object. The entered budgeted and actual performance data of the project can be found in Appendix H. The contractual start date of this project is January 3, 1991.

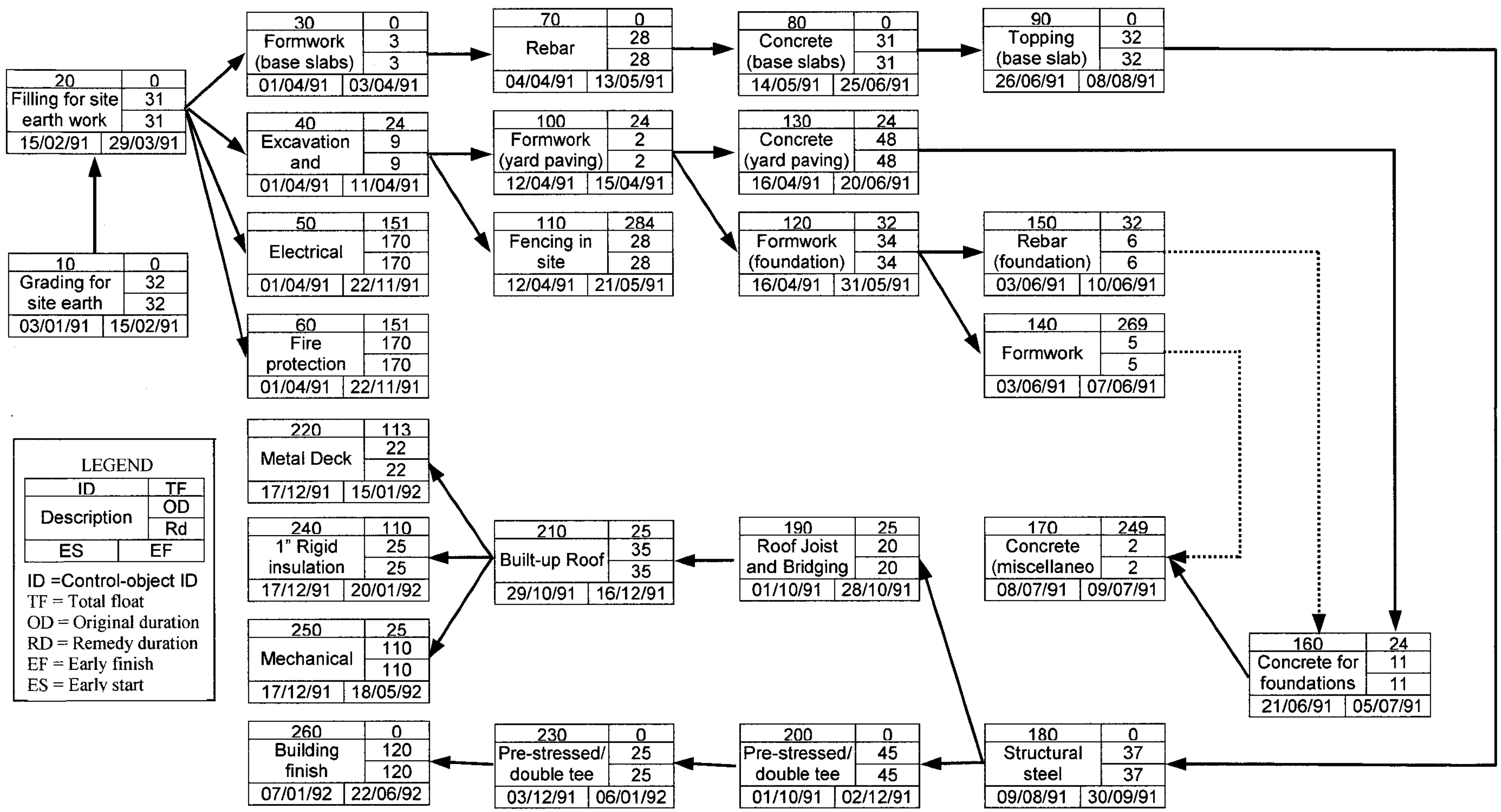


Figure 7. 11 The Activity Network for Warehouse Project

7.3.3.1 Performance Evaluation Reports

The IT/CC system is used to track and to control the performance of this project. The budgeted and actual data of the project are entered into and saved in the web-based project database. Examples of online data entry forms are included in User Interface, which has been described in Section 6.5.1. Fig. 7.12 is the budgeted data report of control-objects for the warehouse project, generated using the input and reporting modules. The pie chart report of a control-object can be viewed by activating the links under the title of the pie chart. A new window is prompted to display the resource distribution of a control-object in a pie chart as shown in Fig. 7.13. After all the data are input to the system, the user has to specify the method of resource allocation for the budgeted data. Fig. 7.14 is the interface to be used for resource allocation. The user has the right to select an allocation method from the default setting for the whole project or for an individual control-object. Instead of selecting an allocation method from the system setting, the IT/CC system also allows users to define their own method for resource allocation by entering the data into the system. According to the actual performance data, a uniform resource distribution for the warehouse project is chosen.

Once the resource allocation is defined, the IT/CC system can be invoked to execute performance evaluation. Fig. 7.15 is a screen snapshot of a labor performance evaluation report, generated using the evaluating and reporting modules, from January 3, 1991 to May 1, 1991 at the site manager's level (values in brackets are negative). The report summarizes all calculated earned-value parameters for the reporting period including BCWS, BCWP, ACWP, CV, PC_a, SV, CPI, and SPI. The positive and negative cost variances, reported in Fig.7.15, represent cost saving and overrun, respectively. Similarly, positive and negative schedule variances represent schedule advance and delay, respectively. The threshold values for cost and schedule are set to zero for all the control-objects being evaluated. Clearly, the performance of control-object 12100 as reported in Fig.7.15, indicates cost underrun and schedule delay at this reporting date. The performance of control-object 11200, on the other hand, indicates cost overrun and schedule delay at this reporting date. The performance of control-object 13122, however, indicates cost underrun and schedule advanced at this reporting date. The scope of works covered by control-objects 13111, 13121, and 11130 was accomplished by this reporting date, but with cost overrun associated with the control-object 13121. This is a tabular format report. The user can also activate the link under the title of control-object to view the earned-value graphic report in a new window as shown in Fig. 7.16. Because the resource allocation for this case is uniformly distributed, the BCWS, BCWP and ACWP curve is presented linearly. The crewmember type of control-object 12100 is a carpenter. The detailed list of crewmember names can be viewed by activating the link under the title of craft. A new window is prompted to report all the names of this crewmember as shown in Fig. 7.17. The user can get the estimated indicators' impact-cost for unfavorable performance by activating the link under the title of CV. A tabular and graphic impact-cost report, generated using the evaluating and reporting modules, will be prompted as shown in Fig. 7.18 (values in brackets are negative). The positive impact-cost represents cost saving and schedule advancing, respectively; similarly, the negative impact-cost represents cost overrun and schedule delay, respectively. The variance chart at the bottom of this figure represents the impact-cost in graphic format. The horizontal bars at the left side represents the negative impact-cost; the horizontal bars on the right side represents the positive impact-cost. The site manager, who can also access the system, evaluates the material, equipment, and sub-contractors performance in a similar manner. Examples of the reports can be found in Appendix I.

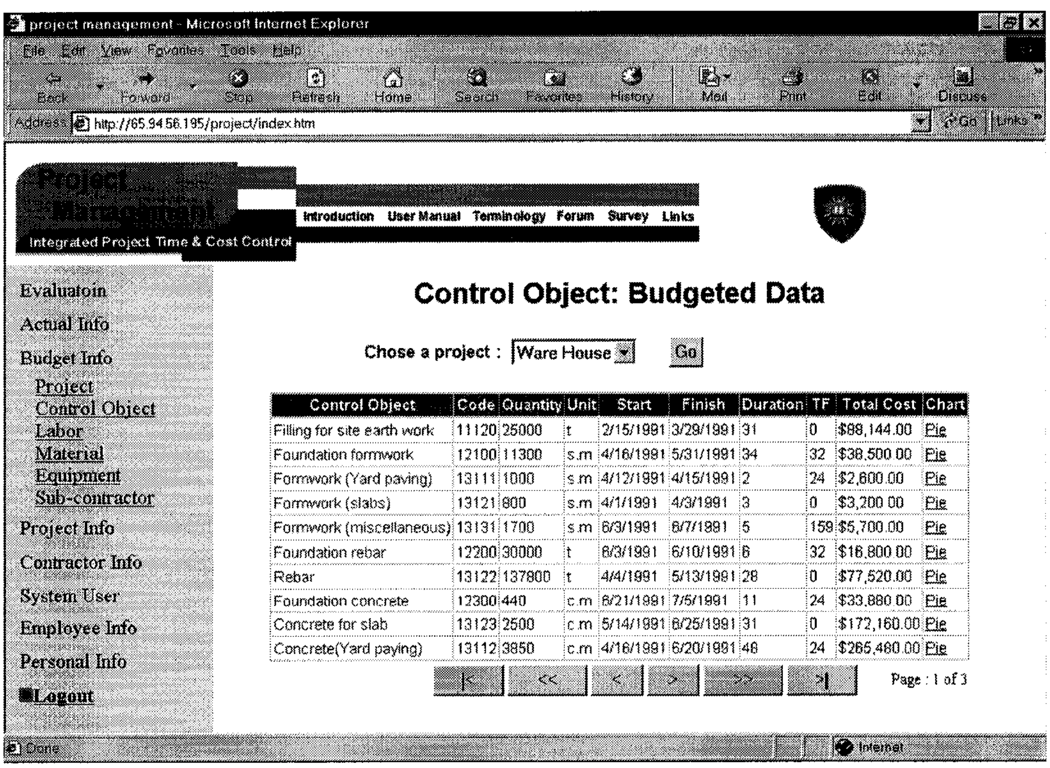


Figure 7. 12 Baseline Data

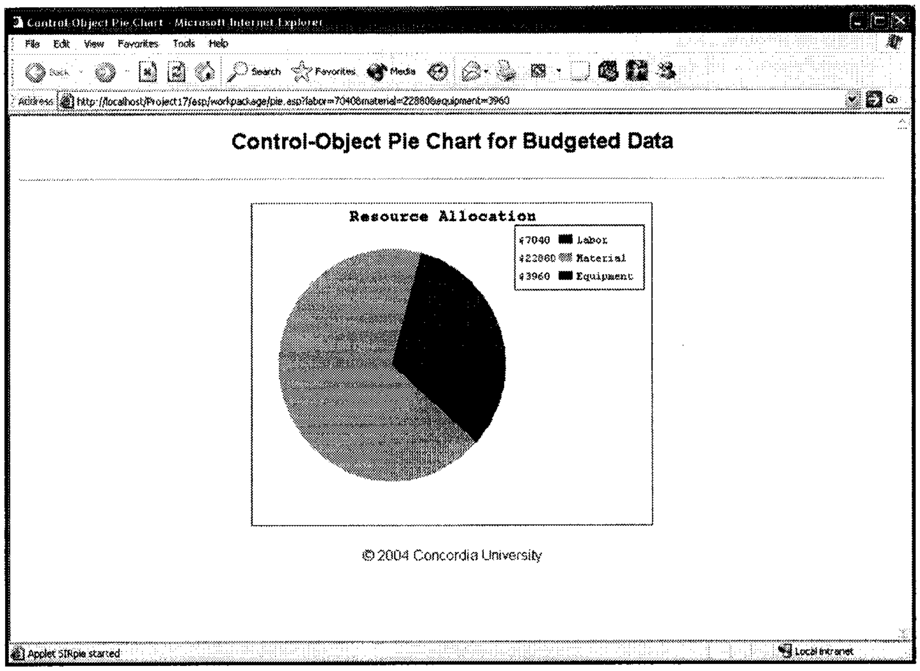


Figure 7. 13 Pie Chart for Planned Data of Control-Object

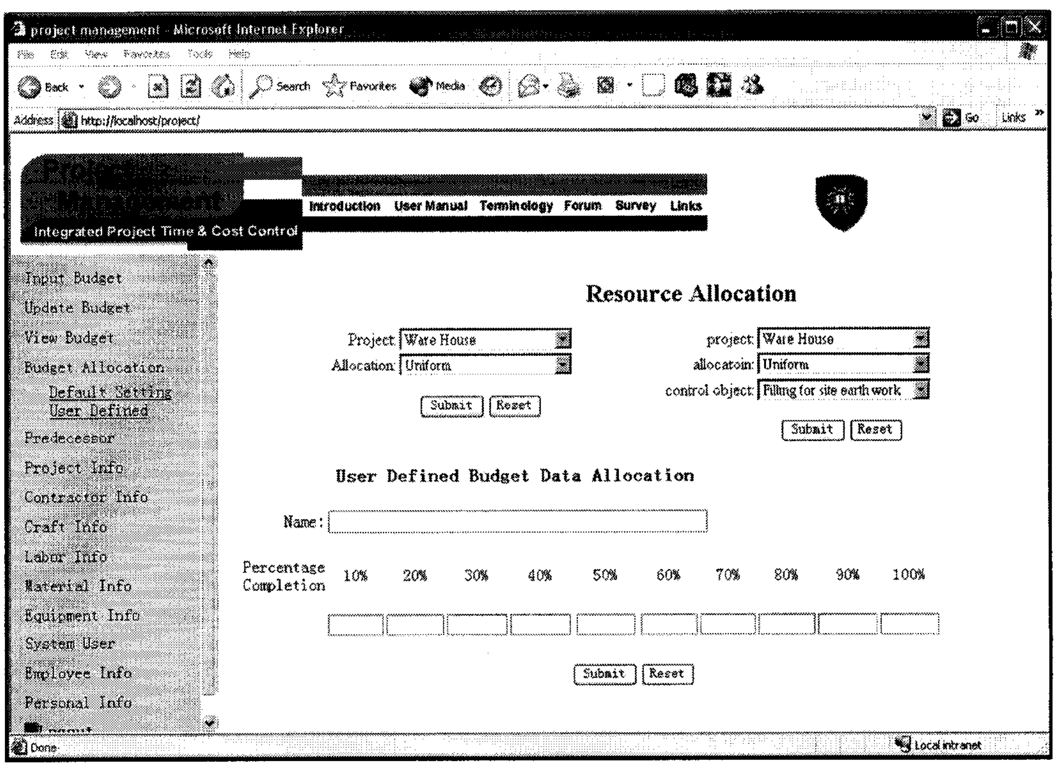


Figure 7. 14 Define the Method for Resource Allocation

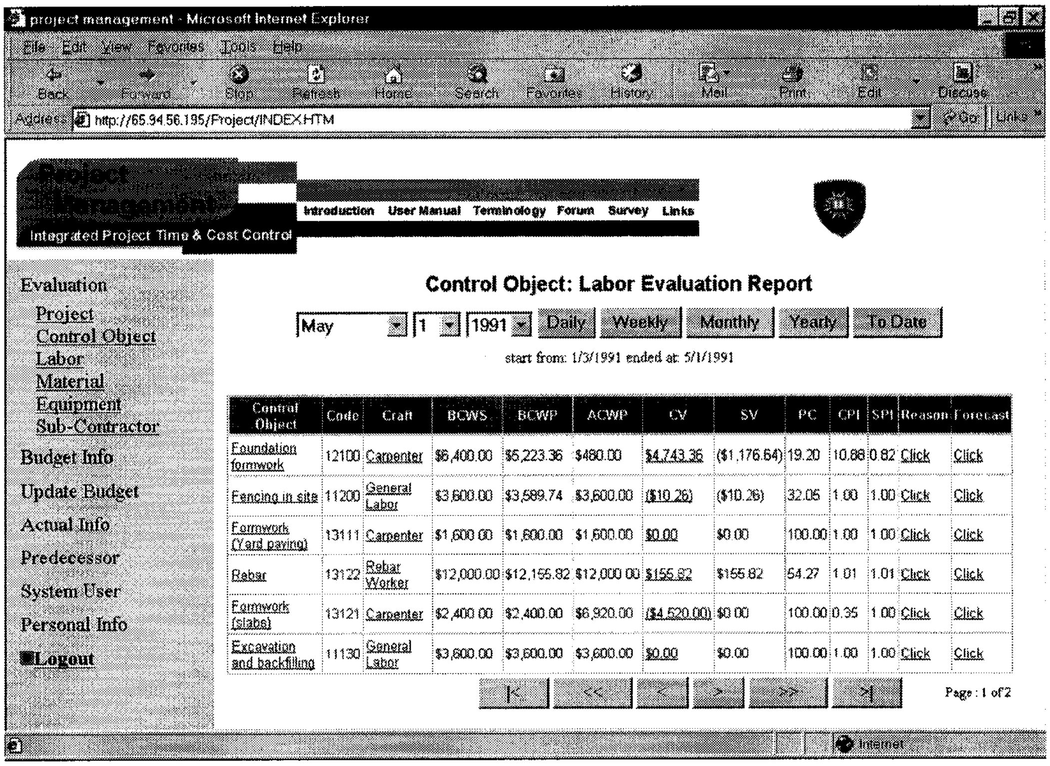


Figure 7. 15 Labor Performance Evaluation Report

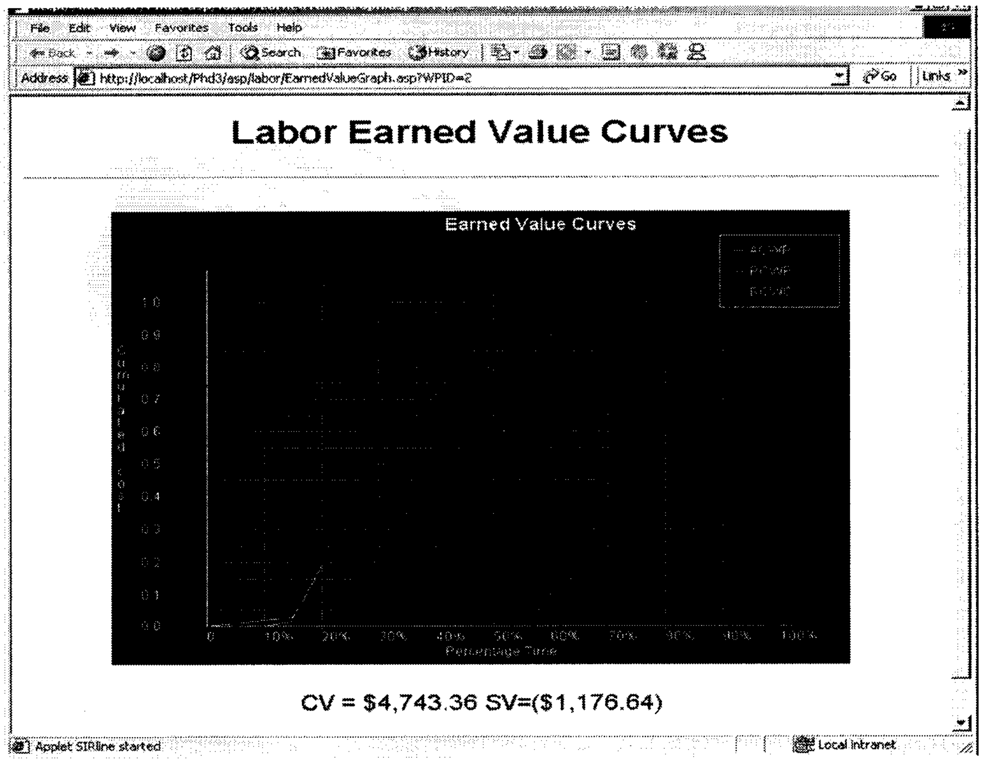


Figure 7. 16 Earned-Value Graphic Report

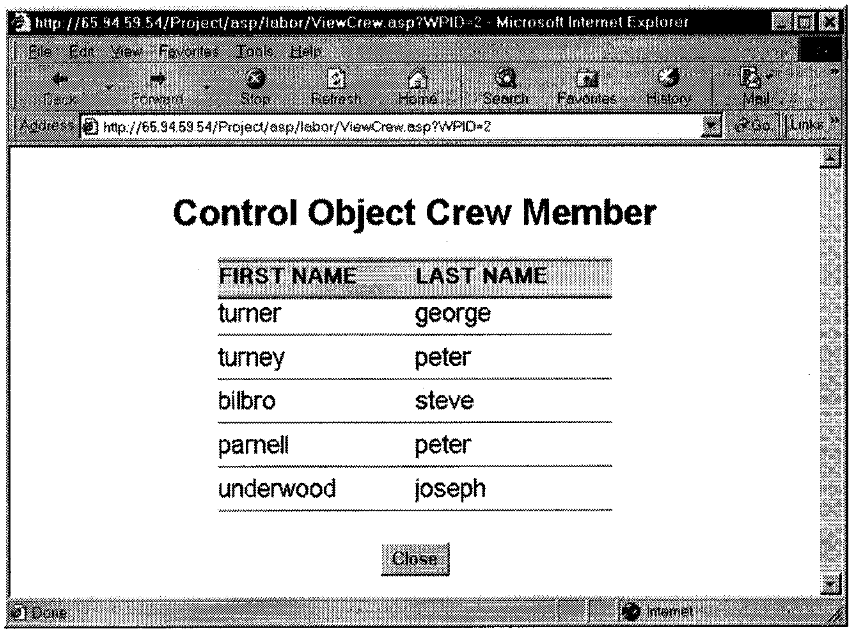


Figure 7. 17 Control-Object Crewmembers

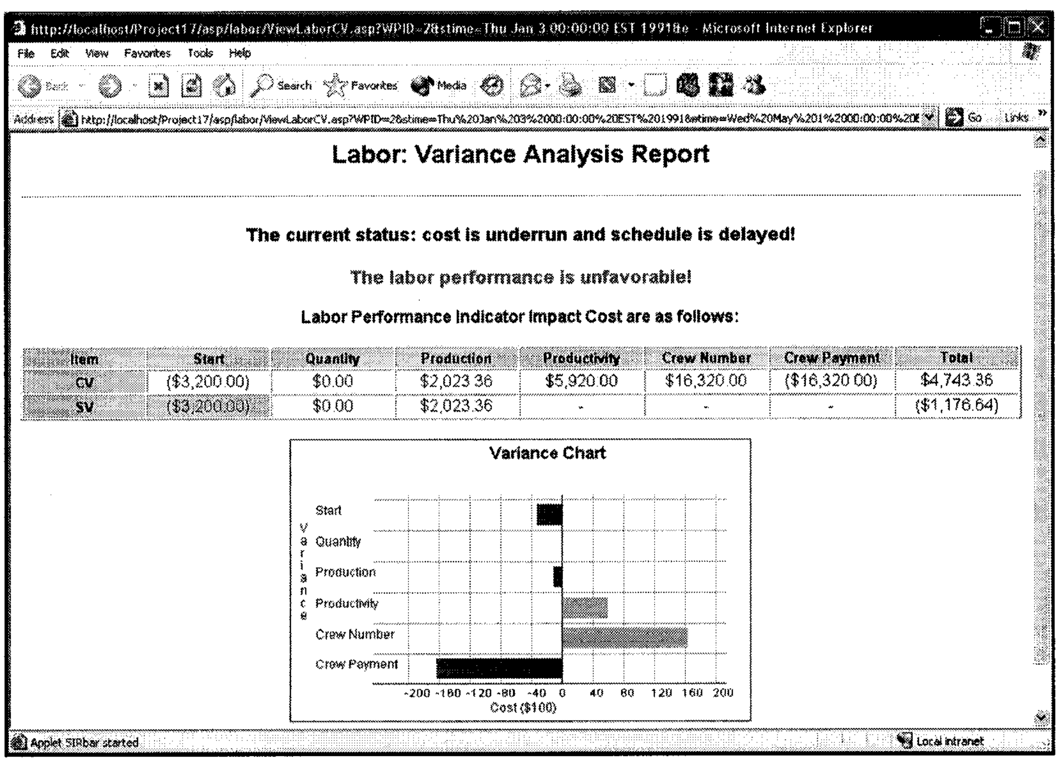


Figure 7. 18 Labor Variance Analysis Report

The manager, who can access the system, evaluates performance at control-object level and generates a similar earned-value evaluation report as shown in Fig. 7.19. Fig. 7.20 is the detailed variance analysis report of control-object 11120, generated using the revaluating and reporting modules at the control-object level. It should be noted that the control-object variance could be caused by the variances of labor, material, equipment and/or sub-contractors.

The project manager, who can access the system, evaluates performance at project level and generates a similar earned-value evaluation report for one project. The detailed variance analysis of this project is also included in this report. Fig. 7.21 is an example of this report for the warehouse project at the reporting, generated using the evaluation and reporting modules, from January 3, 1991 to May 1, 1991 at the project manager's level.

Table 7.1 presents a comparison of the proposed earned-value report generated using the proposed system with that generated by Abudayyeh (1991) using the earned-value method for control-object 11130 at reporting date March 11, 1993. It should be noted that the two reports are identical when the threshold values of time and cost variances are set equal to zero. However, unlike the result of Abudayyeh (1991, 1993), the developed system can account for changes in the start date of the tasks performed in each control-object.

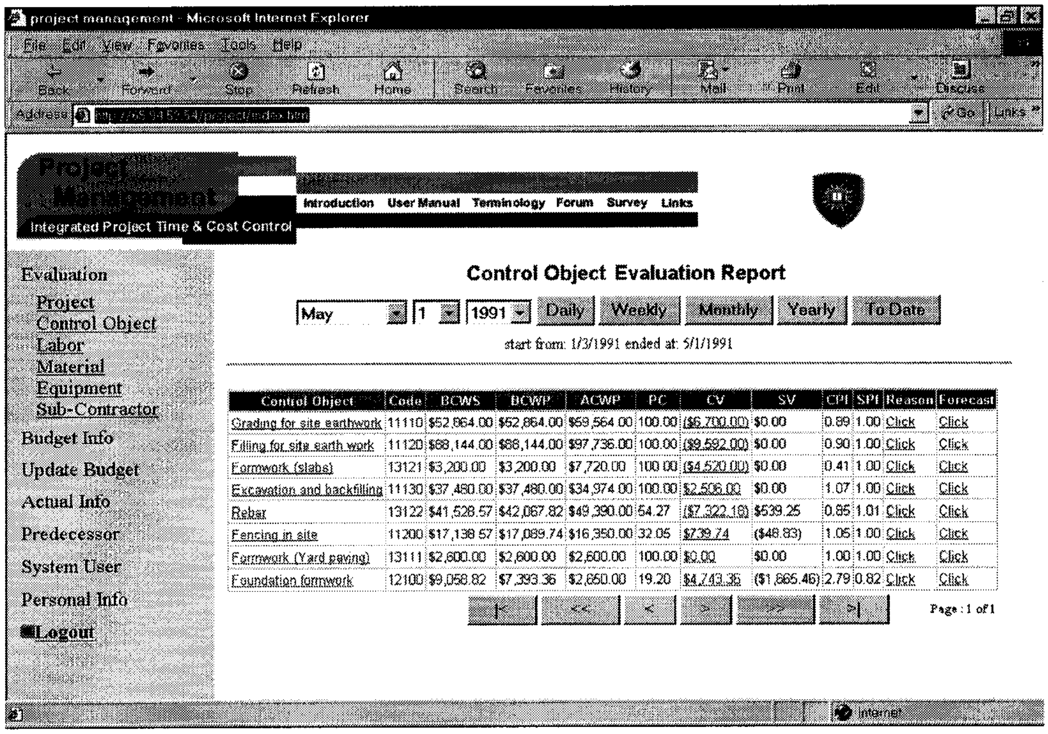


Figure 7. 19 Control-Object Performance Evaluation Report

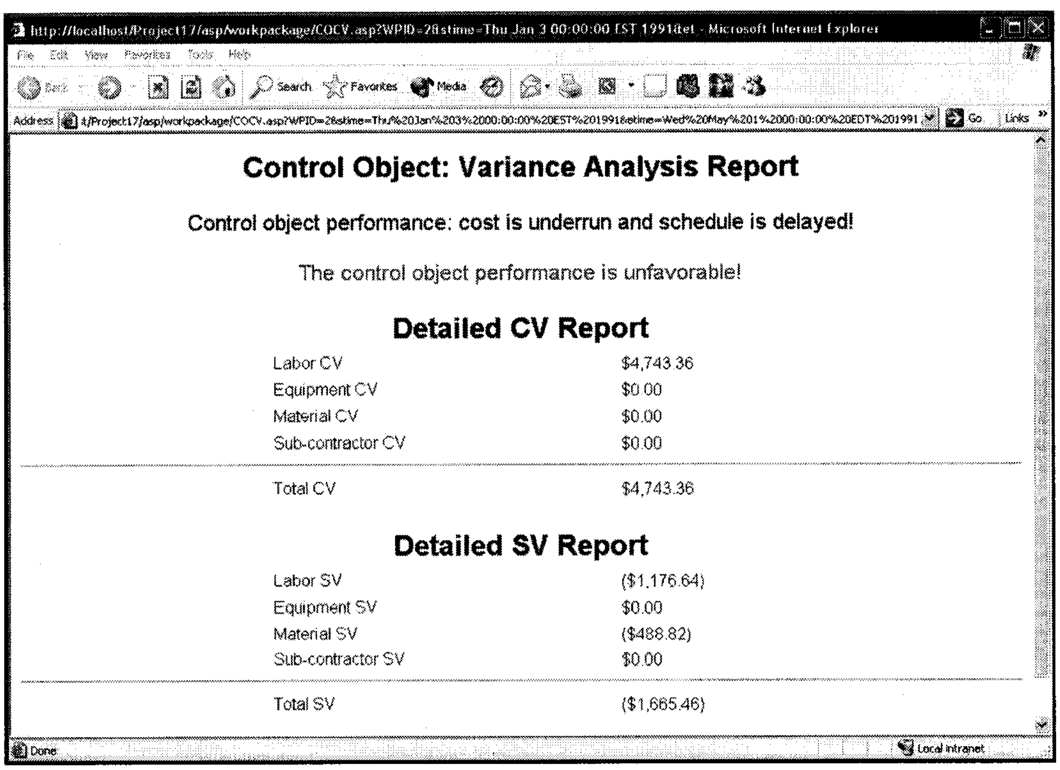


Figure 7. 20 Control-Object Variance Analysis Report

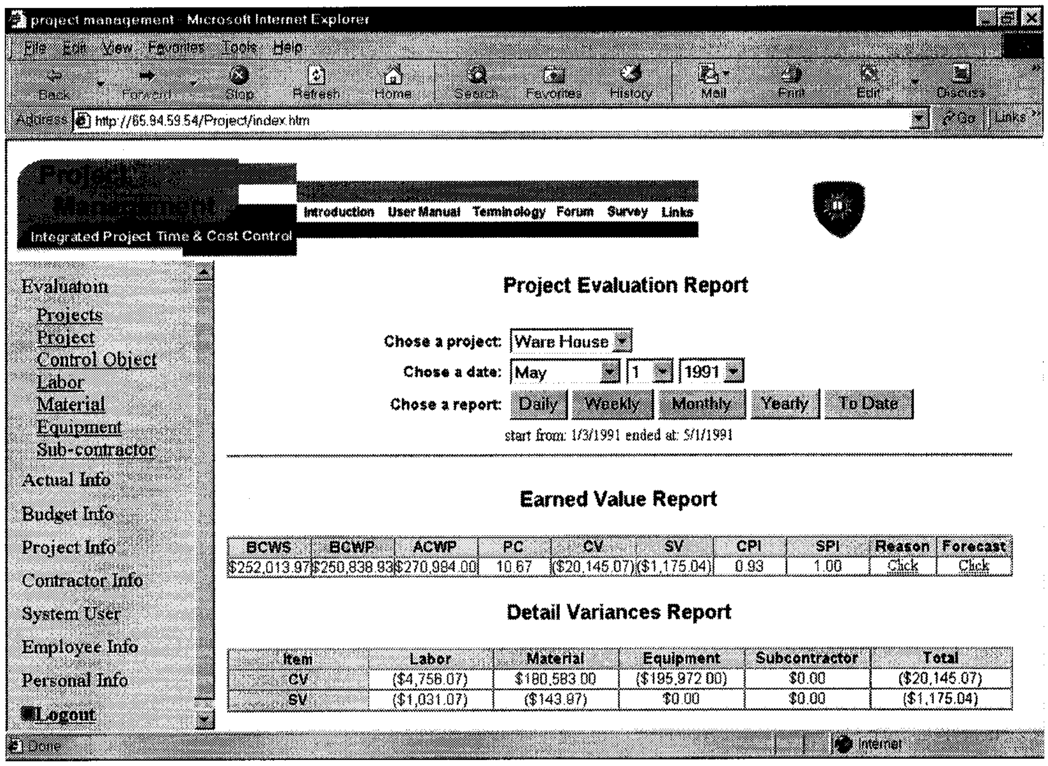


Figure 7. 21 Project Performance Evaluation Report

Table 7. 1 The Comparison of the Earned-Value Reports

Control-object 11130		BCWS	BCWP	ACWP	CV	SV	CPI	SPI
Abdudayyeh	Labor	$2,000.00	$1,987.20	$2,000.00	-$12.80	-$12.80	0.99	0.99
	Material	$16,666.67	$16,560.00	$15,870.00	$690.00	-$106.67	1.04	0.99
	Equipment	$2,155.56	$2,141.76	$1,435.00	$706.76	-$13.80	1.49	0.99
Proposed model without start variance	Labor	$2,000.00	$1,987.20	$2,000.00	-$12.80	-$12.80	0.99	0.99
	Material	$16,666.67	$16,560.00	$15,870.00	$690.00	-$106.67	1.04	0.99
	Equipment	$2,155.56	$2,141.76	$1,435.00	$706.76	-$13.80	1.49	0.99
Proposed model with start variance	Labor	$2,800.00	$1,987.20	$2,000.00	-$12.80	-$812.80	0.99	0.71
	Material	$23,333.33	$16,560.00	$15,870.00	$690.00	-$6,773.33	1.04	0.71
	Equipment	$3,017.78	$2,141.76	$2,141.76	$706.76	-$876.02	1.49	0.71

7.3.3.2 Reasoning Reports

The proposed reasoning process is incorporated into and represents an added utility to the IT/CC system as described earlier. Therefore, the IT/CC system provides tools to assist members of project teams in identifying reasons behind unacceptable performance and in suggesting corrective actions, accordingly. To find reason(s) for a project, a control-object, and an individual type of resource, users need to activate the links under the reason tile in their performance evaluation windows as shown in Figs. 7.15, 7.19, and 7.21. A new window appears for reasoning purpose. The use of the process is illustrated by input and output screens shown in Figs. 7.22~7.26, 7.28, 7.30, 7.31, and 7.33. For example, the data pertinent to planned conditions of control-object 11120 for the warehouse project is shown in Table 7.2. Based on the actual cost and the schedule data reported on March 11,1991, the cost and schedule variances (CV and SV) of that control-object along with its percentage completion (PC_a) can be found in Table 7.3. Clearly, the performance of control-object 11120 is cost overrun and schedule delay at this reporting date. In order to find reasons behind that unacceptable performance, the impact-cost of its resources of labor, material and equipment on March 11, 1991 are estimated as listed in Tables 7.4, 7.5 and 7.6, respectively. There are positive and negative impact-costs that represent cost saving and overrun or schedule advanced and delay, respectively. The proposed reasoning process considers only the negative impact-costs, i.e. cost overrun and schedule delay.

Table 7. 2 Control-Object Budgeted Information

Control-Object	Code	Total	Labor	Material	Equipment	Sub-contractor
Filling for site earth work	11120	$88,144.00	$12,400	$75,000	$744	$0.00

Table 7. 3 Control-Object Reported Variances

Code	PC	Variance	Labor	Material	Equipment	Sub-contractor	Total
11120	46.80%	CV	-$421.80	-$2,925.00	$21.19	$0.00	-$3,325.61
		SV	-$196.80	-$1,190.32	-$11.81	$0.00	-$1,398.93

Table 7. 4 Estimated Indicator's Impact-Cost for Labor

Code	Variance	Start	Quantity	Production	Productivity	Crew attendance	Crew payment	Total
11120	CV	$0.00	$0.00	-$196.80	-$151.83	$0.00	-$73.17	-$421.80
	SV	$0.00	$0.00	-$196.80	-	-	-	-$196.80

Table 7. 5 Estimated Indicator's Impact-Cost for Material

Code	Variance	Start	Quantity	Production	Usage	Unit Price	Total
11120	CV	$0.00	$0.00	-$1,190.32	$1,190.23	-$2,925.00	-$2,925.00
	SV	$0.00	$0.00	-$1,190.32	-	-	-$1,190.32

Table 7. 6 Estimated Indicator's Impact-Cost for Equipment

Code	Variance	Start	Quantity	Production	Productivity	Usage	Total
11120	CV	$0.00	$0.00	-$11.81	$33.00	$0.00	$21.19
	SV	$0.00	$0.00	-$11.81	-	-	-$11.81

The normalized negative labor impact-costs for control-object 11120 are represented as X_L (V_L, S_L) relation. The values of X_L (V_L, S_L), shown below, represent the linkage strengths between the labor performance indicators and the variances of cost and schedule. The degree of linkage strength between the cost variance and the labor production, for example, is expressed as X_L (v_{L1},

s_{L3}). Its value is calculated as the impact-cost of production from Table 7.4 divided by the summation of all the negative impact-costs, (-196.80)/(-421.80)=0.467.

$$X_L(V_L, S_L) = \begin{array}{c} \\ v_{L1} \\ v_{L2} \end{array} \begin{array}{c} \begin{array}{cccccc} s_{L1} & s_{L2} & s_{L3} & s_{L4} & s_{L5} & s_{L6} \end{array} \\ \begin{pmatrix} 0.000 & 0.000 & 0.467 & 0.360 & 0.000 & 0.173 \\ 0.000 & 0.000 & 1.000 & 0.000 & 0.000 & 0.000 \end{pmatrix} \end{array}$$

where,

s_{L1}, s_{L2}, s_{L3}, s_{L4}, s_{L5}, and s_{L6} denote the factor indicator of start-variance and the terminal indicators of quantity, production, productivity, crew attendance, and crew payment, respectively; v_{L1} and v_{L2} denote the labor cost and schedule variances of control-object 11120, respectively.

As stated earlier, only the impact-cost associated with highlighted indicators are estimated. The highlighted indicators of control-object 11120 at this reporting date are production, productivity, and crew payment. The impact-cost for other indicators such as control-object quantity and crew attendance are set to zero. In order to define the values of the Y_L (S_L, F_L) relation, the factors associated with the highlighted indicators are extracted from the factor database and displayed in Fig. 7.22. The users can specify the linkage strengths between the indicators and the factors using a scale of 0 to 10. In this example, the user-specified linkage strengths for the factors of 1.1, 3.5, 3.6, and 4.8, as listed in Table 3.4 and their respective associated indicators as listed in Tables 4.2 and

4.3, are assumed as 7, 10, 8, and 9, respectively. These values are, then divided by 10 to convert to the values of the Y_L (S_L, F_L) relation as shown below. It is assumed that one factor has the same degree of linkage strength with its associated indicators. Therefore, the factor 4.8 has the same degree of linkage strength with the indicator of s_{L2} and s_{L5}.

$$Y_L(S_L, F_L) = \begin{array}{c} \\ s_{L3} \\ s_{L4} \\ s_{L6} \end{array} \begin{array}{c} \begin{array}{cccc} f_{L1.1} & f_{L3.5} & f_{L3.6} & f_{L4.8} \end{array} \\ \begin{pmatrix} 0.0 & 0.0 & 0.0 & 0.9 \\ 0.7 & 0.0 & 0.8 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.9 \end{pmatrix} \end{array}$$

By applying the max-min composition operation of Equation (4.10). It is possible to express the P_L (V_L, F_L) relation as:

$$P_L(V_L, F_L) = \begin{array}{c} \\ v_{L1} \\ v_{L2} \end{array} \begin{array}{c} \begin{array}{cccc} f_{L1.1} & f_{L3.5} & f_{L3.6} & f_{L4.8} \end{array} \\ \begin{pmatrix} 0.360 & 0.173 & 0.360 & 0.467 \\ 0.00 & 0.00 & 0.00 & 0.900 \end{pmatrix} \end{array}$$

Sample calculation using max-min

$$P_L\ (V_L,\ F_L)=\text{max-min}\ [X_L\ (v_{Li},\ s_{Lj}),\ Y_L\ (s_{Lj},\ f_{Lk})]$$

For example, $P_L(v_{L1}, f_{L4.8})$, one element of P_L (V_L, F_L) matrix can be calculated as:

$$P_L(v_{L1}, f_{L4.8}) = \text{max-min}\ [(0.467, 0.900), (0.360, 0.000), (0.173, 0.900)]$$

$$= \max (0.467, 0.000, 0.173)=0.467$$

The rank of factor 4.8 is calculated as:

$PS_{L14.8}$ =0.467/(0.360+0.173+0.360+0.467)=34.31%

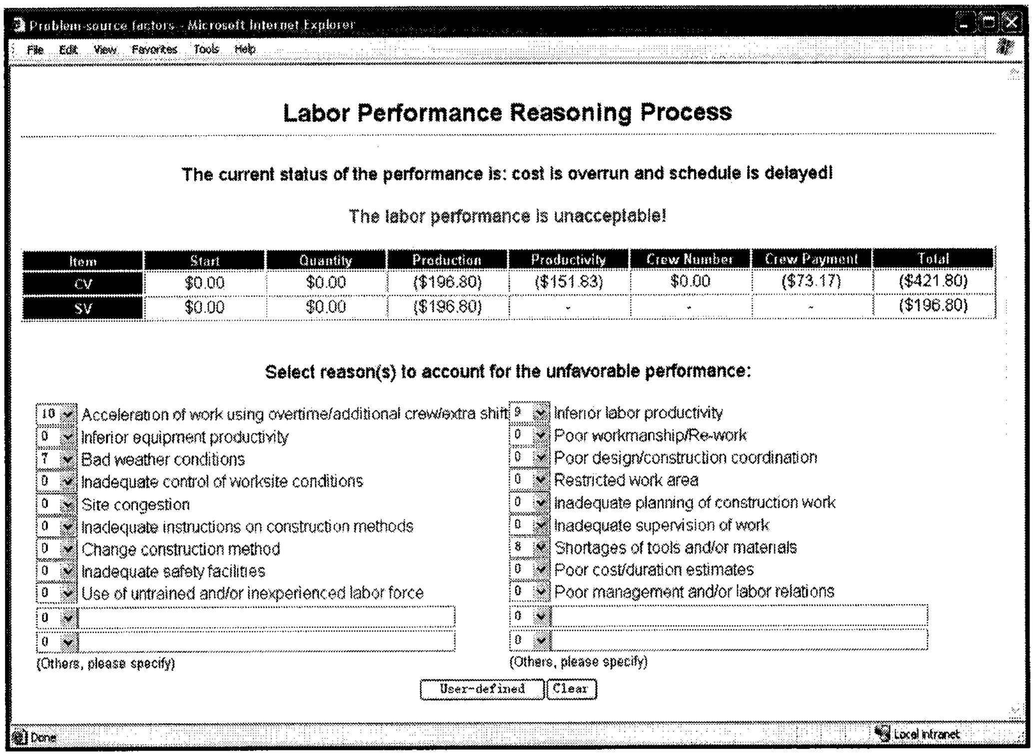


Figure 7. 22 User-Specified Factors for Labor Performance

By applying the cum-min composition operation of Equation (4.11). The P_L (V_L, F_L) relation can be expressed as:

$$
P_L(V_L, F_L) = \begin{array}{c c} & \begin{array}{cccc} f_{L1.1} & f_{L3.5} & f_{L3.6} & f_{L4.8} \end{array} \\ \begin{array}{c} v_{L1} \\ v_{L2} \end{array} & \begin{pmatrix} 0.360 & 0.173 & 0.360 & 0.640 \\ 0.000 & 0.000 & 0.000 & 0.900 \end{pmatrix} \end{array}
$$

Sample calculation using cum-min

$$P_L\ (V_L,\ F_L)=\text{cum-min}\ [X_L\ (v_{Li},\ s_{Lj}),\ Y\ (s_{Lj},\ f_{Lk})]$$

For example, $P_L(v_{L1},\ f_{L4.8})$, one element of $P_L\ (V_L,\ F_L)$ matrix can be calculated as:

$$P_L\ (v_{L1},\ f_{L4.8})=\text{cum-min}\ [(0.467,\ 0.900),\ (0.360,\ 0.000),\ (0.173,\ 0.900)]$$

$$=\text{cum}\ (0.467,\ 0.000,\ 0.173)=0.640$$

The rank of factor 4.8 is calculated as:

$$PS_{L14.8}=0.640/(0.360+0.173+0.360+0.640)=41.70\%$$

The factors for poor cost performance, using the max-min composition operation, are factors 4.8, 3.6, 1.1, and 3.5 as listed in Table 3.4, with calculated strengths of 34.31%, 26.47%, 26.47%, and 12.76%, respectively. The factor for poor schedule performance is 4.8 as listed in Table 3.4, with calculated strength of 100%. These factors were also identified, using the cum-min composition operation, but with calculated strengths of 41.7%, 23.5%, 23.5%, 11.3%, and 100%, respectively. It should be noted that the ranks of the output factors/actions are not necessarily equal to the ranks of the user-specified linkage strengths. This is because the linkage strength between the indicators and the variances has great impact on determining the output factors/actions. The developed reasoning system could account for factors beyond those included in Table 3.4. Users are allowed to add new factors during the reasoning process as shown in Fig.7.22. The value of the X_L (V_L, S_L) relation for a newly added factor is assumed to be 1.0.

A similar process applies to generate the recommended corrective action(s). Based on the identified factors, possible corrective actions are extracted from the factor database and are then displayed as shown in Fig.7.23. The users can specify the linkage strengths between the factors and the actions using a scale from 0 to 10. In this example, the user-selected linkage strengths for actions 3.2, 3.9, 4.6, and 6.4 as listed in Table 4.1 and their respective associated factors as listed in Tables 4.2 and 4.3, are 7, 8, 10, and 9, respectively. These values are then divided by 10 to convert to the values of the Z_L (F_L, A_L) relation as shown below.

$$Z_L(F_L, A_L) = \begin{array}{c} \\ f_{L1.1} \\ f_{L3.5} \\ f_{L3.6} \\ f_{L4.8} \end{array} \begin{array}{c} \begin{array}{cccc} a_{L3.2} & a_{L3.9} & a_{L4.6} & a_{L6.4} \end{array} \\ \begin{pmatrix} 0.7 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.8 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.9 \\ 0.0 & 0.0 & 1.0 & 0.0 \end{pmatrix} \end{array}$$

By applying the max-min composition operation of Equation (4.10), the C_L (V_L, A_L) relation for labor can be expressed as:

$$C_L(V_L, A_L) = \begin{array}{c} \\ v_{L1} \\ v_{L2} \end{array} \begin{array}{c} \begin{array}{cccc} a_{L3.2} & a_{L3.9} & a_{L4.6} & a_{L6.4} \end{array} \\ \begin{pmatrix} 0.360 & 0.173 & 0.467 & 0.360 \\ 0.000 & 0.000 & 0.900 & 0.000 \end{pmatrix} \end{array}$$

Also, by applying the cum-min composition operation of Equation (4.11), the C_L (V_L, A_L) relation for labor can be expressed as:

$$C_L(V_L, A_L) = \begin{array}{c c} & \begin{array}{cccc} a_{L3.2} & a_{L3.9} & a_{L4.6} & a_{L6.4} \end{array} \\ \begin{array}{c} v_{L1} \\ v_{L2} \end{array} & \begin{pmatrix} 0.360 & 0.173 & 0.640 & 0.360 \\ 0.000 & 0.000 & 0.900 & 0.000 \end{pmatrix} \end{array}$$

The recommend corrective actions to improve cost performance, using the max-min composition operation, are actions of 4.6, 3.2, 6.4, 3.99 as listed in Table 4.1, with calculated strengths of 34.3%, 26.5%, 26.5%, and 12.7%, respectively. The action to improve schedule performance is an action of 4.6 as listed in Table 4, with calculated strength of 100%. These corrective actions were also identified using the cum-min composition operation, but with calculated strengths of 41.7%, 23.5%, 23.5%, 11.3%, and 100%, respectively. Upon completion of the analysis, the labor performance reasoning report is then generated, using the reasoning and reporting modules, as shown in Fig. 7.24. It should be noted that the developed reasoning system could account for actions beyond those included in Table 4.1. Users are allowed to add new actions during the reasoning process as shown in Fig. 7.23. The value of the Z_L (F_L, A_L) relation for a newly added action is assumed to be 1.0.

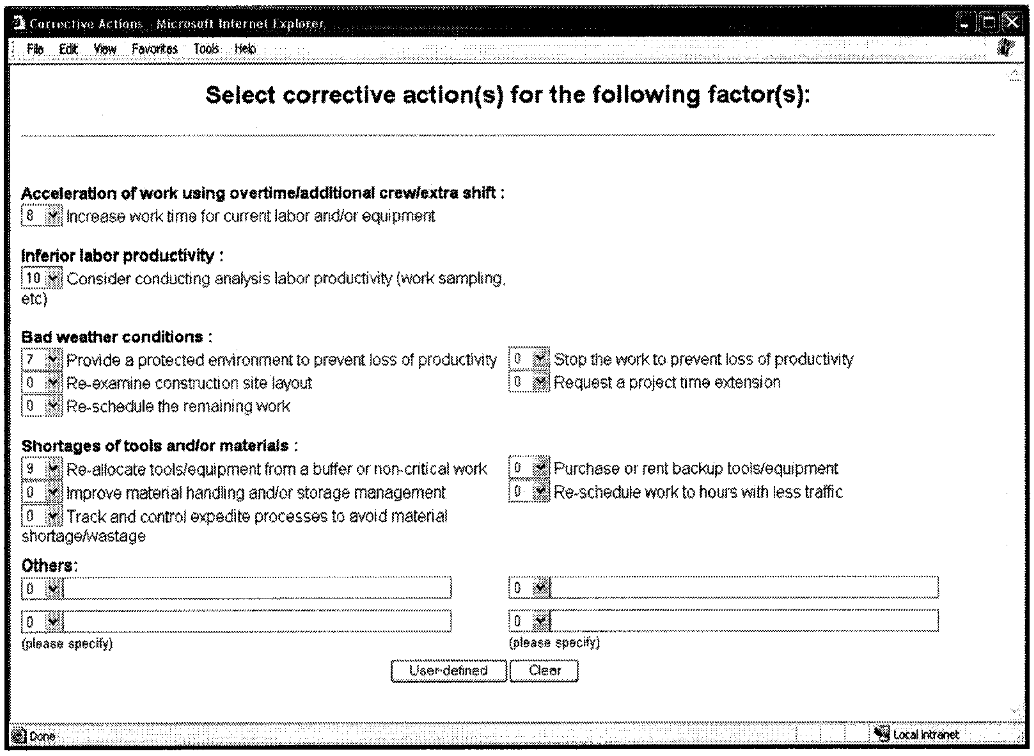


Figure 7. 23 User-Specified Corrective Actions for Labor Performance

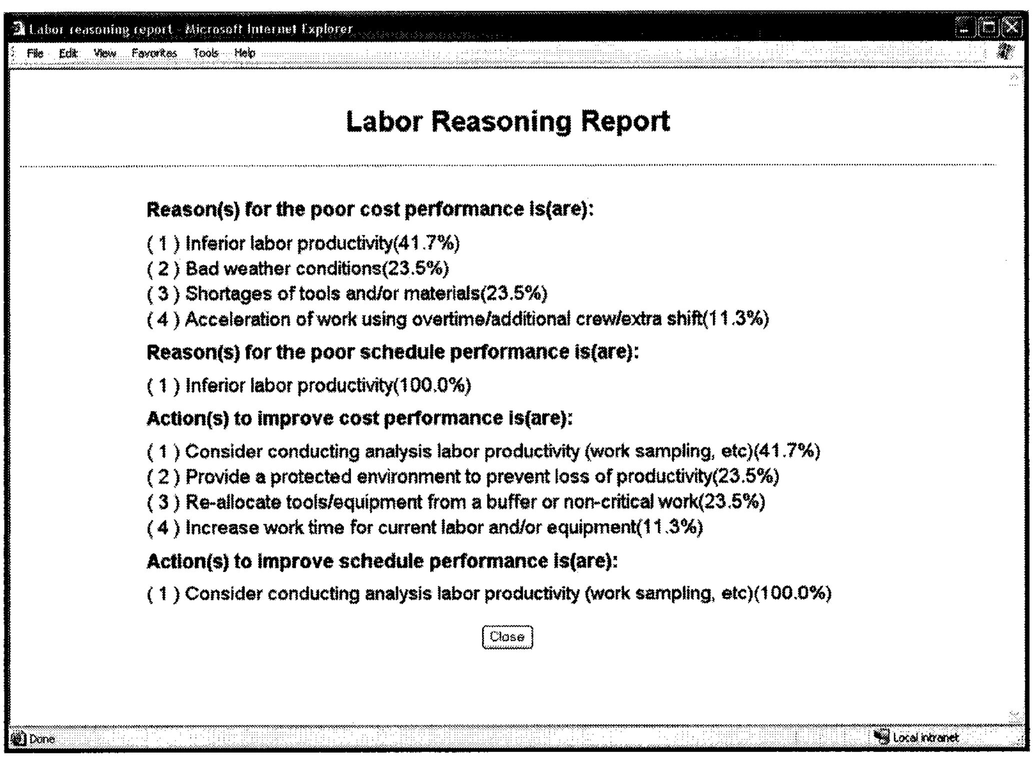


Figure 7. 24 Labor Reasoning Report

Similarly, the P_r (V_r, F_r) and C_r (V_r, A_r) relations for poor material and equipment performance using the two fuzzy composition operations (Equations 4.10 and 4.11) are obtained as shown in Table 7.7. The material and equipment reasoning reports including the factors and actions selection processes can be found in Appendix I. In this example, the user added a factor of "unexpected type of soil" and an action of "increase the soil strength" during the equipment reasoning process. Unlike the labor reasoning results, the reasoning results obtained using max-min composition and cum-min composition operations for material and equipment (Table 7.7) are the same for this control-object being considered. It should be noted that the cum-min composition is more suitable for the aggregation process used in this model as it accumulates the weights of the factor(s) and action(s) for each individual resource. Therefore, it is used in the developed reasoning system to identify possible problem-source factor(s) and to suggest corrective action(s) for an individual resource. In the eventuality of errors in the generation of the baseline (i.e. the budgeted cost of work planned), the system would be able to diagnose such problem based-on the highlighted indicators of labor productivity and/or material usage that lead to the problem-source factor of "Poor cost/duration estimate" listed in Table 3.4. As well this problem could also be detected based-on the threshold value of the variances detected and their persistence over a period of time. It should be noted that the user could specify such threshold value.

Table 7. 7 Values of P_r (V_r, F_r) and C_r (V_r, A_r) for Material and Equipment

Material						Equipment					
max-min (cum-min)			max-min (cum-min)			max-min (cum-min)			max-min (cum-min)		
$V_M \backslash F_M$	$f_{M1.2}$	$f_{M4.8}$	$V_M \backslash A_M$	$a_{M2.5}$	$a_{M4.6}$	$V_E \backslash F_E$	$f_{E4.8}$	f_{EOther}	$V_E \backslash A_E$	$a_{E4.6}$	a_{EOther}
v_{M1}	0.711	0.289	v_{M1}	0.711	0.289	v_{E1}	0.000	0.000	v_{E1}	0.000	0.000
v_{M2}	0.000	0.900	v_{M2}	0.000	0.900	v_{E2}	0.750	1.000	v_{E2}	0.500	1.000

The control-object reasoning is a weighted aggregation of the reasoning results of its own resources. The relative weights (W_r) of labor, material, and equipment for control-object 11120 are 0.141, 0.851, and 0.008, which are computed according to the data provided in Table 7.2. The elements of the matrix P_r (V_r, F_r), which describe the relation between the variances and problem source factors associated with control-object 11120 are calculated as $W_r \times P_r$ (V_r, F_r), and shown in Table 7.8.

Table 7. 8 Values of P_r (V_r, F_r) Relation for Resources

cum-min								
Resource	Labor				Material		Equipment	
$V_r \backslash F_r$	$f_{L1.1}$	$f_{L3.5}$	$f_{L3.6}$	$f_{L4.8}$	$f_{M1.2}$	$f_{M4.8}$	$f_{E4.8}$	f_{EOther}
V_{cv}	0.051	0.024	0.051	0.090	0.605	0.246	0.000	0.000
V_{sv}	0.000	0.000	0.000	0.127	0.000	0.766	0.006	0.008

By applying the fuzzy union operation of Equation (4.13), the P_{Co} (V_{Co}, F_{Co}) relation for control-object 11120 can be shown in Table 7.9.

Table 7. 9 Values of P_{Co} (V_{Co}, F_{Co}) Relation for Control-Object 11120

Resource	Labor			Material		Equipment
$V_{Co}\backslash F_{Co}$	$f_{L1.1}$	$f_{L3.5}$	$f_{L3.6}$	$f_{M1.2}$	$f_{M4.8}$	f_{EOther}
V_c	0.051	0.024	0.051	0.605	0.246	0.000
V_{sv}	0.000	0.000	0.000	0.000	0.766	0.008

The reasons for the poor cost performance of control-object 11120, using the fuzzy union operation, are factors 1.2, 4.8, 3.6, 1.1, and 3.5 as listed in Table 3.4, with calculated strength of 61.9%, 25.2%, 5.2%, 5.2%, and 2.5%, respectively. The reasons behind the poor schedule performance are factor 4.8 as listed in Table 3.4 and the user-specified factor of "un-expected soil type", with calculated strength of 99% and 1%, respectively.

Similarly, the elements of the matrix C_r (V_r, A_r), which represent the relation between the variances and the corrective actions associated with control-object 11120, were calculated as $W_r \times C_r$ (V_r, A_r), and shown in Table 7.10.

Table 7. 10 Values of C_r (V_r, A_r) Relation for Resources

cum-min								
Resource	Labor				Material		Equipment	
$V_r\backslash A_r$	$a_{L3.2}$	$a_{L3.9}$	$a_{L4.6}$	$a_{L6.4}$	$a_{M2.5}$	$a_{M4.6}$	$a_{E4.6}$	a_{EOther}
v_{r1}	0.051	0.024	0.090	0.051	0.605	0.246	0.000	0.000
v_{r2}	0.000	0.000	0.127	0.000	0.000	0.766	0.004	0.008

By applying the fuzzy union operation of Equation (4.13), the C_{Co} (V_{Co}, A_{Co}) relation for control-object 11120 can be shown in Table 7.11.

Table 7. 11 Values of C_{Co} (V_{Co}, A_{Co}) Relation for Control-Object 11120

Resource	Labor			Material		Equipment
$V_r \backslash A_r$	$a_{L3.2}$	$a_{L3.9}$	$a_{L6.4}$	$a_{M2.5}$	$a_{M4.6}$	a_{EOther}
v_{r1}	0.051	0.024	0.051	0.605	0.246	0.000
v_{r2}	0.000	0.000	0.000	0.000	0.766	0.008

The suggested actions to improve cost performance of control-object 11120, using the fuzzy union operation, are actions 2.5, 4.6, 3.2, 6.4, and 3.9 as listed in Table 4.1, with calculated strength of 61.9%, 25.2%, 5.2%, 5.2%, and 2.5%, respectively. The suggested actions to improve schedule performance are action 4.6 as listed in Table 4.1 and the user-specified action of “increase the strength of the soil”, with calculated strength of 99% and 1%, respectively. The reasoning report for control-object 11120 is then generated, using the reasoning and reporting modules, as shown in Fig. 7.25. In the developed system, the user can get this report by activating the link under the title of reason in the control-object level performance evaluation report as shown in Fig. 7.19.

A similar process is implemented for the project level reasoning. The project level reasoning report generated, using the reasoning and reporting modules for the time period, is captured as shown in Fig. 7.26. There is only one control-object in construction progress at this reporting date. Therefore, the project level reasoning report is the same as the control-object level reasoning report. The user can get this report by activating the link under the title of reason in the project level performance evaluation report as shown in Fig. 7.21.

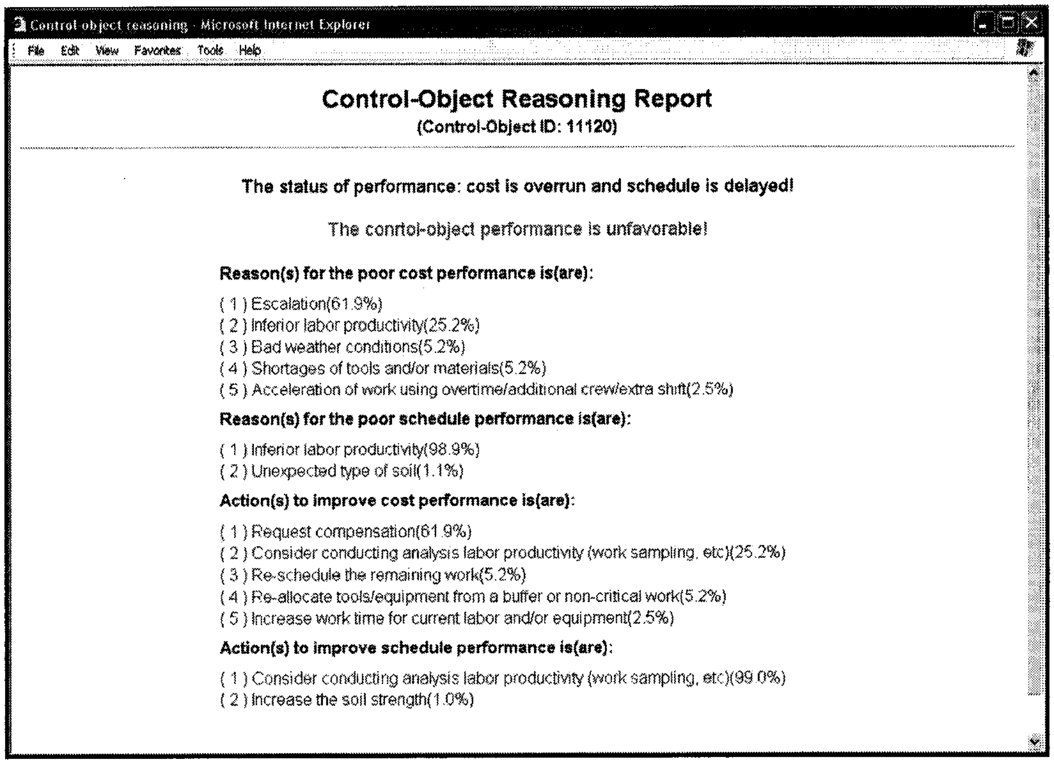


Figure 7. 25 Control-Object Reasoning Report

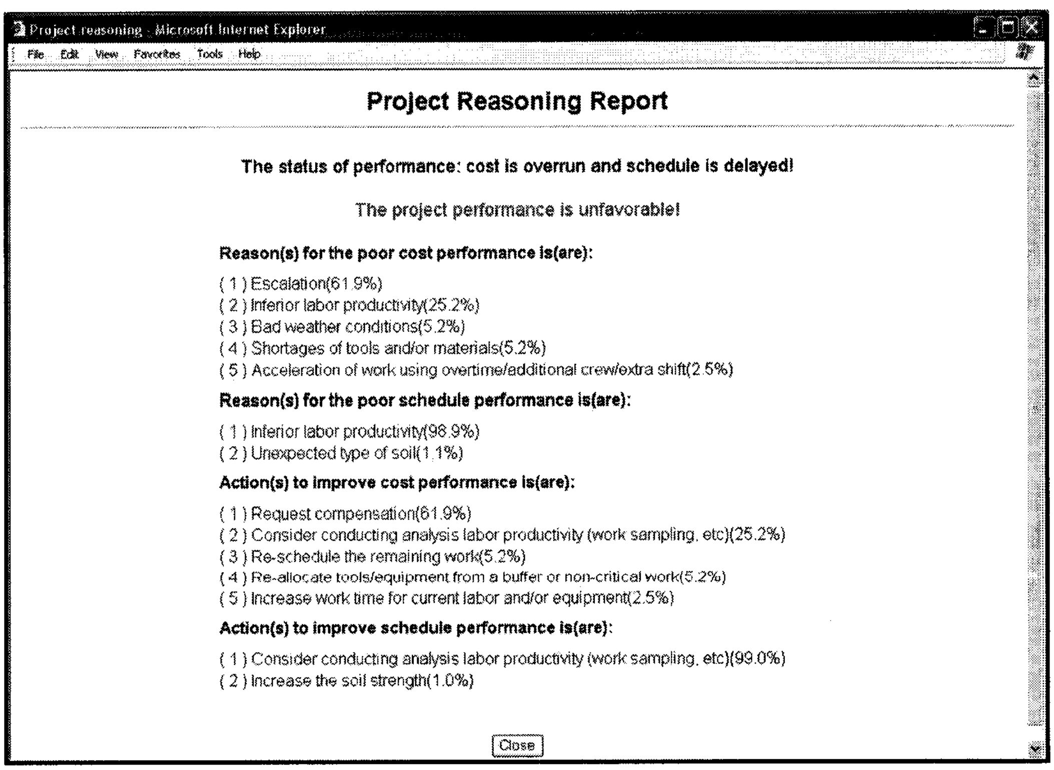


Figure 7. 26 Project Reasoning Report

7.3.3.3 Forecasting Reports

The proposed forecasting method is incorporated into and is an added utility to the IT/CC system as described earlier. Therefore, the IT/CC system provides tools to assist members of project teams in prediction of the duration and cost at remaining time horizon and at completion. To forecast duration and cost for a project, a control-object, and an individual type of resources, users need to activate the links under the forecast tile in their performance evaluation windows as shown in Figs. 7.15, 7.19, and 7.21. A new window is appeared to prompt the user input the future improvement/deteriorate conditions for each input variable before forecasting precede as shown in Figs. 7.28 and Appendix I. It is assumed that the future performance prior to the reporting date remains unchanged throughout the rest of the project, therefore, the default setting of those conditions are 1.0. The control-object 11120, which is used in the reasoning process, will continuously be utilized here to validate and to demonstrate the uses of the developed forecasting method. In order to demonstrate the functions of the developed prototype forecasting system, different types of scenarios are assumed and generated. A daily labor forecasting report is generated according to the actual cost and schedule data reported on March 11,1991. The calculated ratios for the indicators of control-object quantity, production, labor productivity, crew number, and crew payment at this reporting date are 1.0000, 0.9672, 0.9436, 1.0000, and 1.0121, respectively. These values serve as input variables for labor cost forecasting at the resource level. The MBFs of those input variables are then determined by undertaking a statistical analysis of the collected daily performance data for control-object 11120 from the starting date on Feb 15, 1991 till the evaluation date on March 11, 1991. The obtained standard deviations for these indicators of control-object quantity, production, labor productivity, crew number, and crew payment are 0.000, 0.074, 0.071, 0.000, and 0.0038, respectively. Those values are compared with the default threshold value of 0.279 (discussed in Section 5.4). Therefore, the default value of standard deviation is utilized to construct the MBFs for the 5 input variables. The mean values of these indicators are 1.0000, 0.8756, 0.8717, 1.0000, and 1.0017, respectively. The MBFs of those input variables were established accordingly (see example in Fig. 7.27).

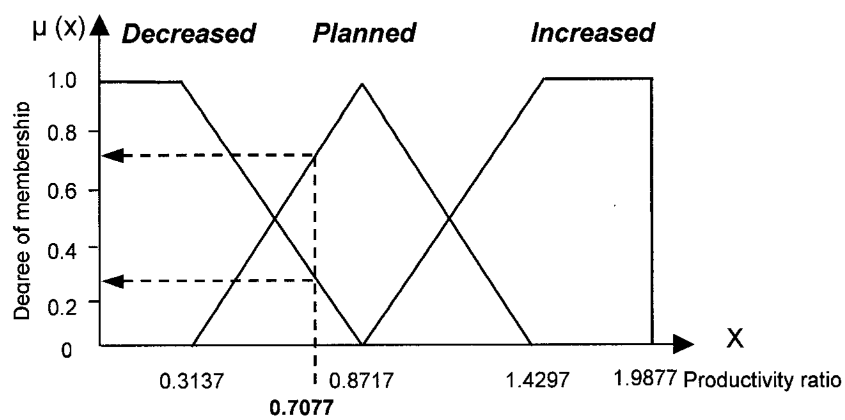


Figure 7. 27 MBFs for Input Variables of Labor Productivity

For calculating the degree of membership using the crisp value of the input indicator, the membership functions depicted in Fig. 7.27 are used. For the indicator of labor productivity, if the current value equals 0.9436, the degree of membership to the *Planned* status can be calculated using Equation (5.4):

$$\mu(0.9436) = \left| \frac{1.4297 - x}{0.558} \right| = \left| \frac{1.4297 - 0.9436}{0.558} \right| = 0.8711$$

The developed prototype forecasting system also allows users to specify percentage of improvement for each indicator through the web-page interface shown in Fig. 7.28. If the labor productivity in the near future will deteriorate by 25%, then, the current value of labor productivity is decreased 25% to reflect this change. The modified ratio of labor productivity is obtained as 0.9436 x (1-0.25)=0.7077. The modified labor productivity belongs to the *Decreased* and *Planned* values to degrees of 0.2939 and 0.7061, respectively (Fig. 7.27).

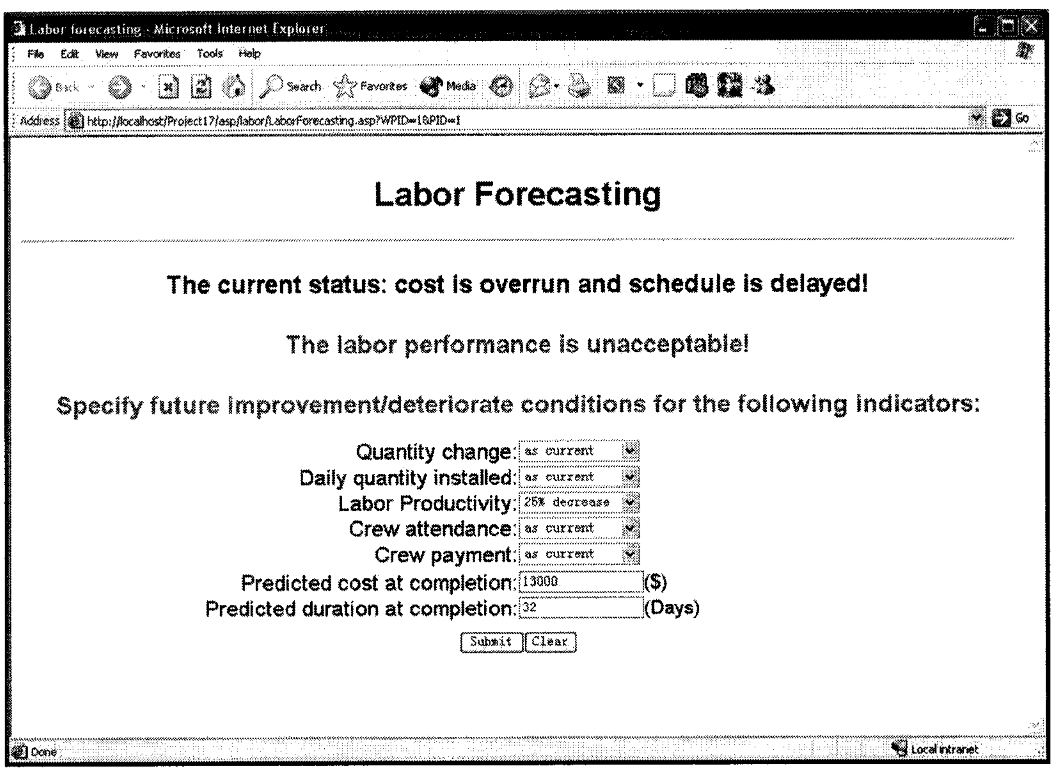


Figure 7. 28 Labor Forecasting

The 5 input variables are used for labor cost forecasting and their degrees of membership are obtained using Equations (5.1 to 5.6) can be expressed as a matrix of $\mu_{A_{1..5}}(u_o)$:

$$\mu_{A_{1..5}}(u_o) = \begin{array}{ll} & \begin{array}{ccc} \textit{Decreased} & \textit{Planned} & \textit{Increased} \end{array} \\ \begin{array}{l} \text{Quantity} \\ \text{Production} \\ \text{Productivity} \\ \text{Crew Number} \\ \text{Crew Payment} \end{array} & \begin{pmatrix} 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.8347 & 0.1653 \\ 0.2939 & 0.7061 & 0.0000 \\ 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.9812 & 0.0188 \end{pmatrix} \end{array}$$

Each rule has 1.0 degree of membership to its corresponding linguistic term. Therefore, the degrees of membership for all of corresponding rules can be expressed in a matrix form $\mu_{C_{1..5}}(w)$:

$$\mu_{C_{1..5}}(w) = \begin{array}{ll} & \begin{array}{ccc} \textit{Decreased} & \textit{Planned} & \textit{Increased} \end{array} \\ \begin{array}{l} \text{Quantity} \\ \text{Production} \\ \text{Productivity} \\ \text{Crew Number} \\ \text{Crew Pavment} \end{array} & \begin{pmatrix} 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 \end{pmatrix} \end{array}$$

By applying fuzzy inference of Equation (5.13), the consequences for labor cost forecasting can be expressed as a matrix of $\mu_{C'_{1..5}}(w)$:

$$\mu_{C_{1..5}}(w) = \begin{array}{l} \\ \text{Quantity} \\ \text{Production} \\ \text{Productivity} \\ \text{Crew Number} \\ \text{Crew Pavment} \end{array} \begin{array}{c} \begin{array}{ccc} \textit{Underrun} & \textit{Planned} & \textit{Overrun} \end{array} \\ \begin{pmatrix} 0.0000 & 1.0000 & 0.0000 \\ 0.1653 & 0.8347 & 0.0000 \\ 0.0000 & 0.7061 & 0.2939 \\ 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.9812 & 0.0188 \end{pmatrix} \end{array}$$

An example of graphic representation of fuzzy inference results $\mu_{C'_{1..5}}(w)$ using MBFs at 50% completion is shown in Fig. 7.29. The defuzzified values of the resultant fuzzy set using COS method for future interim horizons is listed in Table 7.12. These defuzzified values are, then, converted into the predicted values by multiplying the budgeted labor cost of $12400. The predicted cost using the data of the previous period at current reporting date is $9208.47. It should be noted that the previously predicted costs are initial forecasted cost without any adjustment. Clearly, it is greater than the actual cost, which is $6225.00. The cost difference is $2983.47. A self-learning process defined by Equation (5.15) is, then, applied to adjust the initial predicted values. The adjusted prediction of labor cost at completion and at interim future horizons is shown in Fig. 7.30. The actual labor cost at completion for control-object 11120 is $13825. The adjusted prediction results are very close to the actual cost at completion.

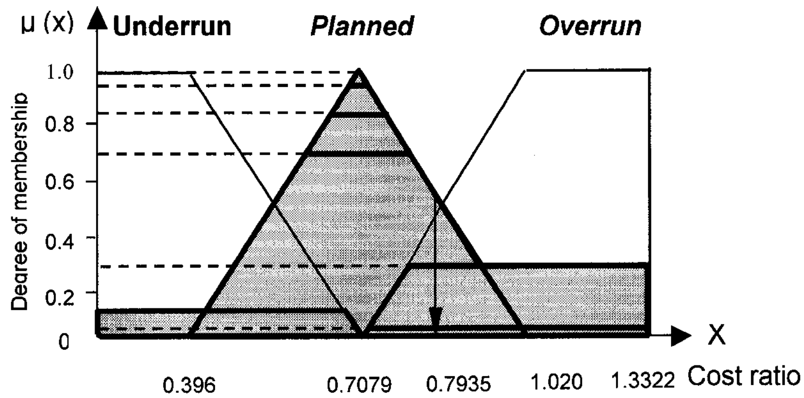


Figure 7. 29 Fuzzy Inference Results for Labor Cost

Table 7. 12 Defuzzification Result

Defuzzification method	Future interim horizons					
	50%	60%	70%	80%	90%	100%
COS	0.7935	0.9495	1.1055	1.2615	1.4175	1.584

Similarly, cost forecasting of material and equipment can be carried out. In order to generate different type of scenarios, the material usage in the future is assumed to be decreased 25% and equipment usage is assumed to be decreased 25%, their predicted cost at completion and at interim future horizons are listed in Table 7. 13. Their implementation reports can be found in Appendix I.

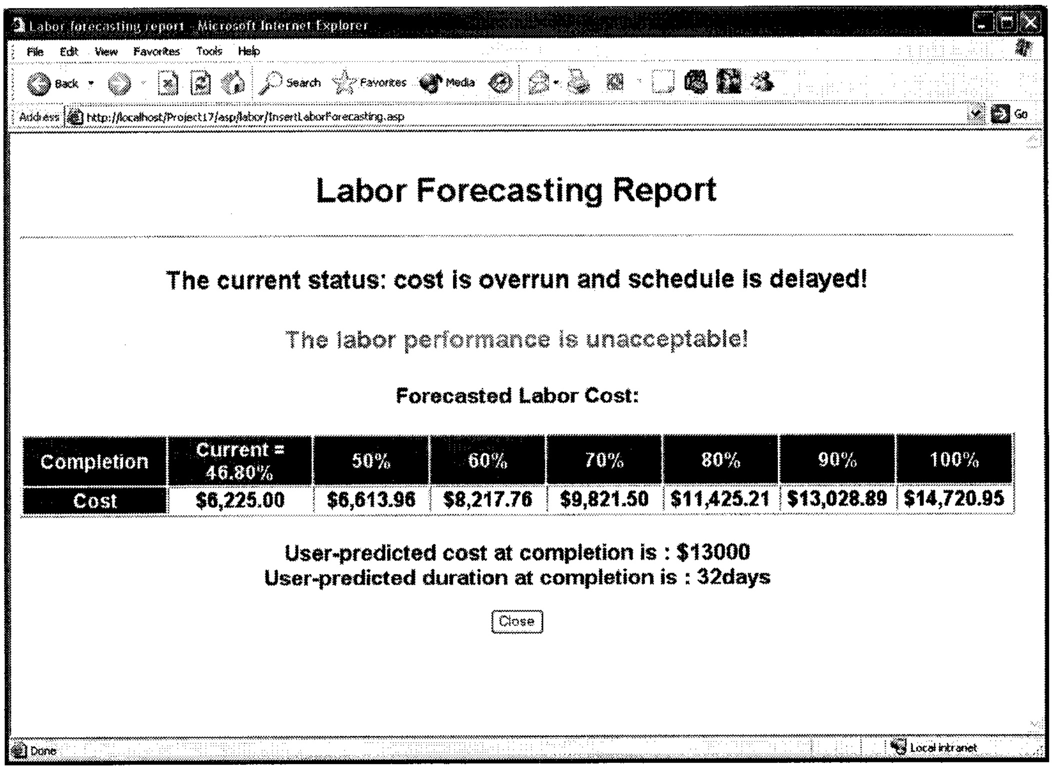
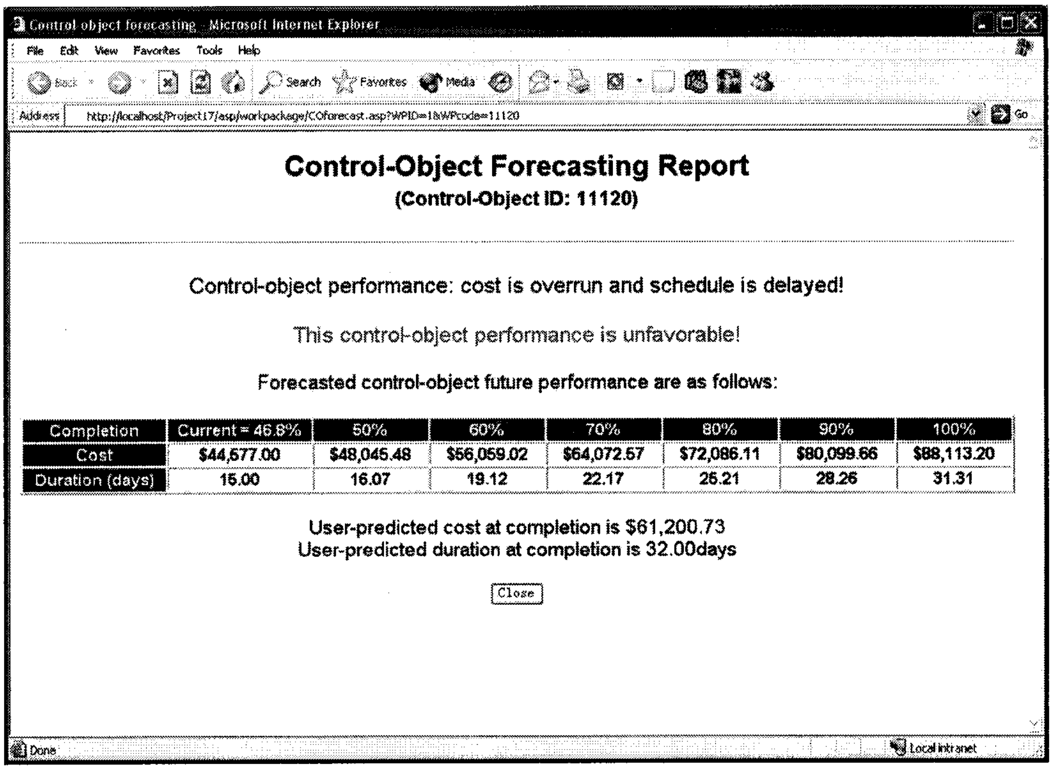


Figure 7. 30 Labor Forecasting Report

Table 7. 13 Forecasted Costs for Material and Equipment

Resource	Current	Future work progress horizons					
	46.80%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Material	$38,025.00	$40,453.96	$49,226.13	$57,997.89	$66,769.40	$75,540.75	$84,912.68
Equipment	$327.00	$346.91	$426.81	$506.71	$586.60	$666.49	$751.88

The cost forecasting at control-object level summarizes the cost forecasting results obtained from the forecasting method at the resource level. Control-object 11120 has its resources of labor, material, and equipment. Therefore, the predicted cost of control-object 11120 at reporting date of March 11, 1991 summarizes the predicted results for labor, material, and equipment as shown in Fig. 7.31. A similar method as cost forecasting at resource level is implemented for duration forecasting at control-object level as described below.



Control-Object Forecasting Report
(Control-Object ID: 11120)

Control-object performance: cost is overrun and schedule is delayed!

This control-object performance is unfavorable!

Forecasted control-object future performance are as follows:

Completion	Current = 46.8%	50%	60%	70%	80%	90%	100%
Cost	$44,577.00	$48,045.48	$56,059.02	$64,072.57	$72,086.11	$80,099.66	$88,113.20
Duration (days)	15.00	16.07	19.12	22.17	25.21	28.26	31.31

User-predicted cost at completion is $61,200.73
User-predicted duration at completion is 32.00days

Close

Figure 7. 31 Control-Object Forecasting Report

Two input variables are used for control-object duration forecasting. Their degrees of membership obtained using Equations (5.1 to 5.6) can be expressed as:

$$\mu_{A_{1,2}}(u_o) = \begin{array}{c c} & \begin{array}{ccc} \textit{Decreased} & \textit{Planned} & \textit{Increased} \end{array} \\ \begin{array}{c} \text{Quantity} \\ \text{Production} \end{array} & \begin{pmatrix} 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.8347 & 0.1653 \end{pmatrix} \end{array}$$

The degrees of membership for corresponding rules can also be expressed in the following form:

$$\mu_{C_{1,2}}(w) = \begin{array}{c c} & \begin{array}{ccc} \textit{Decreased} & \textit{Planned} & \textit{Increased} \end{array} \\ \begin{array}{c} \text{Quantity} \\ \text{Production} \end{array} & \begin{pmatrix} 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 \end{pmatrix} \end{array}$$

By applying fuzzy inference of Equation (5.13), the consequences for duration inference can be expressed as:

$$\mu_{C'_{1,2}}(w) = \begin{array}{l} \\ \text{Quantity} \\ \text{Production} \end{array} \begin{array}{c} \begin{array}{ccc} \textit{Decreased} & \textit{Planned} & \textit{Increased} \end{array} \\ \begin{pmatrix} 0.0000 & 1.0000 & 0.0000 \\ 0.1653 & 0.8347 & 0.0000 \end{pmatrix} \end{array}$$

An example of graphic representation of the resultant fuzzy set $\mu_{C'_{1,2}}(w)$ using MBFs at 50% completion is shown in Fig. 7.32. The defuzzified values using COS method for the remaining future work progress horizons are 0.4781, 0.5732, 0.6683, 0.7641, 0.8591, and 0.9542, respectively. The previously predicted duration at current reporting date using COS method is 13.86 days. Clearly, it is lower than the actual duration, which is 15.00 days. The duration difference is 1.14 days. Equation (5.16) is, then, applied to adjust the initial obtained values. The revised prediction of control-object duration at completion and at interim future horizons is shown in Fig. 7.31. The actual duration at completion for control-object 11120 is 31 days. The revised prediction results are also very close to the actual duration at completion.

The cost forecasting at project level only considers cost at completion. It summarizes the cost forecasting results for all the ongoing control-objects as well as actual costs for all accomplished control-objects. The duration forecasting at project-level summarizes predicted durations for the ongoing control-objects as well as actual durations for accomplished control-objects on the critical path. An example of project forecasting report on March 11, 1991 is shown in Fig.7.33.

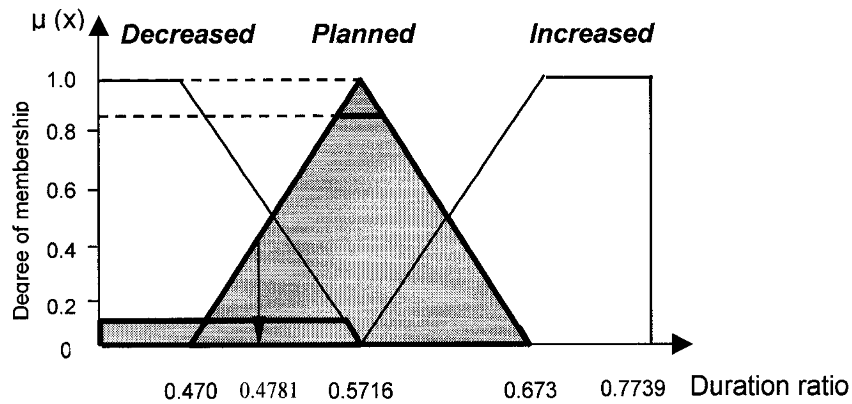


Figure 7. 32 Fuzzy Inference Results for Control-Object Duration

Another interesting feature of the developed forecasting system is that it allows the user to enter at completion cost and duration for each type of resources based on his/her own judgment and the experience. If the user-predicted cost and duration at completion for labor are $13000 and 31 days as shown in Fig.7.28, the system automatically saves these values into the "Reason" database for the use of control-object level forecasting. The user-predicted values are reported on the output screen as shown in Fig. 7.30. If a control-object like 11120 contains its resources of labor, material, and equipment, the user only predicts the labor cost and duration, the system predicted costs of material and equipment at completion are utilized to generate the user-predicted cost at control-object level as shown in Fig. 7.31. The user-predicted duration at control-object level takes the maximum value of the user-predicted durations for its associated resources as shown in Fig. 7.31. A similar method is implemented to generate the user-predicted cost at project level as shown in Fig.7.33. The user-predicted duration for a project summarizes the user-predicted durations for the on-going control-objects and the actual durations for accomplished control-objects on the critical path as shown in Fig. 7.33. If one or several user-predicted durations are missing, the use of the system predicted durations instead.

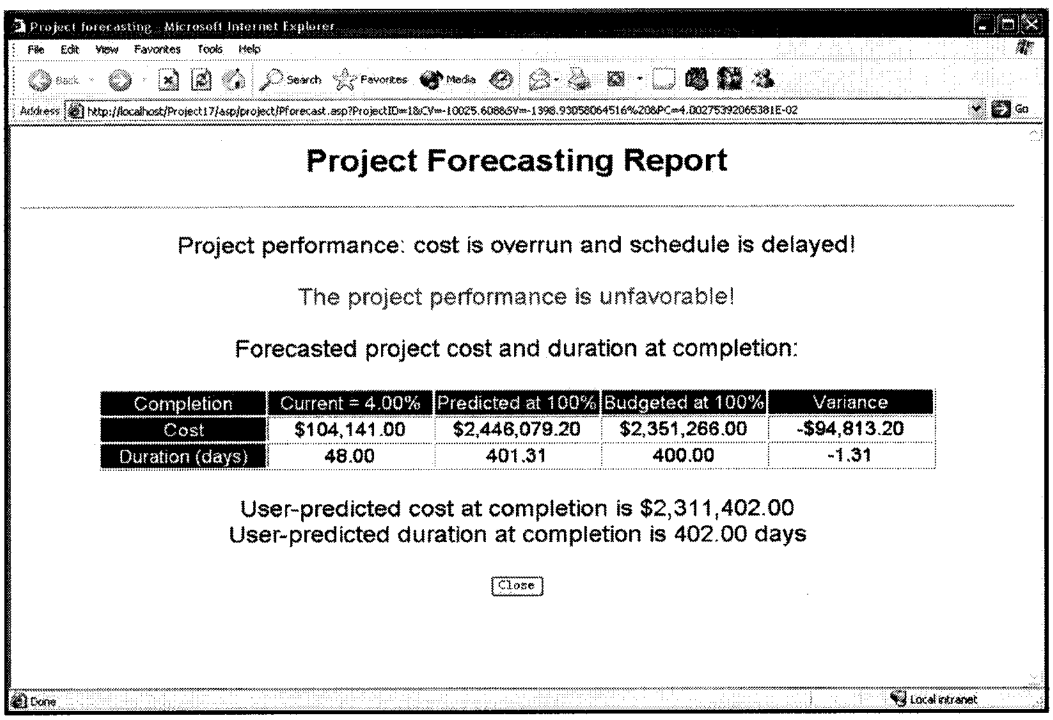


Figure 7. 33 Project Forecasting Report

7.3.3.4 Comparison with Earned-Value Based Methods

The developed forecasting method was also analyzed using the same case described in Section 7.3.3 and compared with those obtained using 4 earned-value based methods reported in the literature listed in Table 7.14. Mean absolute percent error (MAPE) is used to evaluate the accuracy of the developed forecasting method. The MAPE calculates average of the absolute values of the difference between the forecasted and actual encountered values and then expresses the difference as a percentage of the actual encountered value. Forecasted cost and duration using the developed method for the period of January 3 1991 to April 24 1991 are listed in Tables 7.15 and 7.16, respectively. Forecasted at completion cost and duration using the earned value-based methods and the developed methods for the same reporting period are listed in Tables 7.17 and 7.18, respectively. It should be noted that the accuracies of the prediction results are increased with the progress of control-objects. And that, unlike the earned-value based forecasting methods, the developed forecasting method not only predicts the cost and duration at completion, but also predicts their values at future interim horizons. With more historical performance data available, when each input variable has its own default value of standard deviation, the better forecasting results could be generated by the developed forecasting method. The results also indicate that the constant performance efficiency factor method (Fleming and Koppelman 1994) provides the best prediction result for cost. The generic index-based method (Christensen 1992) provides the best prediction result for duration.

Table 7. 14 Earned Value-Based Forecasting Methods

Reference		Forecast at completion	
No.	**Name**	**Cost**	**Duration**
1	Shtub et al. (1994)	$EAC = \frac{BAC}{CPI}$	$D_c = \frac{D_b}{SPI}$
2	Fleming and Koppelman (1994)	$EAC = \frac{BAC}{CPI \times SPI}$	$D_c = \frac{D_b}{SPI \times CPI}$
3	Christensen (1992) and Christensen et al. (1995)	$EAC = ACWP + (BAC - BCWP)$	$D_c = D_a + D_b(1 - PC_a)$
4	Christensen (1992) and Christensen et al. (1995)	$EAC = ACWP + (\frac{BAC - BCWP}{CPI \times SPI})$	$D_c = D_a + \frac{D_b(1 - PC_a)}{CPI \times SPI}$

Table 7. 15 The Accuracy of the Developed Cost Forecasting Method

Work completion	Future interim horizons (MAPE %)										Average
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
0~10%	36.51	35.76	35.05	40.00	34.56	29.38	28.69	27.98	23.28	20.50	31.17
10~20%		13.92	14.52	16.71	15.52	14.41	14.26	13.62	11.43	10.49	13.88
20~30%			-0.26	8.41	8.74	8.77	9.07	9.53	9.15	9.44	7.86
30~40%				2.56	5.03	6.65	7.24	7.56	7.93	9.13	6.59
40~50%					3.53	4.25	4.56	4.75	5.88	7.08	5.01
50~60%						1.29	0.91	1.65	2.42	3.59	1.97
60~70%							1.40	1.19	1.67	2.43	1.67
70~80%								1.59	1.83	2.42	1.95
80~90%									1.69	1.85	1.77
90~100%										0.94	0.94

Table 7. 16 The Accuracy of the Developed Duration Forecasting Method

Work completion	Future interim horizons (MAPE %)										Average
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	
0~10%	65.86	45.04	36.92	33.26	32.03	31.01	29.72	28.41	27.29	26.39	35.59
10~20%		7.89	4.24	3.75	5.39	6.38	6.59	6.37	6.14	5.95	5.86
20~30%			10.34	6.27	6.13	5.93	5.67	5.32	5.03	4.80	6.19
30~40%				5.10	2.17	2.87	3.05	2.93	2.81	2.72	3.10
40~50%					0.91	1.49	1.65	1.63	1.53	1.44	1.44
50~60%						0.58	1.10	1.65	2.00	2.33	1.53
60~70%							0.56	0.31	0.87	1.32	0.77
70~80%								0.91	0.66	0.51	0.69
80~90%									0.38	0.37	0.37
90~100%										0.13	0.13

Table 7. 17 Comparison the Accuracy of Cost Forecasting Methods

Work completion	No. 1	No.2	No.3	No.4	Proposed
0~10%	7.25	60.46	15.67	56.91	20.50
10~20%	4.66	47.19	18.96	41.04	10.49
20~30%	2.68	33.06	17.08	25.12	9.44
30~40%	4.57	30.49	16.07	21.26	9.13
40~50%	3.97	19.00	13.58	11.98	7.08
50~60%	3.23	13.43	11.23	7.77	3.59
60~70%	2.80	10.33	9.00	5.32	2.43
70~80%	2.93	7.80	7.00	4.08	2.42
80~90%	2.20	5.79	4.58	2.71	1.85
90~100%	0.64	3.80	1.83	0.83	0.94
Average	3.49	23.14	11.50	17.70	6.79

Table 7. 18 Comparison the Accuracy of Duration Forecasting Methods

Work completion	No. 1	No.2	No.3	No.4	Proposed
0~10%	26.84	84.22	9.43	79.18	26.39
10~20%	15.02	52.62	6.85	47.83	5.95
20~30%	7.42	40.98	6.81	33.12	4.80
30~40%	5.01	35.96	5.55	25.46	2.72
40~50%	5.79	26.29	4.56	16.27	1.44
50~60%	5.77	21.20	3.43	10.78	2.33
60~70%	5.98	17.95	2.47	7.08	1.32
70~80%	6.36	15.41	1.67	4.53	0.51
80~90%	9.33	13.75	1.20	2.84	0.37
90~100%	0.21	14.45	0.08	1.50	0.13
Average	8.77	32.28	4.20	22.86	4.60

7.4 Summary

In this Chapter, the proposed evaluating, reasoning, and forecasting methods along with their implementation scenarios were introduced. A numerical example drawn from literature is utilized to test and validate the developed prototype and to demonstrate the use and capabilities of the developed IT/CC system. The results obtained using the developed evaluating and forecasting methods are compared to those produced by earned-value based methods. The results have shown that the developed evaluation, reasoning, and forecasting methods can improve the current practices of project control functions. IT/CC system also provides an efficient collaborative information-sharing environment for project teams in monitoring and controlling construction site activities by taking advantage of the World Wide Web.

SUMMARY, CONTRIBUTIONS AND RECOMMENDATIONS

8.1 Summary

A methodology for evaluating and forecasting construction performance and reasoning about it with respect to time and cost has been developed. The developed methodology was implemented on the Internet. The developed IT/CC system evaluates project performance, diagnoses reason(s) behind poor performance, suggests possible corrective action(s), and forecasts the cost and duration at completion and at interim future horizons. The system utilizes an object model, evaluation method, reasoning process, and forecasting method for performing its tasks. It can be accessed via the Internet.

The developed object model represents the data structure of a project using an Object-Oriented concept. It facilitates the integration of project time and cost information for control purposes. The model is flexible enough to accommodate different configurations of building components such as WBS and PBS. A hierarchy structure of a three-level performance evaluation method is established based on the earned-value concept, which is still the most commonly used method for identifying the time and cost variances in an integrated manner. Performance evaluation can be executed at project, control-object, and resource levels. The developed method not only calculates the time and cost variances at each control level for an on-going project, but also evaluates the calculated variances according to pre-defined criteria.

The developed reasoning method uses causal models and fuzzy binary relation operations to explain the reason(s) behind unacceptable performance. This method uses 18 resource performance indicators and one factor indicator as sensors to help users diagnose the impact factor(s), referred to as reasons, behind the identified variances. Four causal models are developed to define the relationships among the indicators. The estimated impact-cost for each indicator defines the linkage strengths between the indicators and the cost and schedule variances. The identified reason(s) is (are) further used to recommend corrective action(s).

The forecasting method is developed using a fuzzy inference engine. This method uses 13 terminal indicators as input variables to predict future cost values. Two terminal indicators are used to predict the future durations. Statistical analysis of collected data is used to establish the MBFs for each input and output variable. Three linguistic terms define the linguistic values for input and output variables in the fuzzy inference process. Thirty-six rules are elicited for the inference process. The COS method is used to defuzzify the output values into crisp numbers. A self-learning adjustment process is developed to improve the accuracy of the forecasted values.

The prototype IT/CC system is developed using Three-Tier Client Server architecture. UML (Unified Modeling Language) is used in the design of the system. Sixty web forms serving different input, browsing, and editing purposes are developed. Five databases, namely, *Project*, *Reason, Coefficient*, *Case,* and *Historical,* are developed to facilitate the implementation of the IT/CC system. The *Project* database represents the data structure of the developed object model. It contains the budgeted cost data, the actual cost data, and the planned data of a project. The *Reason*, and the *Factor* databases manage performance impact factors, corrective actions, user-defined linkage strengths for reasoning purposes, and user-defined weights for forecasting purposes. The *Case* database saves, for future reference, planned and actual performance data of control-objects that have repetitive nature. Upon project completion, all information collected in the project database is transferred to the *Historical* database. The IT/CC system takes advantage of the World Wide Web to provide an efficient data sharing and collaborating environment for tracking and control of construction activities. It also provides timely generation and dissemination of site progress reports. Daily, weekly, monthly and/or yearly, period-by-period, and cumulative to-date performance reports are generated to provide the status at project, control object, and resource levels. The on-line data sharing capabilities provide real-time data for team members and allows them to react in a timely manner.

The system has been developed using Microsoft Access database 2000, ASP, JavaScript, Java Applet, VB script, and HTML. It runs in Microsoft Window NT and Window 2000 environments. A numerical example has been analyzed to validate the functions of the developed system and to demonstrate its essential features. The developed IT/CC system provides a new efficient mechanism to help project teams to track and control engineering, procurement, and construction projects.

8.2 Contributions

Aiming to provide an efficient methodology for integrated project time-and-cost control, the contributions of this research towards circumventing the limitations associated with current practice can be summarized as follows:

1. A comprehensive review of the project control models, performance evaluation methods, reasoning methods, and forecasting methods was done.

2. State-of-the-art review of computer technology difficulties in collaborative project control was done, including methods and platforms used.

3. Development of an object model that facilitates the integration of project time-and-cost control functions. The model has the flexibility to include

different configurations of building components such as WBS and PBS. It can also be incorporated with the standard of IFCs.

4. Development and implementation of three-level hierarchy structure performance evaluation method to calculate and assess the time and cost variances at each control level for an on-going project.

5. Development and implementation of fuzzy reasoning process to explain the reason(s) behind unacceptable performance and to suggest corrective action(s) accordingly.

6. Development and implementation of a fuzzy forecasting method to predict cost and duration at completion and at future interim horizons.

7. Development and implementation of web based *Project*, *Factor*, *Reason, Case*, and *Historical* databases to facilitate the storage of the project information for control purposes.

8. Development and implementation of a web-based integrated project time and cost control system (IT/CC) based on the developments and implementations referred to above. IT/CC establishes a hierarchy

structure of a three-level project control platform. It provides an efficient collaborative information-sharing environment for project teams in monitoring and controlling construction site activities by taking advantage of the World Wide Web.

9. Validation and demonstration of the capabilities of the developed methods through a real project case drown from the literature.

8.3 Limitations of the Developed System

The developed systems and methods, however, suffer a number of limitations as described below:

1. The developed IT/CC system is limited to time and cost control of construction projects.

2. The reasoning system is limited to helping users identify, interactively, factor(s) behind unacceptable performance along with related corrective action(s) if possible.

3. The user-specified factors and actions only apply for one time reasoning. Higher-level approval is needed when they are added in the system.

There is no syntax and grammar check for the user-specified problem-source factor(s) and corrective action(s).

4. The data about the project budget and the data about the actual performance have to be manually input into the system database through specially designed web forms.

5. The system can only be used when a project baseline has been determined.

8.4 Recommendations for Future Work

A methodology and a computational platform for tracking and control of the time and cost of a construction project have been presented in this study. The platform is flexible and can be applied to a wide range of project. However, in order to expand the potential applications of this platform, the following recommendations for future research can be made:

1. Explore the use of additional factor indicators in the reasoning method. Consider other types of composition methods, beyond used in this study, such as product and neural networks. The domain-specific default values of linkage strengths may be determined in the future by considering the

project history performance data. More real cases are needed to test and validate each reasoning scenario.

2. Consider improvement of the membership functions for input and output variables using fuzzy clusters when more repetitive projects and/or control-objects data are available. Also expand these membership functions to include intervals such as "*Small Decrease*", "*Medium Decrease*", and "*Large Decrease*".

3. Consider the use of fuzzy-neural networks when more historical data are available, and regression models making use of the resource performance indicators.

4. Consider the interdependency of the input variables in the developed forecasting method.

5. Link the developed reasoning and forecasting methods.

6. Automatic data entry.

7. Expand the reporting module in the developed IT/CC system to generate customized reports.

8. Consider the integration of the developed system with the standards of IFCs.

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Appendix (A) Internet-Based Questionnaire Surveys

A.1 Questionnaire Survey I

Integrated Project Time and Cost Control System

Questionnaire Survey

This is the first part of an internet based questionnaire survey intended to consolidate available knowledge on integrated construction project time and cost control systems. This part contains questions on the project time and cost performance indicators. The second part is on corrective actions.

Please answer all the following questions if possible.

---

1. Respondent Background:

First Name:	(Optional)
Last Name:	(Optional)
Country:	[select answer from list]
You are working in:	[select answer from list]
Working experience in Industry:	[select answer from list]
Working experience in Contractor administration:	[select answer from list]

---

2. Please Select The Effective Project Control Element for Contractors:

- **Work-package**
- **Activity**
- **Work task**
- **Others** (please specify)

---

3. Please Select the Time Span of Project Control for Contractors (you may select one or all of them):

- **Accumulated to date**
- **In a time period**
- **At completion**
- **Others** (please specify)

---

4. Identification Project Time and Cost Performance Evaluation Criteria for Contractors:

The following project time and cost performance evaluation criterion has been identified in the literature. Please select the criteria that in your opinion best evaluate the time and cost performance at project level.

4.1) Criteria for 'Time Performance' aspects:

- [ ] **Schedule Variance**
- [ ] **Schedule Performance Index SPI**
- [ ] **Detailed Productivity Analysis**
- [ ] **Duration Trend Analysis**
- [ ] **Working Hour Per Unit Analysis**

Others ______ **(please specify)**

Comments on schedule performance: ______ (please specify)

4.2) Criteria for 'Cost Performance' aspects:

- [ ] **Cost Variance**
- [ ] **Cost Performance Index CPI**
- [ ] **Detailed Cost Ratio Analysis**
- [ ] **Cost Trend Analysis**
- [ ] **Unit Cost Analysis**

Others ______ (please specify)

Comments on cost performance criteria: ______ (please specify)

Please enter any other evaluation criteria recommended by you with your comments/ suggestions:

---

5. Identification of Project Time and Cost Performance Evaluation Sub-criteria for Control Elements of Contractors:

Please chose project time and cost performance evaluation sub-criteria for tracking and control the following aspects of project performance. You may select one or more items.

5.1) Sub-criteria for 'Labor' aspects:

5.1.1) Labor Time Performance

- Crew Working Hour Variance
- Crew Working Hour Ratio
- Crew Productivity Ratio
- Crew Working Hour Trend Analysis

Others (please specify)

5.1.2) Labor Cost Performance

- Crew Cost Variance
- Unit Crew Cost Ratio
- Average Crew Cost Per Working Hour
- Crew Cost Trend Analysis
- Crew Mix Rate (Crew Number Analysis)
- Average Crew Pay Rate (Crew Salary Analysis)

Others (please specify)

Comments on labor sub-criteria: (please specify)

5.2) Sub-criteria for 'Material' aspects:

5.2.1) Material Time Performance

- Material Delivery Delay

Others (please specify)

5.2.2) Material Cost Performance

- Material Cost Variance
- Unit Material Cost Ratio
- Material Unit Price Ratio
- Unit Material Quantity Usage Ratio

Others (please specify)

Comments on material sub-criteria: (please specify)

5.3) Sub-criteria for 'Equipment' aspects:

5.3.1) Equipment Time Performance

- [ ] **Equipment Working Hour Variance**
- [ ] **Equipment Working Hour Ratio**
- [ ] **Equipment Productivity Ratio**
- [ ] **Equipment Working Hour Trend Analysis**

Others (please specify)

5.3.2) Equipment Cost Performance

- [ ] **Equipment Cost Variance**
- [ ] **Equipment Cost Ratio**
- [ ] **Operating Cost Ratio**
- [ ] **Maintenance Ratio**
- [ ] **Equipment Cost Trend Analysis**
- [ ] **Equipment Cost Per Working Hour**
- [ ] **Equipment Usage Rate**

Others (please specify)

Comments on equipments sub-criteria: (please specify)

Please enter any other evaluation sub-criteria that you recommended with your comments/ suggestions:

---

6. Please answer all the following questions if possible:

6.1 Comparing with the total project cost, How much in percentage saving can be achieved through tracking and control the performance of projects.

(Please select the percentage recommended by you.)

- <5%
- 5%~10%
- 10%~15%
- 15%~20%
- >20%
- No Comments

6.2 Which of the following activities need to be tracked in order to achieve effective project control:

(Please select the activities recommended by you)

- **Critical Path Activities**
- **All Activities**
- **Activities with a total free time of zero**
- **Activities with a cost of** [No Comments] **of total project cost (absolute threshold value)**

---

7. Any other comments and suggestions:

Overall comments (optional):

Please press the 'Submit' button for submitting your response or 'Clear' button for clearing the whole form to fill it up again.

Submit

Clear

A.2 Questionnaire Survey II

Project Time & Cost Control System

Questionnaire Survey II

This is the second part of an Internet-based questionnaire survey intended to consolidate available 'knowledge' on construction project time and cost control system. This part contains questions on possible 'Problem Source Factors' and possible 'Corrective Actions.' Please answer all questions if possible.

---

1. Respondent's Background:

First Name: (optional)

Last Name: (optional)

Email Address: (optional)

Name of your organization: (optional)

Country: [select best answer from list]

You are working in: [select best answer from list]

Working experience in Industry: [select best answer from list]

Working experience in Project Management/Contract administration: [select best answer from list]

---

2. Identification of possible 'Problem Source Factors' that are associated with the indicators used in project control:

A set of indicators representing labor, material, equipment, and subcontractors has been used to diagnose the reason(s) behind variances. Please select possible 'Problem Source Factors' that impact individual indicator. You may choose one or more factors for each indicator.

---

2. 1) Factors attributed to 'Quantity' variation in work package/product unit (or activity, or work element):

Inadequate and/or incomplete design

The work scope changes within contract limits/Change orders

Others (please specify)

Additional comments: (please specify)

2. 2) Factors attributed to inferior 'Labor Productivity':

- Unsuitable weather or climate conditions
- Inadequate control of worksite conditions
- Restricted work area
- Site congestion
- Inadequate planning of construction work
- Inadequate instruction on construction methods
- Inadequate supervision of work
- Change of construction methods
- Shortages of working tools or materials
- Poor design/construction coordination
- Inadequate safety facilities
- Poor cost/duration estimates
- Poor management and/or labor relations
- Use of untrained and/or inexperienced labor force
- Change of crew attendance
- Others ______ (please specify)

Additional comments: ______ (please specify)

2. 3) Factors attributed to Crew Payment' variation:

- Poor workmanship/re-work
- Accelerating of work using overtime
- Change of crew attendance
- Inferior labor productivity
- Inferior equipment productivity
- Others ______ (please specify)

Additional comments: ______ (please specify)

2. 4) Factors attributed to Crew Attendance' variation:

- Inadequate skilled labor force
- Use of unbalanced crew/crew mix change
- Labor absentee/Crew attendance
- Labor unrest/on strike

Others ______ (please specify)

Additional comments: ______ (please specify)

2. 5) Factors attributed to 'Material Usage' variation:

- Poor estimation
- Delayed material delivery
- Inferior equipment productivity
- Material damage, loss, or theft
- Poor workmanship/re-work
- Inferior labor productivity
- Material wastage

Others (please specify)

Additional comments: (please specify)

---

2. 6) Factors attributed to 'Material Price' variation:

- Escalation
- Use of alternative material

Others (please specify)

Additional comments: (please specify)

---

2. 7) Factors attributed to inferior 'Equipment Productivity':

- Unsuitable weather or climate conditions
- Inappropriate ground conditions
- Use of untrained and/or inexperienced operators
- Poor estimation
- Shortages of working tools or materials

Others (please specify)

Additional comments: (please specify)

---

2. 8) Factors attributed to 'Equipment Usage' variation:

- Inadequate control of equipment operations
- Inadequate planning of equipment operations
- Equipment failure/Inadequate maintenance

Others (please specify)

Additional comments: (please specify)

---

2. 9) Factors attributed to inferior 'Productivity' for sub-contractors (in addition to the factors in 2.2 and 2.7):

- [ ] Inadequate communication and/or coordination
- [ ] Deferred payment

Others (please specify)

Additional comments: (please specify)

---

3. Identification of possible 'Corrective Actions':

The following 'Corrective Actions' for above-mentioned problem source factors have been identified in the literature and experience consortium. Please rank the following aspects by frequency in an ascending order (with '1' being 'rarely adopted,' 'larger number' being 'more frequently adopted,' and 'X' [the default] being 'No comments').

---

3. 1) Corrective actions for poor performance resulting from 'Weather':

X Monitor the work but do nothing

X Provide a protected environment to prevent loss of productivity

X Re-schedule the remaining work

X Stop the work to prevent loss of productivity

X Request a project time extension

Others (please specify)

Additional comments: (please specify)

---

3. 2) Corrective actions for poor performance resulting from 'Unfavorable work conditions":

X Re-examine construction site layout

X Use multiple shifts

X Re-examine safety facilities and program

X Use extra support or shoring to alleviate poor ground conditions

X Use alternative construction method

X Improve worksite conditions

X Conduct site soil investigation

Others (please specify)

Additional comments: (please specify)

---

3. 3) Corrective actions for poor performance resulting from 'Poor estimation':

X Re-examine the planned cost and/or duration

X Consider alternative materials

X Consider revising project baseline

X Re-schedule the remaining work

X Request a project time extension

Others (please specify)

Additional comments: (please specify)

---

3. 4) Corrective actions for poor performance resulting from 'Work scope changes, i.e. Changes of order':

X Re-allocate skilled labor from a buffer or non-critical work

X Request a project time extension

X Re-schedule the remaining work

X Increase work time for current labor and/or equipment

X Use a rover crew (consider specialized crew over and above the regular work force)

Others (please specify)

Additional comments: (please specify)

---

3. 5) Corrective actions for poor performance resulting from 'Escalation or Deflation':

X Consider alternative materials

X Request compensation

Others (please specify)

Additional comments: (please specify)

---

3. 6) Corrective actions for poor performance resulting from 'Inadequate planning, supervision, and control of work':

X Re-examine the work plan

X Re-schedule the remaining work

X Improve design/construction coordination

X Improve supervision of work

X Re-examine the instructions of construction crews

X Use alternative construction method

X Use more equipment and less labor intensive construction method

Others (please specify)

Additional comments: (please specify)

---

3. 7) Corrective actions for poor performance resulting from 'Inadequate skilled labor force':

X Consider additional skilled labor force

X Consider training program

X Increase work time for current labor force

X Re-examine crew balance or mix

X Use more equipment and less labor intensive construction method

X Re-allocate skilled labor from a buffer or non-critical work

Others (please specify)

Additional comments: (please specify)

---

3. 8) Corrective actions for poor performance resulting from 'Low work morale or Labor fatigue':

X Consider financial incentive program and/or other motivational programs

X Consider additional skilled labor force

X Re-examine management of labor relations and safeties

X Improve supervision of work

Others (please specify)

Additional comments: (please specify)

3.9) Corrective actions for poor performance resulting from 'Inferior equipment productivity' (in addition to the actions in 3.1, 3.2, 3.3, and 3.6):

X Improve equipment maintenance system

X Use skilled operator

X Optimize equipment selection

X Re-allocate tools/equipment from a buffer or non-critical work

X Purchase or rent backup tools/equipment

Others (please specify)

Additional comments: (please specify)

---

3. 10) Corrective actions for poor performance resulting from 'Material wastage, damage, loss or theft':

X Improve supervision of work

X Improve material handling and/or storage management

Others (please specify)

Additional comments: (please specify)

---

3. 11) Corrective actions for poor performance resulting from 'Material delivery delay':

X Use alternative routes of access

X Re-schedule work to hours with less traffic

X Improve material handling and/or storage management

Others (please specify)

Additional comments: (please specify)

---

3. 12) Corrective actions for poor performance resulting from 'Inferior sub-contractor productivity' (in addition to the actions in 3.1, 3.2, 3.3, and 3.6):

X Improve sub-contractor coordination

X Improve sub-contractor management

X Consider timely processing of interim payments

X Consider conducting analysis of sub-contractor's productivity

X Use alternate shifts for interfering sub-contractor

Others (please specify)

Additional comments: (please specify)

4. Any other comments and suggestions:

Other comments (optional):

Please press the 'Submit' button for your response or 'Clear' button to clear and fill up the Form again.

Submit

Clear

Appendix (B) Progress Measurement Templates

Table B-1 Generalized Progress Measurement Template

Task Specified Progress Measurement Template		
Task	**Work Content**	**Cumulative % Earned**
Piling		
1	Rig in position	40
2	Drive and inspect	80
3	Trim and finish	95
4	Hand over	100
Earthworks		
1	Excavation	50
2	Backfill	60
3	Compact	90
4	Fine grade	95
5	Hand over	100
Foundations		
1	Building	5
2	Formwork	50
3	Rebar and embedment	80
4	Pour	87
5	Strip cure and grout	95
6	Hand over	100
Main steel structures		
1	Columns	20
2	Beams	40
3	Gratings, handrails, ladders	80
4	Final alignment	85
5	Punch and fix	95
6	Hand over	100
Paving		
1	Lay mesh and formwork	70
2	Pour concrete	90
3	Strip cure	95
4	Hand over	100

Table B-2 Generalized Progress Measurement Template (Continue)

Task	Work Content	Cumulative % Earned
Buildings		
1	Erect structure	20
2	Complete roof	40
3	Complete external walls	55
4	Complete internal walls	70
5	Utilities	95
6	Hand over	100
Piping underground		
1	Install pipe	15
2	Level, butt and joint	40
3	Install fittings and wrap	70
4	Punch and fix	80
5	Hydro test	95
6	Hand over	100
HVAC		
1	Supports	10
2	Ducting and fitting	65
3	Install unit	80
4	Complete and test	90
5	Punch and fix	95
6	Hand over	100

Table B-3 Generalized Progress Measurement Template (Continue)

<table>
<tr><th rowspan="2">COST</th><th colspan="3">DURATION</th></tr>
<tr><th>Very Short</th><th>Short</th><th>Long</th></tr>
<tr><td>Low</td><td>0,100</td><td>50,100</td><td>20,100</td></tr>
<tr><td rowspan="2">High</td><td rowspan="2">0,100</td><td>20,100</td><td rowspan="2">20,100</td></tr>
<tr><td>30,100</td></tr>
</table>

Appendix (C) Rules Developed for Forecasting

Table C-1 Rules Developed for Material Cost

Quantity	(1) *Decreased* Then *Decreased*	(2) *Planned* Then *Planned*	(3) *Increased* Then *Increased*
Production	(4) *Decreased* Then *Increased*	(5) *Planned* Then *Planned*	(6) Increased Then *Decreased*
Usage	(7) *Decreased* Then *Decreased*	(8) *Planned* Then *Planned*	(9) *Increased* Then *Increased*
Unit Price	(10) *Decreased* Then *Decreased*	(11) *Planned* Then *Planned*	(12) *Increased* Then *Increased*

Note: Rule numbers are in parentheses

Table C-2 Rules Developed for Equipment Cost

Quantity	(1) *Decreased* Then *Decreased*	(2) *Planned* Then *Planned*	(3) *Increased* Then *Increased*
Production	(4) *Decreased* Then *Increased*	(5) *Planned* Then *Planned*	(6) Increased Then *Decreased*
Productivity	(7) *Decreased* Then *Increased*	(8) *Planned* Then *Planned*	(9) *Increased* Then *Decreased*
Usage Rate	(10) *Decreased* Then *Decreased*	(11) *Planned* Then *Planned*	(12) *Increased* Then *Increased*

Note: Rule numbers are in parentheses

Table C-3 Rules Developed for Sub-contractor Cost

Quantity	(1) *Decreased* Then *Decreased*	(2) *Planned* Then *Planned*	(3) *Increased* Then *Increased*
Production	(4) *Decreased* Then *Increased*	(5) *Planned* Then *Planned*	(6) Increased Then *Decreased*
Productivity	(7) *Decreased* Then *Increased*	(8) *Planned* Then *Planned*	(9) *Increased* Then *Decreased*
Hourly Rate	(10) *Decreased* Then *Decreased*	(11) *Planned* Then *Planned*	(12) *Increased* Then *Increased*

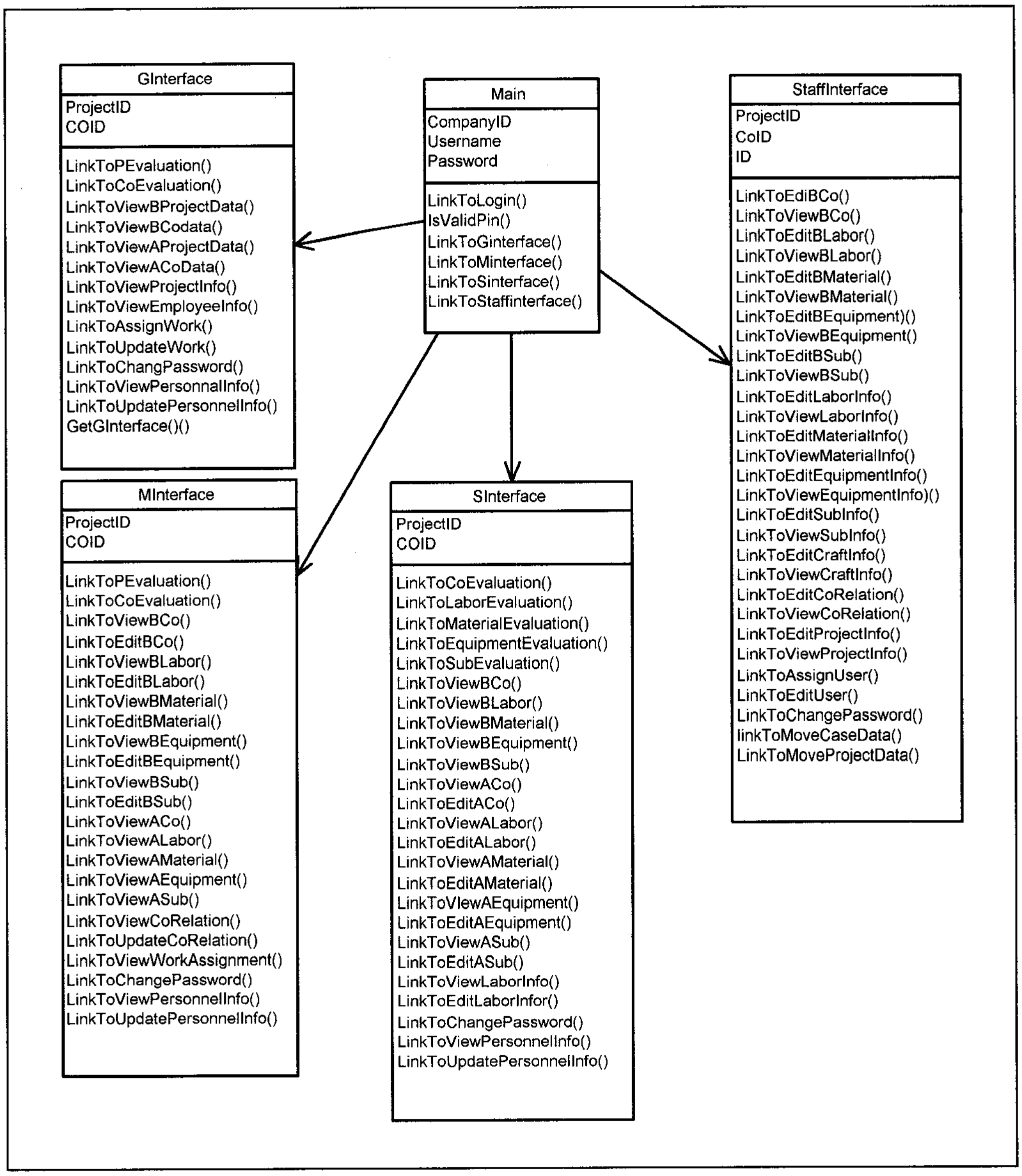
Note: Rule numbers are in parentheses

Table C-4 Rules Developed for Duration

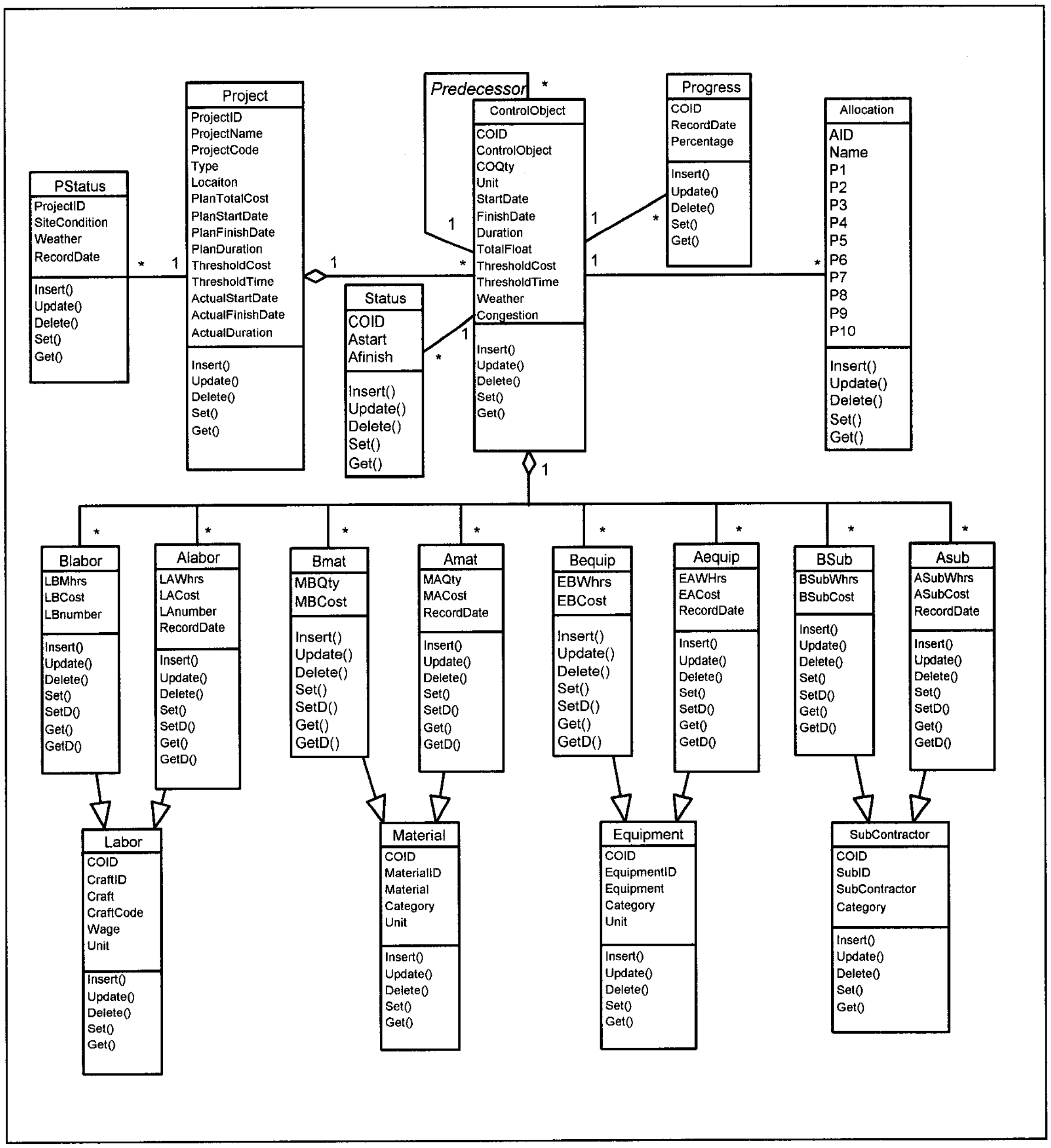
Quantity	(1) *Decreased* Then *Decreased*	(2) *Planned* Then *Planned*	(3) *Increased* Then *Increased*
Production	(4) *Decreased* Then *Increased*	(5) *Planned* Then *Planned*	(6) Increased Then *Decreased*

Note: Rule numbers are in parentheses

Appendix (D) Class Diagrams



Appendix D-1 Class Diagram of User Interfaces



Appendix D-2 Class Diagram of Project Data

Appendix (E) Sample of the Developed Forms

Figure E-1 Login

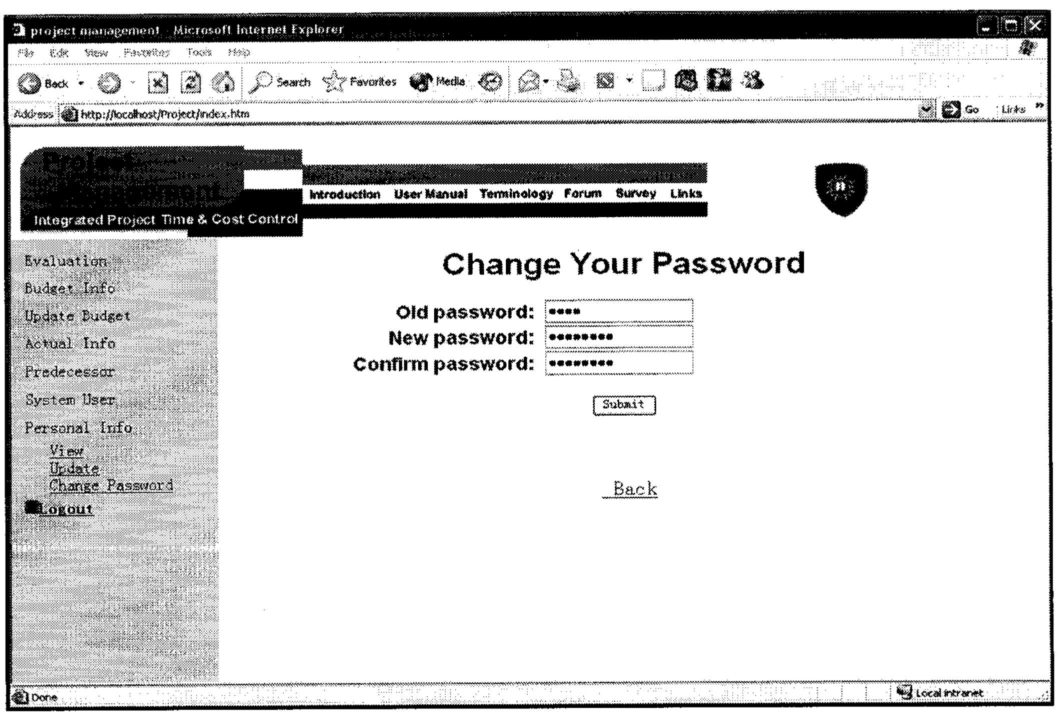


Figure E-2 Change Password

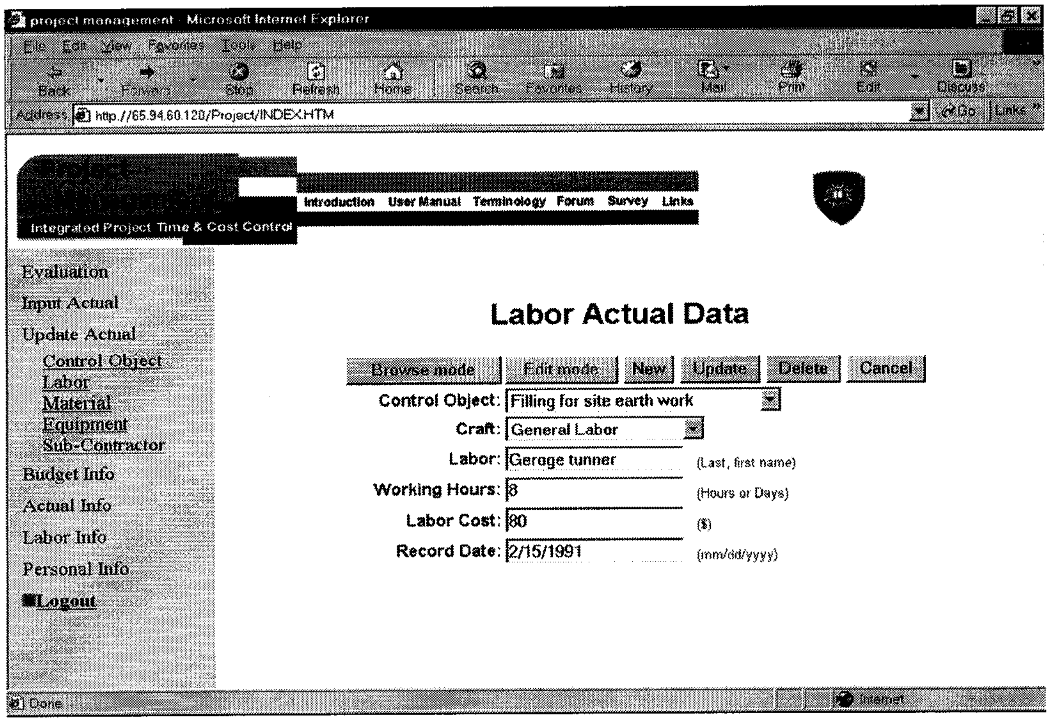


Figure E-3 Input/Update Actual Data

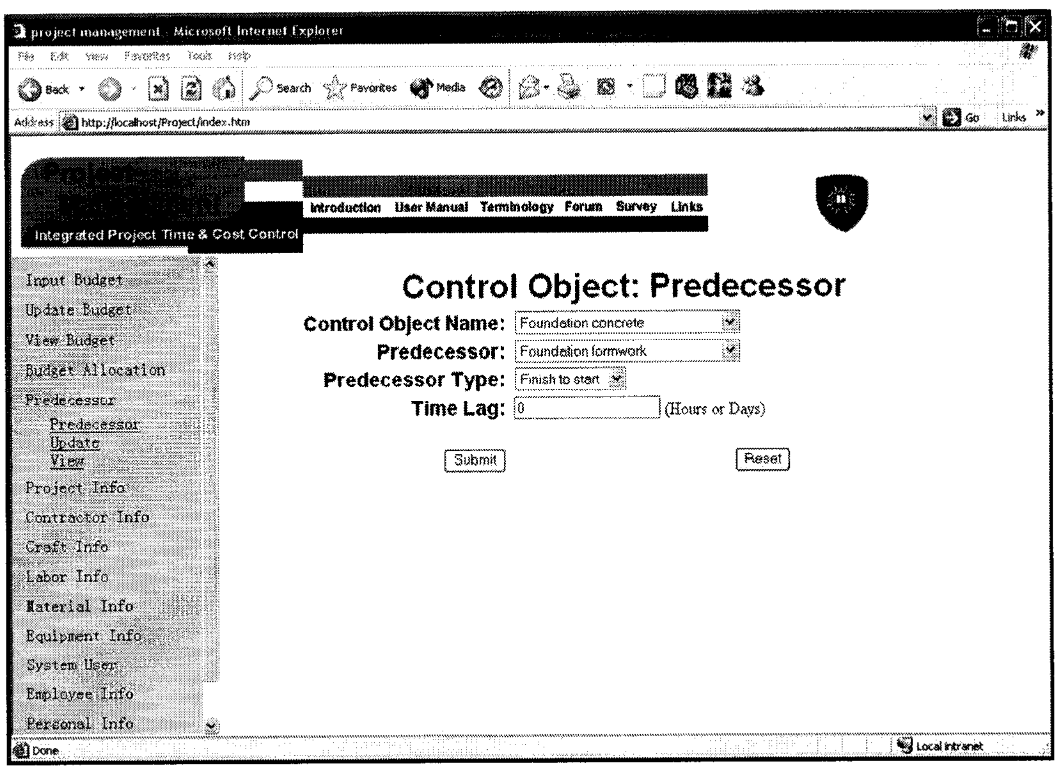


Figure E-4 Define a Predecessor

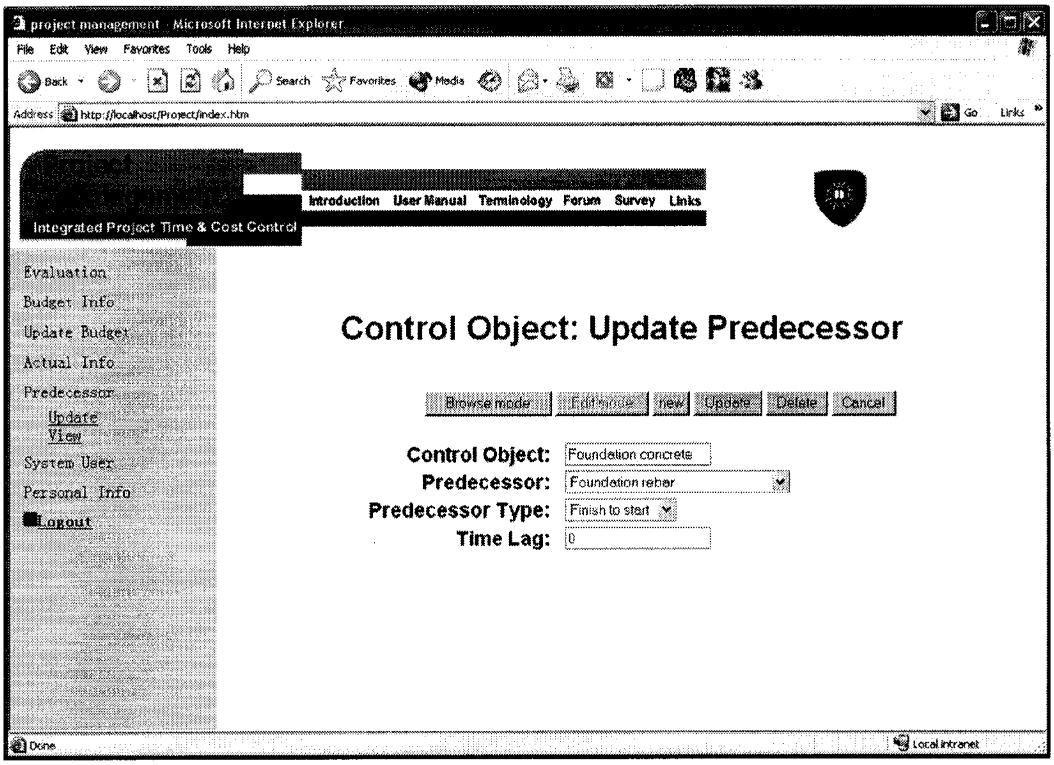


Figure E-5 Predecessor Update

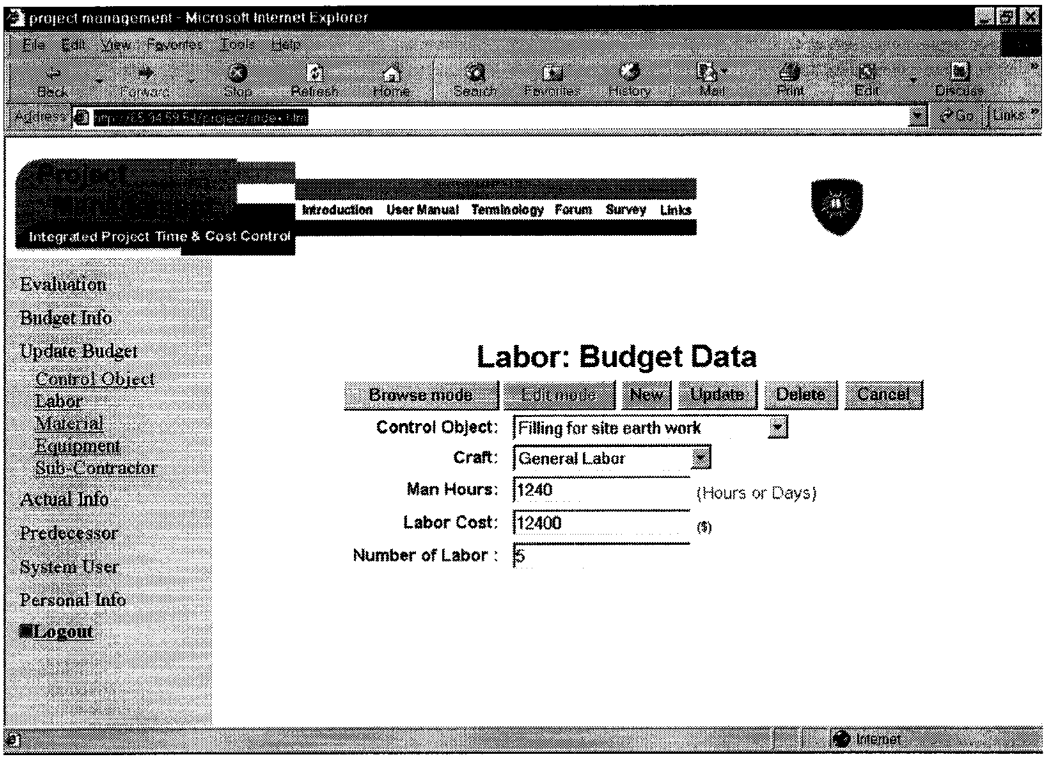


Figure E-6 Budgeted Data Update

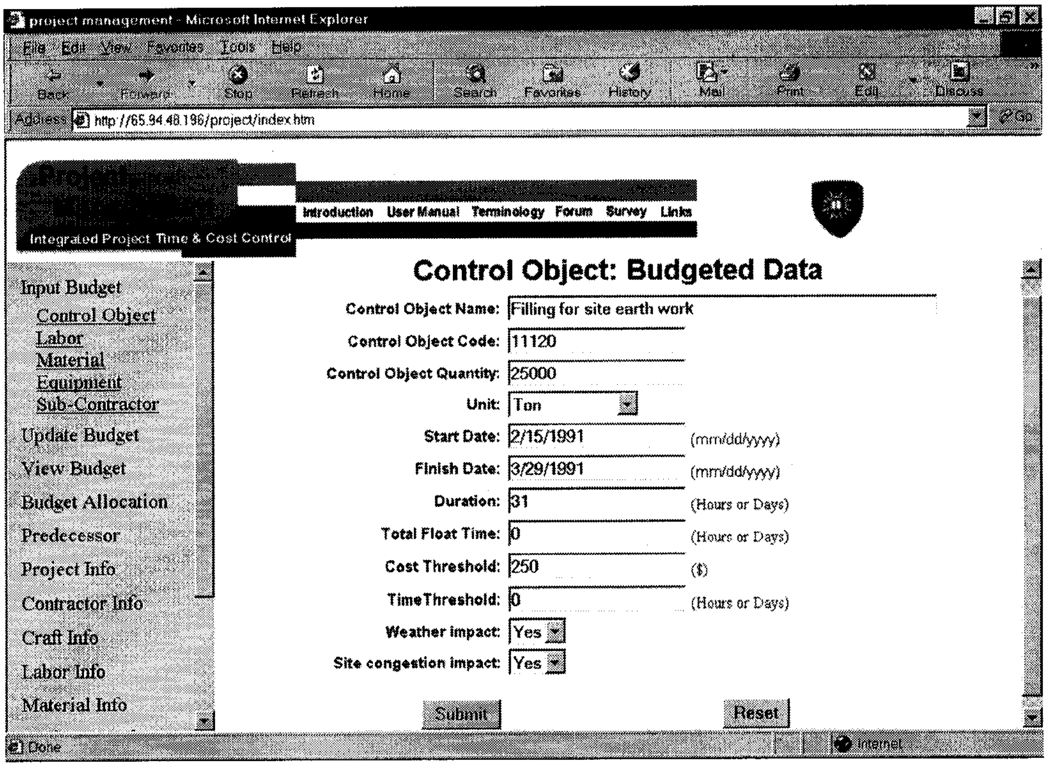


Figure E-7 Input Project Data

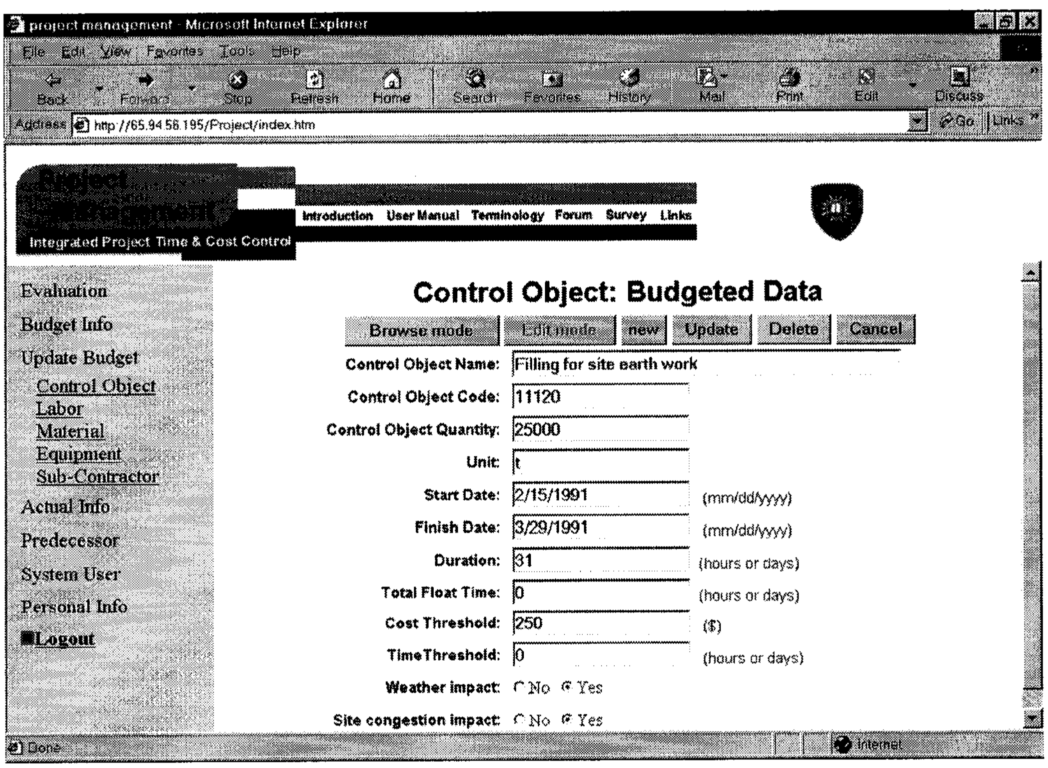


Figure E-8 Update Project Data

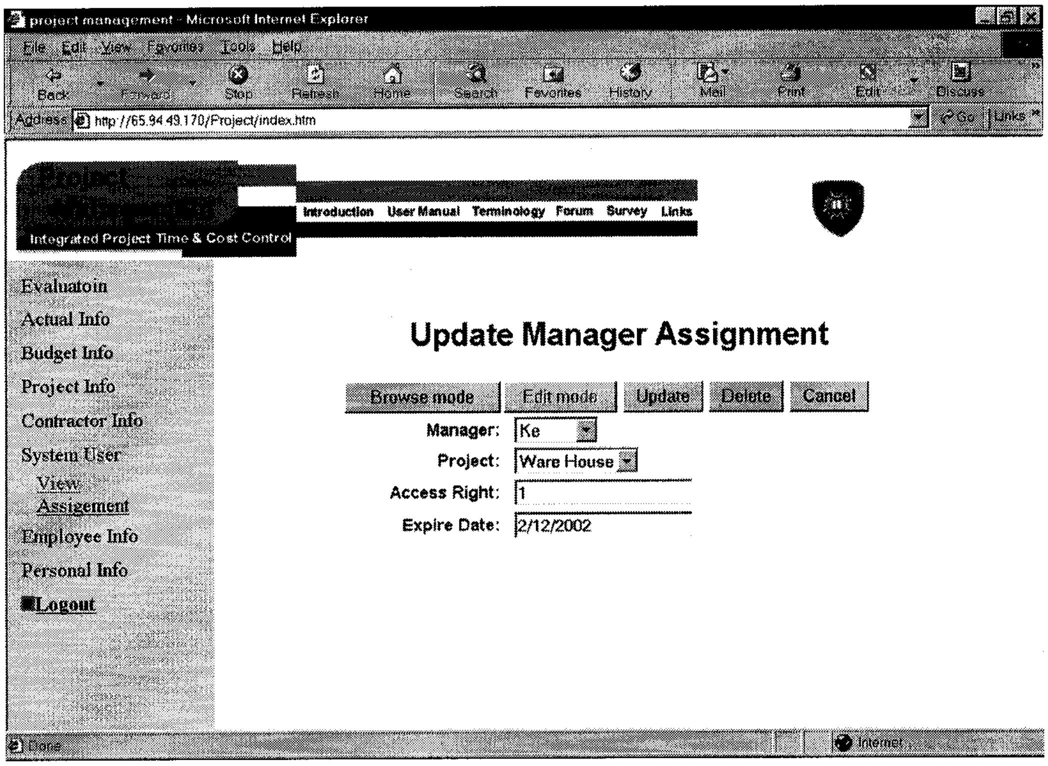


Figure E-9 Update Management Responsibility Assignment

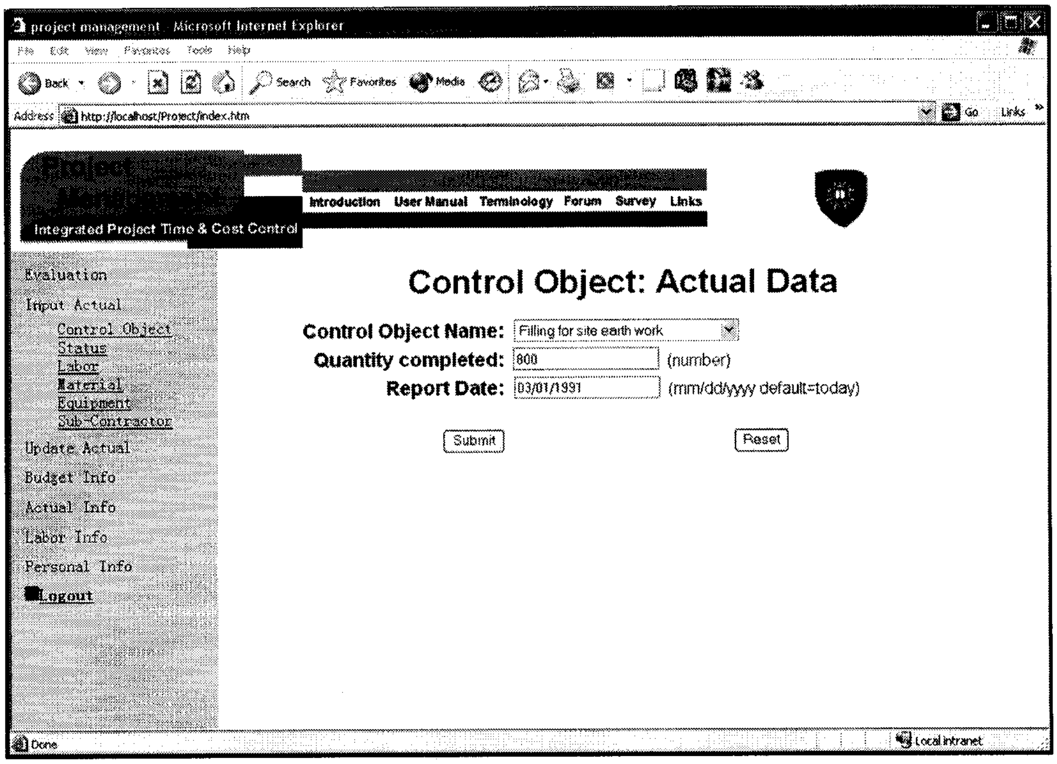


Figure E-10 Input Actual Data

Appendix (F) Attributes of the Databases

Table F-1 Attributes of the Project, Case and Historical Databases

Item	Table	Field Name	Data Type	Size	Description
1	Company	CID	AutoNumber	4	Company ID
		CompanyName	Text	50	Company Name
		RegisterName	Text	10	System username
		Address	Text	50	Company address
		PostCode	Text	8	The post code of the company
		PhoneNumber	Text	15	Company phone number
		FaxNumber	Text	15	Company fax number
		EMail	Text	30	E-mail address of the company
2	Employee	EID	AutoNumber	4	Employee ID
		LastName	Text	25	Last name
		FirstName	Text	25	First Name
		Genda	Text	8	Gender
		Birthday	Date/Time	10	Birthday of the employee
		Address	Text	30	Address of the employee
		HireDate	Date/Time	10	Hired date
		PhoneNumber	Text	15	Contact phone number
		SINNumber	Text	15	Social insurance card number
		Wage	Currency		The wage rate
		OverTimeRate	Currency		The over time wage rate
3	User	UID	Number	4	User ID
		Username	Text	8	Username
		Password	Text	8	Password
		Privilege	Integer	2	Access right
		ExpiryDate	Date/Time	10	Expiry date of the access right
4	Craft	CraftID	AutoNumber	4	Craft ID
		Craft	Text	50	Craft name
		CraftCode	Text	12	Craft code
		Wage	Currency		The wage rate for a type of craft
		Unit	Text	12	The wage unit, hour or day
5	Pstatus	PSID	AutoNumber	4	Project status ID
		SiteCondition,	Text	15	Project site condition
		Weather	Text	10	Weather condition on the site
6	Material	MaterialID	AutoNumber	4	Material ID
		Material	Text	50	Material name
		Category	Text	15	Type of the material
		Unit	Text	20	Material unit
7	Equipment	EuqipmentID	AutoNumber	4	Equipment ID
		Equipment	Text	50	Equipment name
		Category	Text	20	Equipment category
		Unit	Text	20	Equipment unit

Table F-2 Attributes of the Project, Case and Historical Databases (Continue)

Item	Table	Field Name	Data Type	Size	Description
8	Project	ProjectID	AutoNumber	4	Project ID
		ProjectName	Text	50	Project name
		ProjectCode	Text	10	Project code
		Type	Text	15	Type of project
		Location	Text	30	The location of the project
		PlanTotalCost	Currency		Planned total cost
		PlanStartDate	Date/Time	10	Project planned start date
		PlanFinishDate	Date/Time	10	Project planned finish date
		PlanDuration	Number	8	Planned duration
		ThresholdCost	Currency		Cost threshold for the project
		ThresholdTime	Number	8	Time threshold for the project
		ActualStartDate	Date/Time	10	Actual start date of the project
		ActualFinishDate	Date/Time	10	Actual finish date of the project
		ActualDuration	Number	8	Actual duration of the project
9	Control Object	COID	AutoNumber	4	Control object ID
		ControlObject	Text	50	Control object name
		COCode	Text	10	Control object code
		Coquantity	Number	4	Control object quantity
		Unit	Text	20	Unit of quantity
		StartDate	Date/Time	10	Planned start date
		FinishDate	Date/Time	10	Planned finish date
		Duration	Number	8	Planned duration
		TotalFloat	Nubmer	8	Total float of the control object
		ThresholdCost	Number	8	Threshold cost
		ThresholdTime	Nubmer	8	Threshold time
		Weather	Yes/No		Sensitivity to weather
		Congestion	Yes/No		Sensitivity to site congestion
10	Subcontractor	SubID	Number	4	Sub-contractor ID
		SubContractor	Text	50	Subcontractor name
		Category	Text	20	Subcontractor specialization
11	Progress	CPID	AutoNumber	4	Progress ID
		Percentage	Number	4	The percentage completion
12	Allocation	AID	AutoNumber	4	Resource allocation ID
		Name	Text	20	Allocation method
		P1	Number	4	Allocation for 10% completion
		P2	Number	4	Allocation for 20% completion
		P3	Number	4	Allocation for 30% completion
		P4	Number	4	Allocation for 40% completion
		P5	Number	4	Allocation for 50% completion
		P6	Number	4	Allocation for 60% completion
		P7	Number	4	Allocation for 70% completion
		P8	Number	4	Allocation for 80% completion
		P9	Number	4	Allocation for 90% completion
		P10	Number	4	Allocation for 100% completion

Table F-3 Attributes of the Project, Case and Historical Databases (Continue)

Item	Table	Field Name	Data Type	Size	Description
13	Predecessor	PID	AutoNumber	4	Predecessor ID
		Predecessor	Number	4	Types of the predecessor
14	Status	CO_ID	Number	4	Control object ID
		Astart	Date/Time	10	Control-object actual start date
		Afinish	Text	15	Control object actual finish date
15	Labor	Labor_ID	AutoNumber	4	Labor ID
		Last_Name	Text	25	Last name
		First_Name	Text	25	First Name
		Genda	Text	8	Gender
		Birthday	Date/Time	10	Birthday of the employee
		Address	Text	30	Address of the employee
		HireDate	Date/Time	10	Hired date
		Phone_Number	Text	15	Contact phone number
		SIN_Number	Text	15	Social insurance card number
		Wage	Currency		The wage rate
		Over_Time_Rate	Currency		The over time wage rate

Relationships Defined in the Project, Case and Historical Databases:

1) **CompanyProject** (***CID, ProjectID***)

2) **ProjectCO** (***ProjectID, COID***)

3) **BLabor** (***COID, CraftID***, LBnumber, LBMhrs, LBCost)

4) **ALabor** (***COID, LaborID, RecordDate,*** LAWhrs, LACost)

5) **BMaterial** (***COID, MaterialID***, MBCost, MBQty)

6) **AMaterial** (***COID, MaterialID***, ***RecordDate,*** MAcost, MAQty)

7) **BEquipment** (***COID, EquipmentID***, EBWhrs, EBCost)

8) **AEquipment** (***COID, EquipmentID***, ***RecordDate***, EAWhrs, EACost)

9) **BSub** (***COID, SubID***, BSubWhrs, BSubCost)

10) **ASub** (***COID, SubID***, ***RecordDate***, ASubWhrs, ASubCost)

11) **Manager** (***UID, ProjectID***)

12) **SiteManager** (***UID, COID***)

13) **WPA** (***COID, AID***)

14) **CraftLabor** (***CraftID, LaborID***)

15) **EmployeeUser** (***EID, UID***)

16) **CompanyEmployee** (***CID, EID***)

17) **CoPredecessor** (***PID, COID***, Predecessor, Lag)

18) **ProjectStatus** (***ProjectID*, PSID, *RecordDate***)

19) **CoProgress** (***COID*, CPID, *RecordDate*,** COquantity)

Table F-4 Attributes of the Relationships

Item	Relationship	Field Name	Data Type	Size	Description
3	BLabor	LBnumber	Number	8	Planned labor number
		LBMhrs	Number	8	Planned labor working hours
		LBCost	Currency		Planned labor cost
4	ALabor	Record_Date	Date/Time	10	Record date
		LAWhrs	Number	8	Actual labor working hours
		LAcost	Currency		Actual labor cost
5	BMaterial	MBCost	Currency		Planned material cost
		MBQty	Number	4	Planned material quantity
6	AMaterial	MACost	Currency		Actual material cost
		MAQty	Number	4	Actual material quantity
7	BEquipment	EBWhrs	Number	4	Planned working hours
		EBCost	Currency		Planned equipment cost
8	AEquipment	EAWhrs	Number	4	Actual working hours
		EACost	Currency		Actual equipment cost
9	BSub	BSubWhrs	Number	4	Planned working hours
		BSubCost	Currency		Planned subcontractor cost
10	ASub	ASubWhrs	Number	4	Actual working hours
		ASubCost	Currency		Actual sub-contractor cost
11	CoPredecessor	Predecessor	Number	4	Define type of the predecessor
		Lag	Number	4	The planned lag time (day/hours)
12	CoProgress	COquantity	Number	8	Actual quantity installed

Tables F-5 Attributes of the Factor Database

Item	Table	Field Name	Data Type	Size	Description
1	ESFactors	ESFID	AutoNumber	4	ES factor ID
		ESFactors	Text	100	List of ES factors
2	CFactors	CFID	AutoNumber	4	Contract factor ID
		CFactors	Text	100	List of contract factors
3	MgmFactors	MgmFID	AutoNumber	4	Management factor ID
		MgmFactors	Text	100	List of management factors
4	LFactors	LFID	AutoNumber	4	Labor factor ID
		LFactors	Text	100	List of labor factors
5	MFactors	MFID	AutoNumber	4	Material factor ID
		MFactors	Text	100	List of material factors
6	EFactors	EFID	AutoNumber	4	Equipment factor ID
		EFactors	Text	100	List of equipment factors
7	SFactors	SFID	AutoNumber	4	Sub-contractor factor ID
		SFactors	Text	100	List of sub-contractor factors
8	ESActions	ESAID	AutoNumber	4	ES action ID
		ESActions	Text	100	List of ES actions
9	CActions	CAID	AutoNumber	4	Contract action ID
		CActions	Text	100	List of contract actions
10	MgmActions	MgmAID	AutoNumber	4	Management action ID
		MgmActions	Text	100	List of management actions
11	LActions	LAID	AutoNumber	4	Labor action ID
		LActions	Text	100	List of Labor actions
12	MActions	MAID	AutoNumber	4	Material action ID
		MActions	Text	100	List of material actions
13	EActions	EAID	AutoNumber	4	Equipment action ID
		EActions	Text	100	List of equipment actions
14	SActions	SAID	AutoNumber	4	Sub-contractor action ID
		SActions	Text	100	List of sub-contractor actions

Relationships Defined in the Factor Database:

1) **ESR** (***ESFID, ESAID,*** Strength)

2) **ESC** (***ESFID, CAID,*** Strength)

3) **ESMgm** (***ESFID, MgmAID,*** Strength)

4) **CR** (***CFID, CAID,*** Strength)

5) **CMgm** (***CFID, MgmAID,*** Strength)

6) **MgmR** (***MgmFID, MgmAID,*** Strength)

7) **MgmES** (***MgmFID, ESAID,*** Strength)

8) **MgmC** (***MgmFID, CAID,*** Strength)

9) **MgmM** (***MgmFID, MAID,*** Strength)

10) **MgmE** (***MgmFID, EAID,*** Strength)

11) **LMgm** (***LFID, MgmAID,*** Strength)

12) **LR** (***LFID, LAID,*** Strength)

13) **MC** (***MFID, cAID,*** Strength)

14) **MMgm** (***MFID, MgmAID,*** Strength)

15) **MR** (***MFID, MAID,*** Strength)

16) **ER** (***EFID, EAID,*** Strength)

17) **SR** (***SFID, SAID,*** Strength)

Note: the *Strength* attribute represents the default values of the linkage strengths between the problem-source factors and corrective actions for a specified type of project.

Table F-6 Attributes of the Reason Database

Item	Table	Field Name	Data Type	Size	Description
1	LReason	LRID	AutoNumber	4	Labor reason ID
		Factors	Text	100	Labor impact factors
2	MReason	MRID	AutoNumber	4	Material reason ID
		Factors	Text	100	Material impact factors
3	EReason	ERID	AutoNumber	4	Equipment reason ID
		Factors	Text	100	Equipment impact factors
4	SReason	SRID	AutoNumber	4	Subcontractor reason ID
		Factors	Text	100	Subcontractor impact factors
5	LAction	LAID	AutoNumber	4	Labor action ID
		Actions	Text	120	Corrective actions for labor
6	MAction	MAID	AutoNumber	4	Material action ID
		Actions	Text	120	Corrective actions for material
7	EAction	EAID	AutoNumber	4	Equipment action ID
		Actions	Text	120	Corrective actions for equipment
8	SAction	SAID	AutoNumber	4	Subcontractor action ID
		Actions	Text	120	Corrective actions for subcontractor
9	LForecast	LFID	AutoNumber	4	Labor forecast ID
		Indicators	Text	30	Labor terminal Indicators
10	MForecast	MFID	AutoNumber	4	Material forecast ID
		Indicators	Text	30	Material terminal Indicators
11	EForecast	EFID	AutoNumber	4	Equipment forecast ID
		Indicators	Text	30	Equipment terminal Indicators
12	SForecast	SFID	AutoNumber	4	Subcontractor forecast ID
		Indicators	Text	30	Subcontractor terminal Indicators

Relationships Defined in the Reason Database:

1) **CoLReason** (***COID, LRID, RecordDate,*** Types, Weight, Others)

2) **CoMReason** (***COID, MRID, RecordDate,*** Types, Weight, Others)

3) **CoEReason** (***COID, ERID, RecordDate,*** Types, Weight, Others)

4) **CoSReason** (***COID, SRID, RecordDate,*** Types, Weight, Others)

5) **CoLAction** (***COID, LAID, RecordDate,*** Types, Weight, Others)

6) **CoMAction** (***COID, MAID, RecordDate,*** Types, Weight, Others)

7) **CoEAction** (***COID, EAID, RecordDate,*** Types, Weight, Others)

8) **CoSAction** (***COID, SAID, RecordDate,*** Types, Weight, Others)

9) **CoLForecast** (***COID, LFID, RecordDate,*** Weight)

10) **CoMForecast** (***COID, MFID, RecordDate,*** Weight)

11) **CoEForecast** (***COID, EFID, RecordDate,*** Weight)

12) **CoSForecast** (***COID, SFID, RecordDate,*** Weight)

Note: the *Types* attribute represents the category of the time and cost respectively; the *Weight* attribute represents user-specified linkage strengths between the factors and actions as well as the user-specified future improvement/deteriorate values for the terminal indicators; the *Others* attribute represents the user-specified problem-source factors or corrective actions.

Appendix (G) Sequence Diagrams

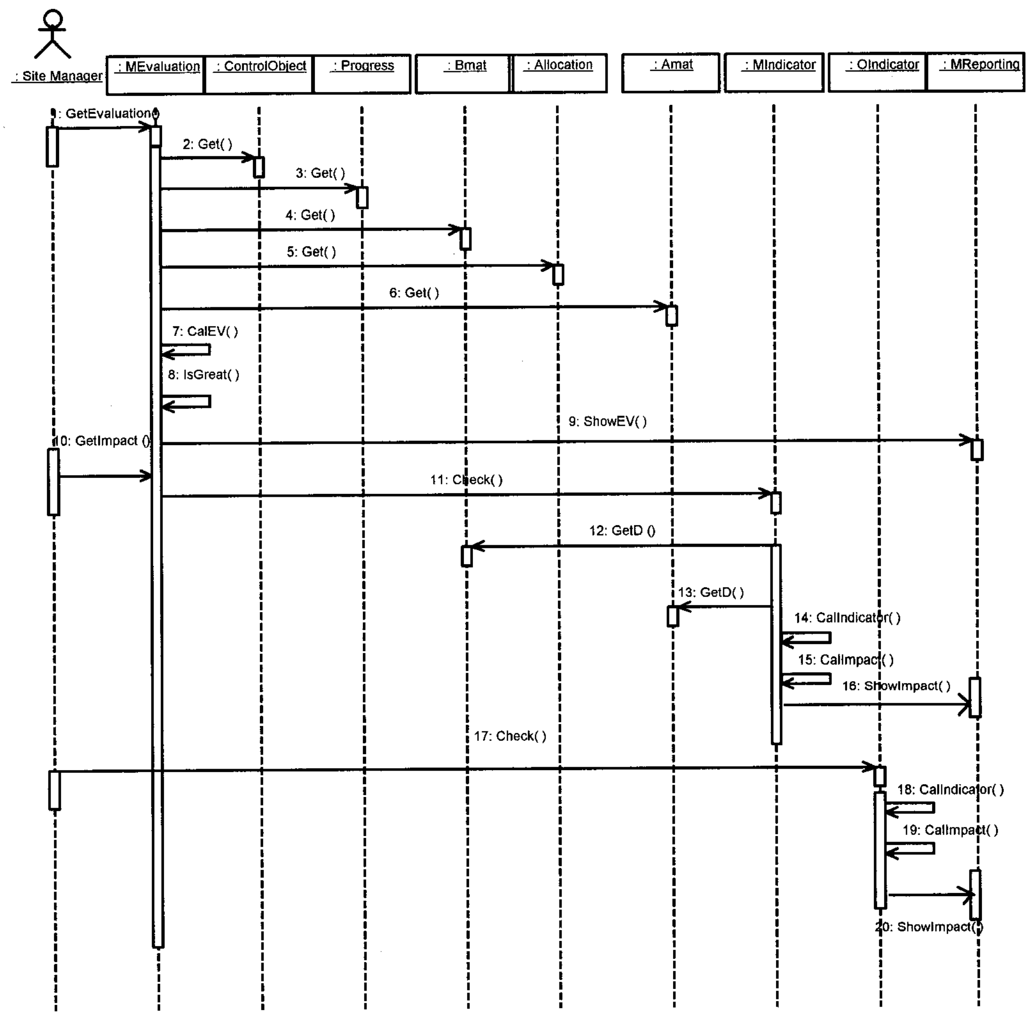


Figure G-1 Sequence Diagram for Material Performance Evaluation

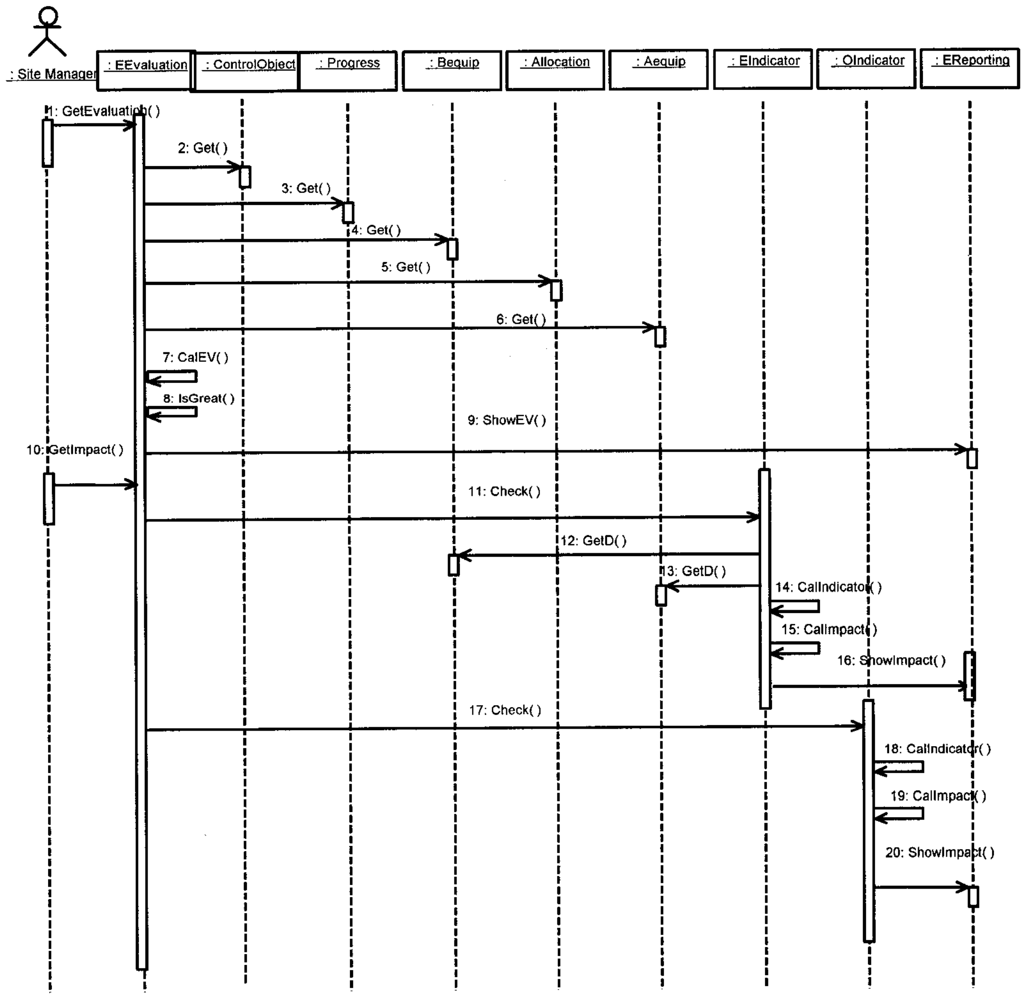


Figure G-2 Sequence Diagram for Equipment Performance Evaluation

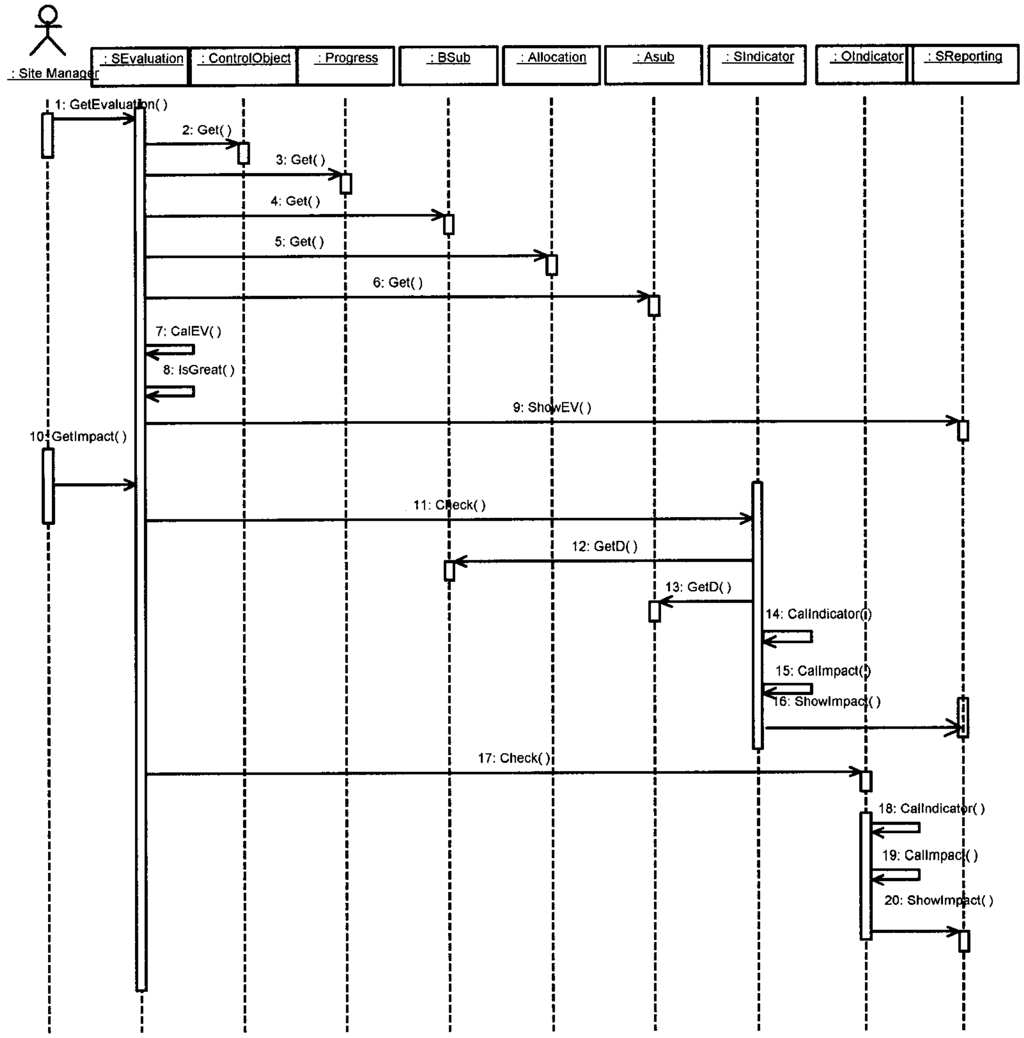


Figure G-3 Sequence Diagram for Sub-Contractor Performance Evaluation

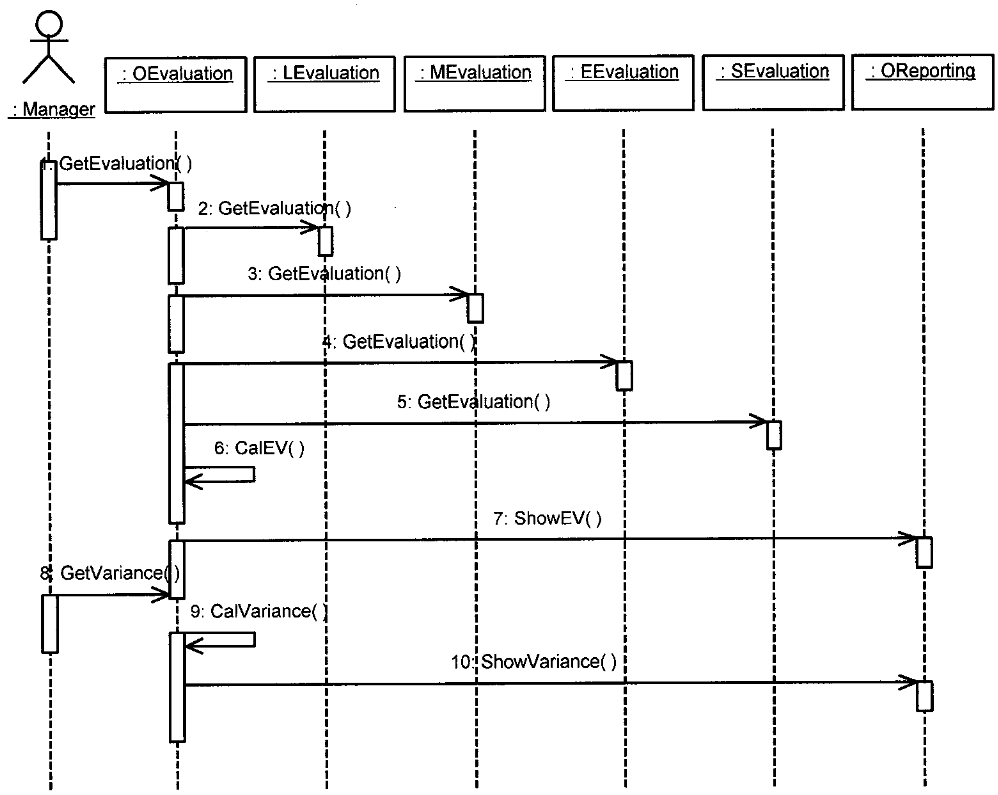


Figure G-4 Sequence Diagram for Control-Object Performance Evaluation

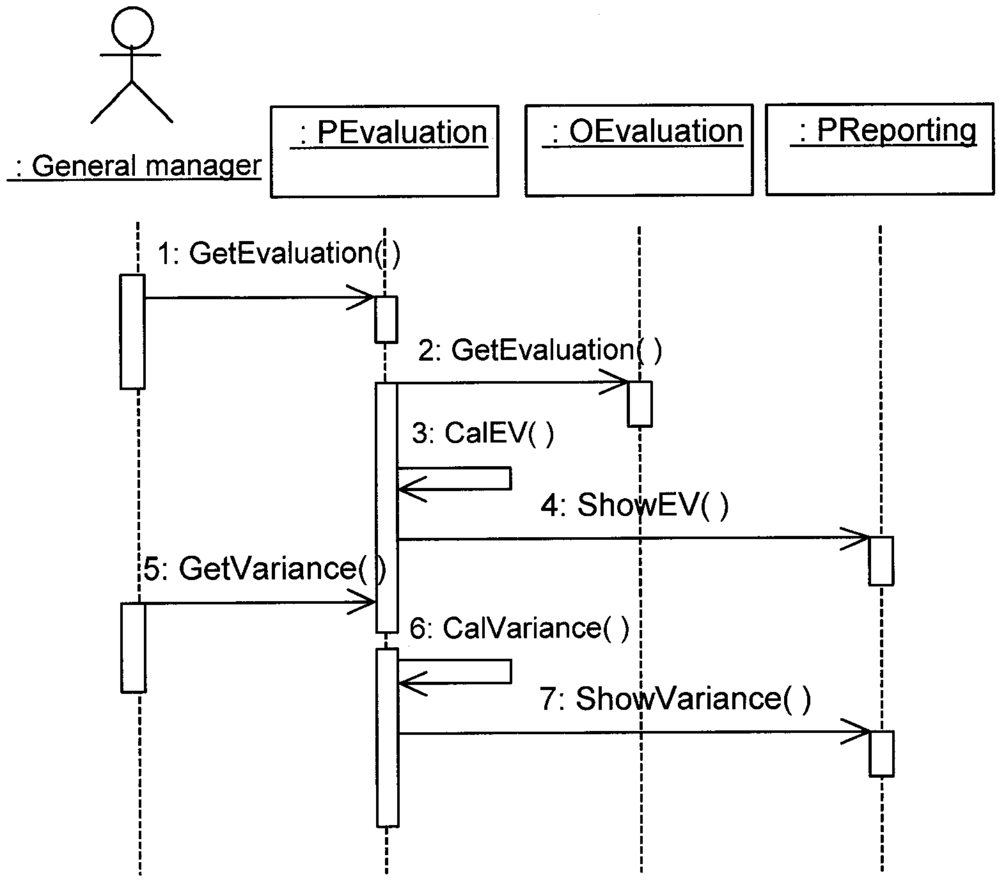


Figure G-5 Sequence Diagram for Project Performance Evaluation

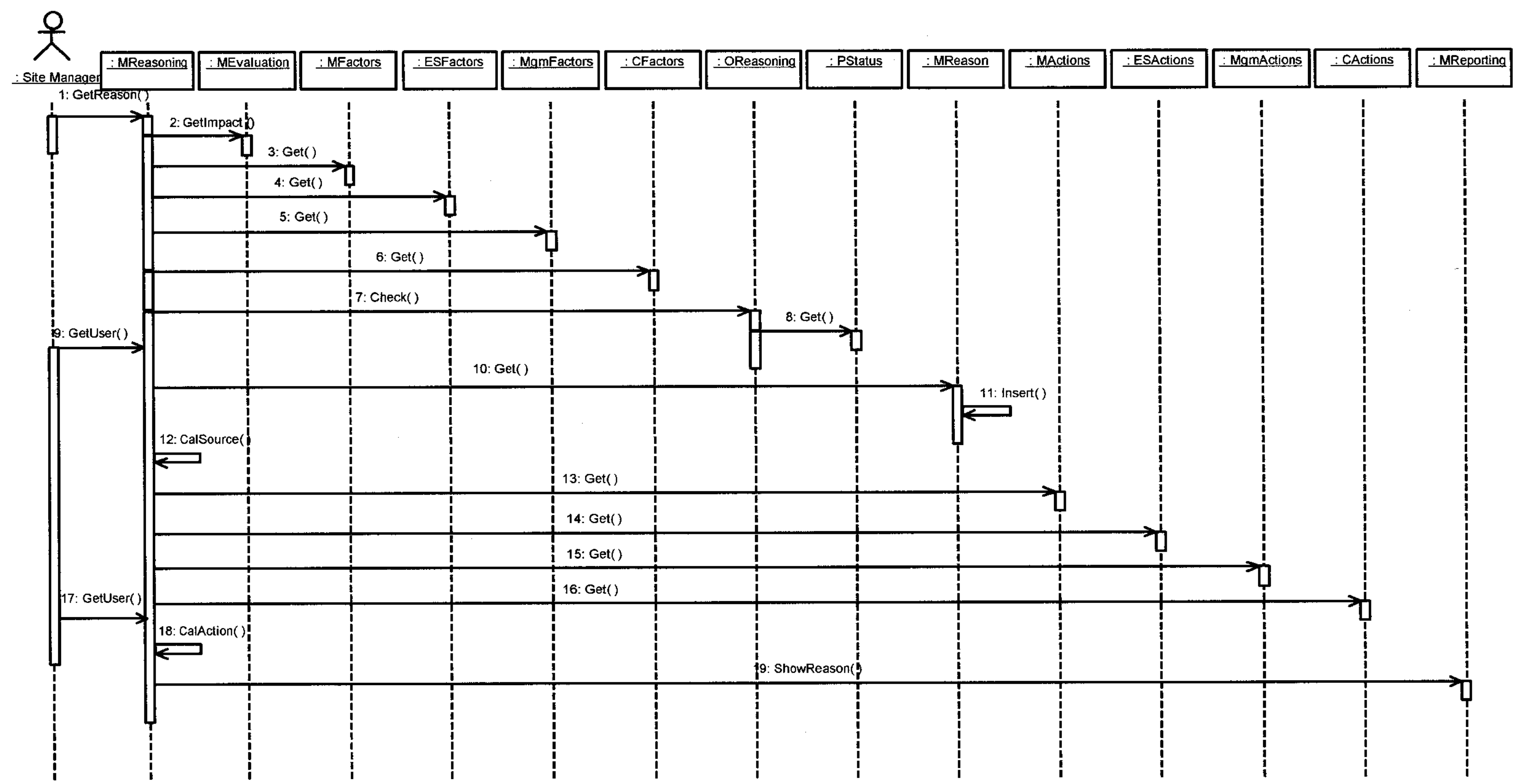


Figure G-6 Sequence Diagram for Material Reasoning

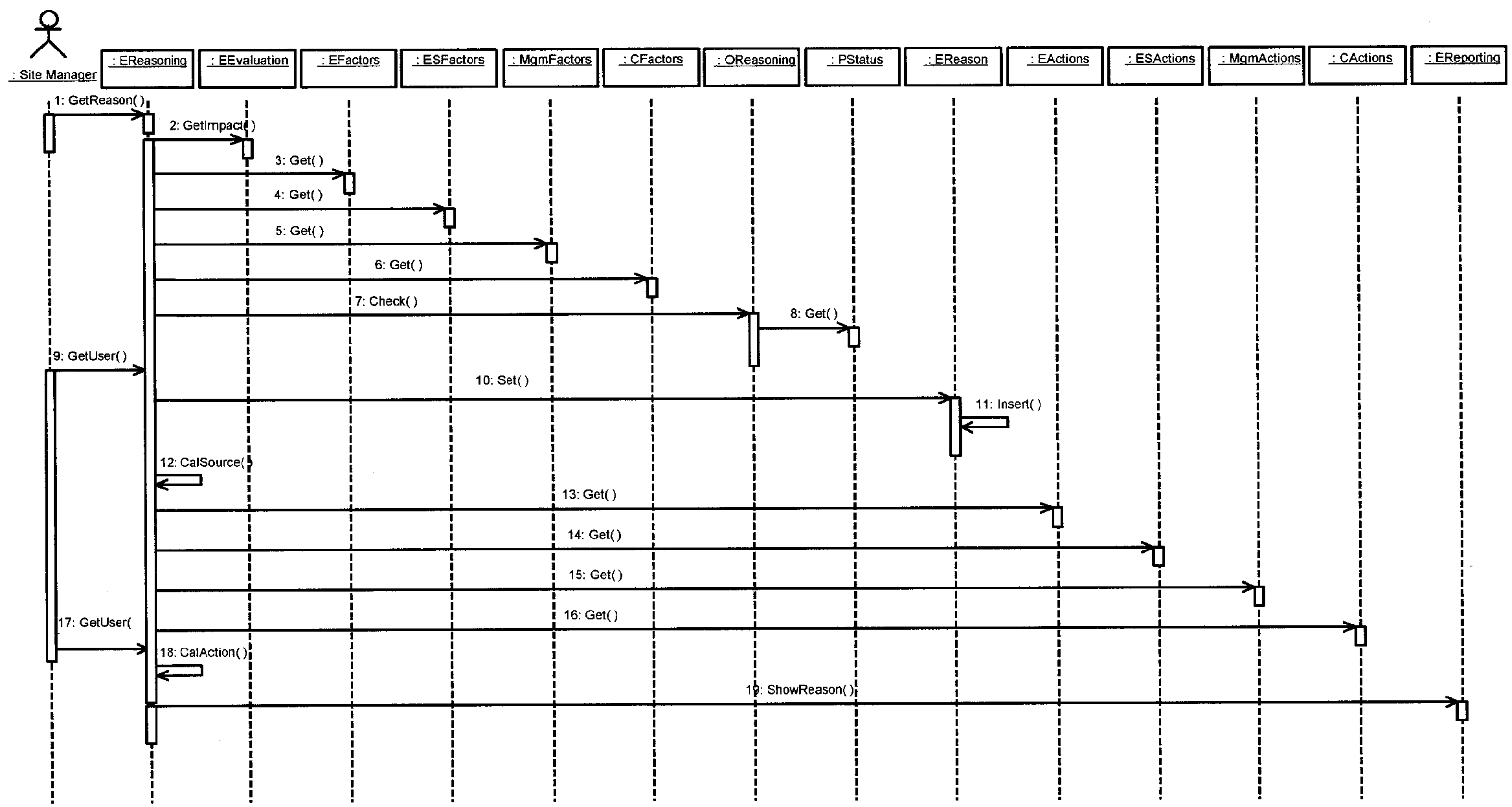


Figure G-7 Sequence Diagram for Equipment Reasoning

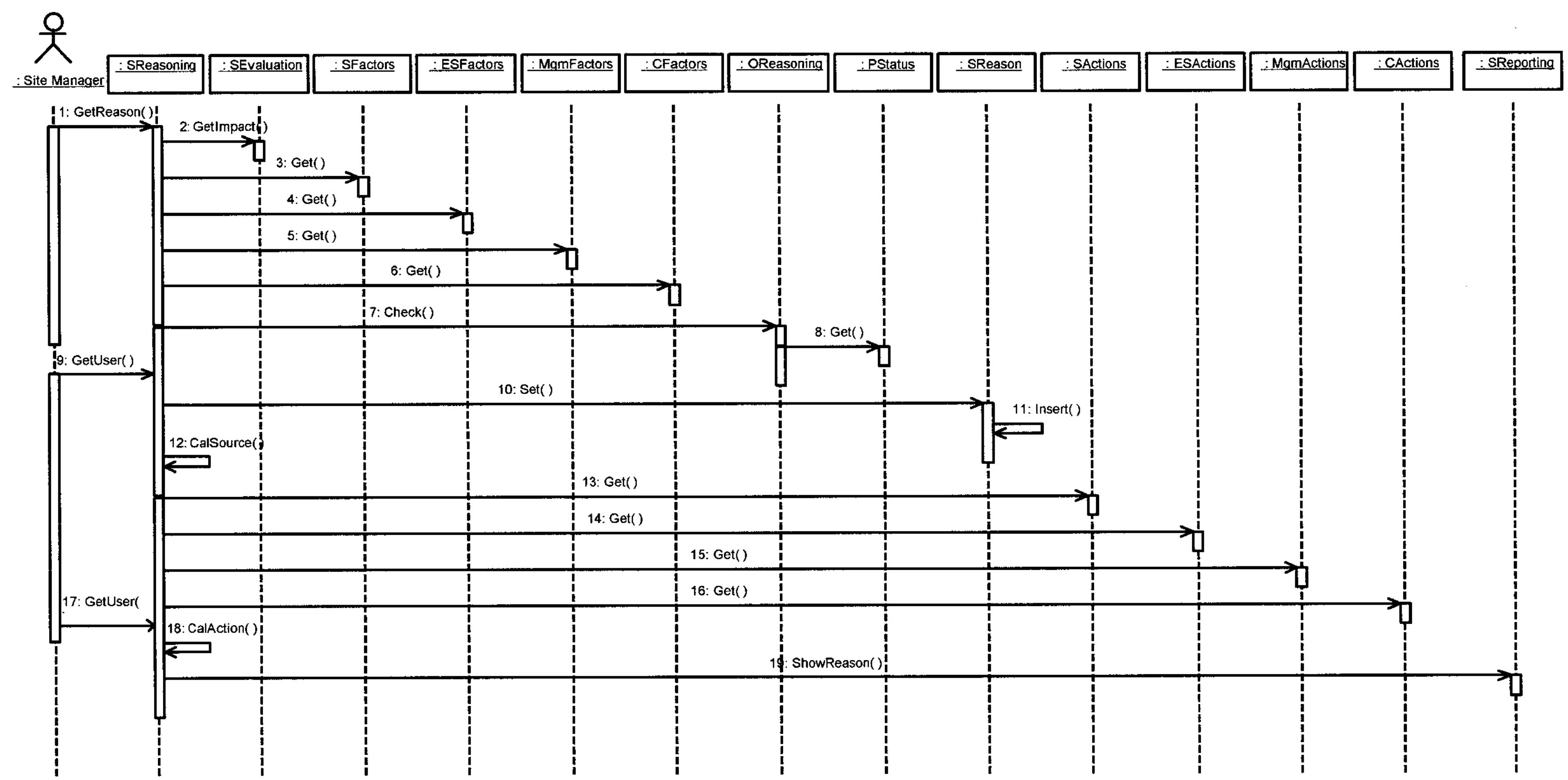


Figure G-8 Sequence Diagram for Subcontractor Reasoning

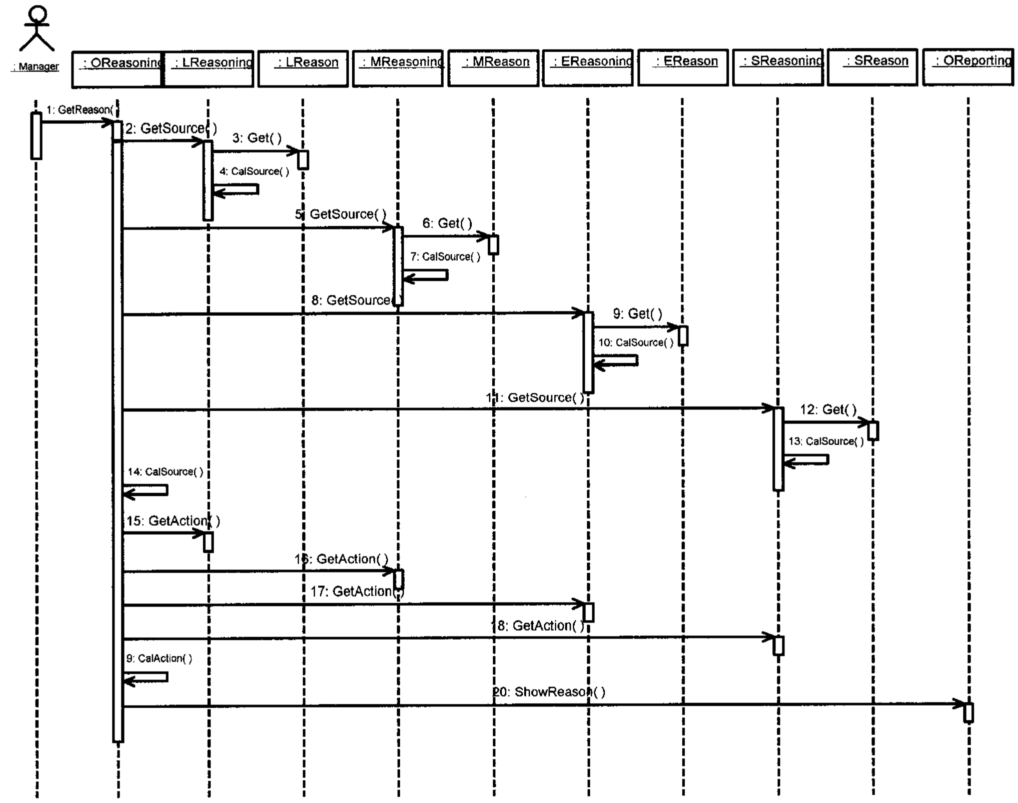


Figure G-9 Sequence Diagram of Control-Object Reasoning

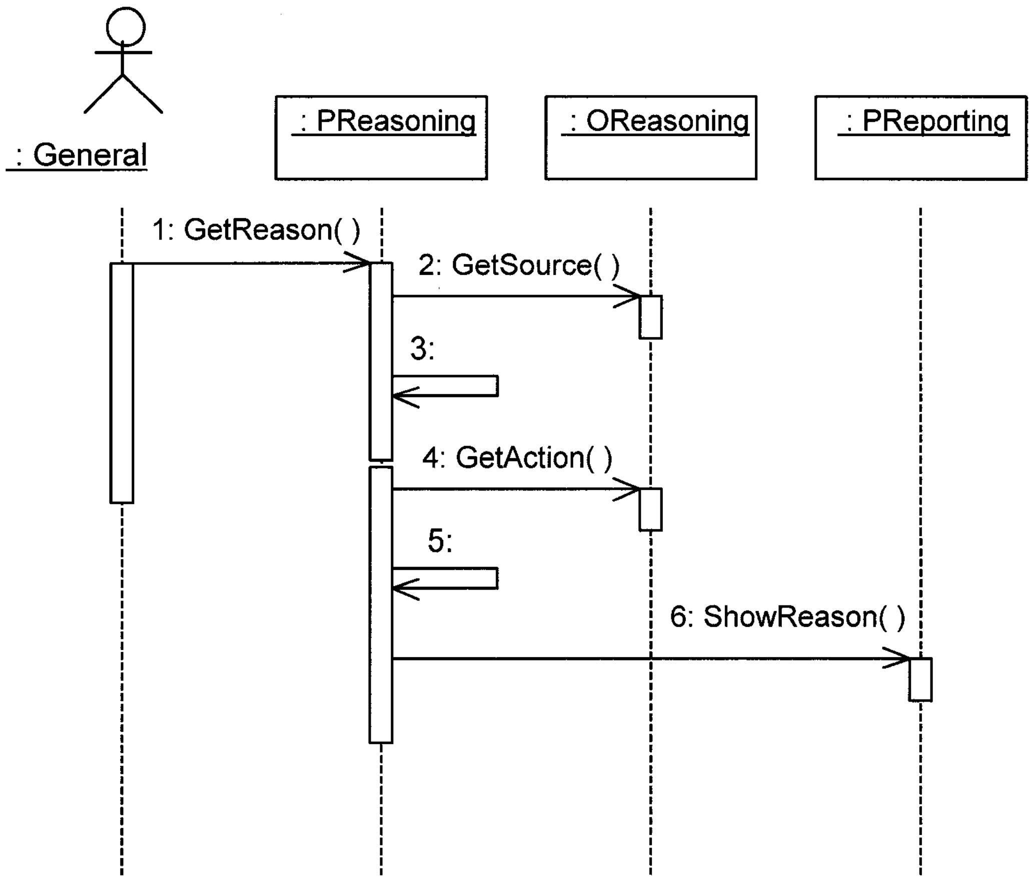


Figure G-10 Sequence Diagram for Project Reasoning

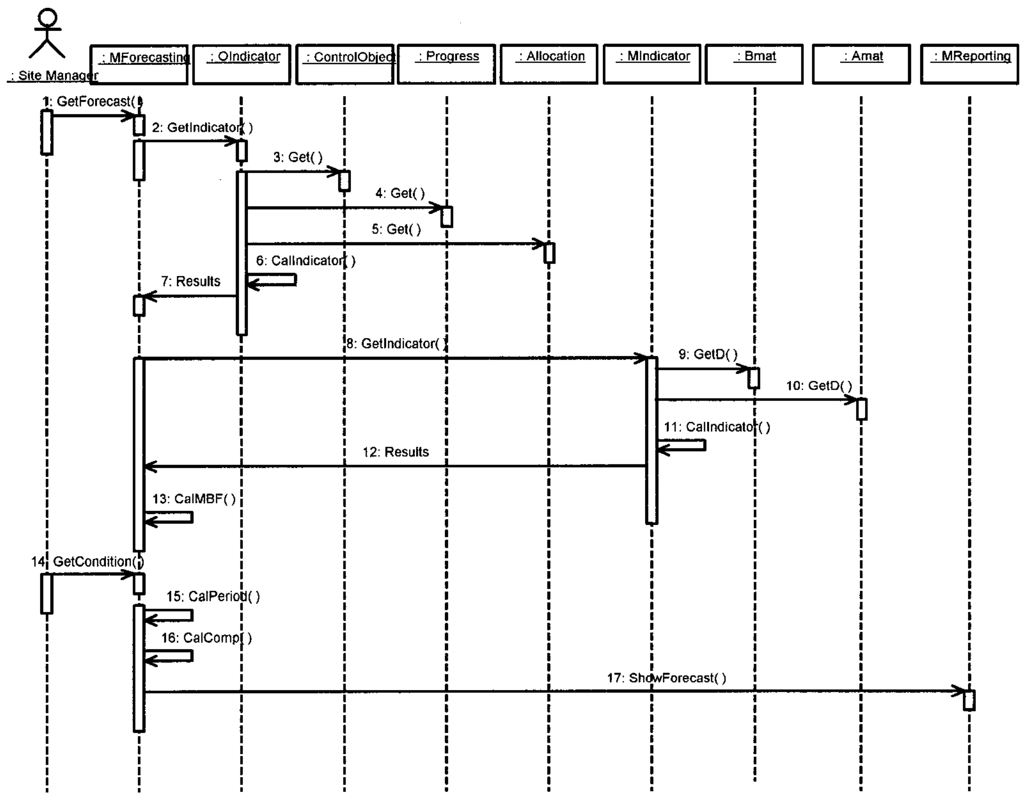


Figure G-11 Sequence Diagram for Material Forecasting

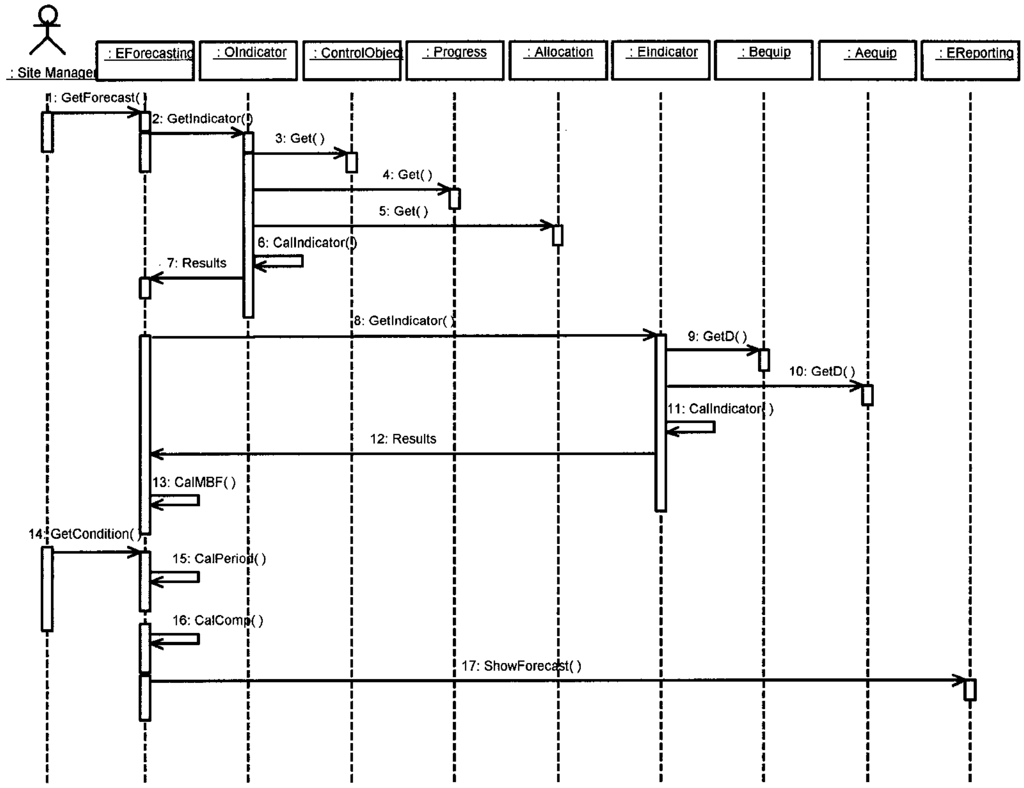


Figure G-12 Sequence Diagram for Equipment Forecasting

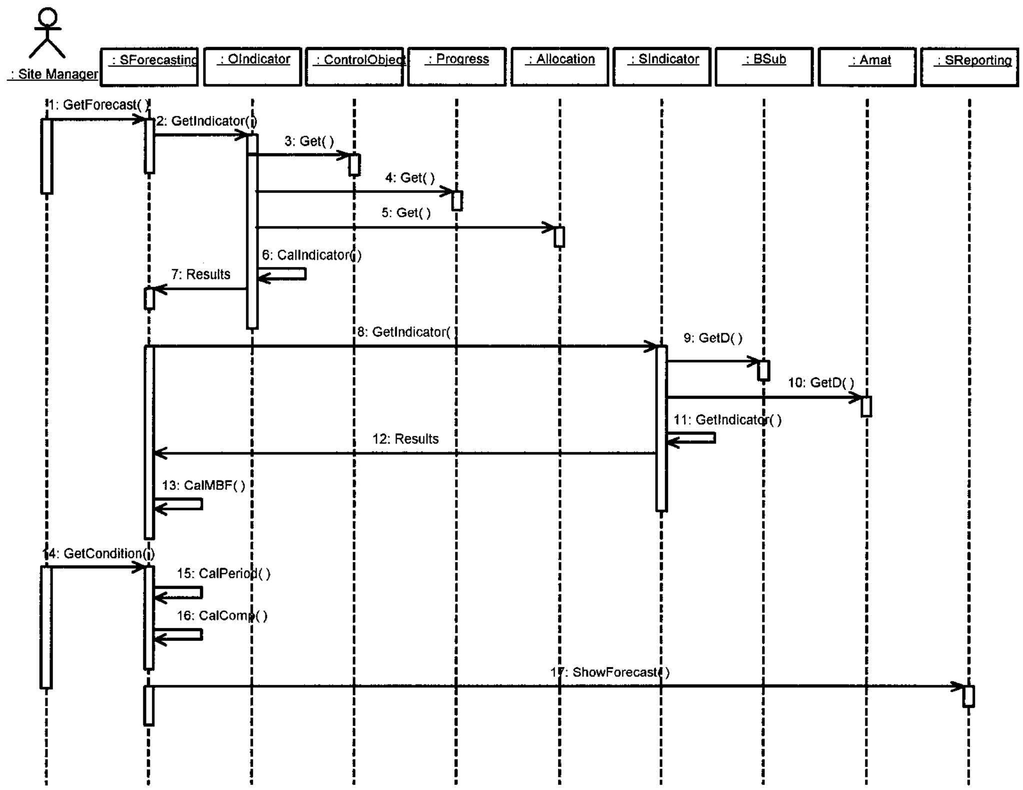


Figure G-13 Sequence Diagram for Subcontractor Forecasting

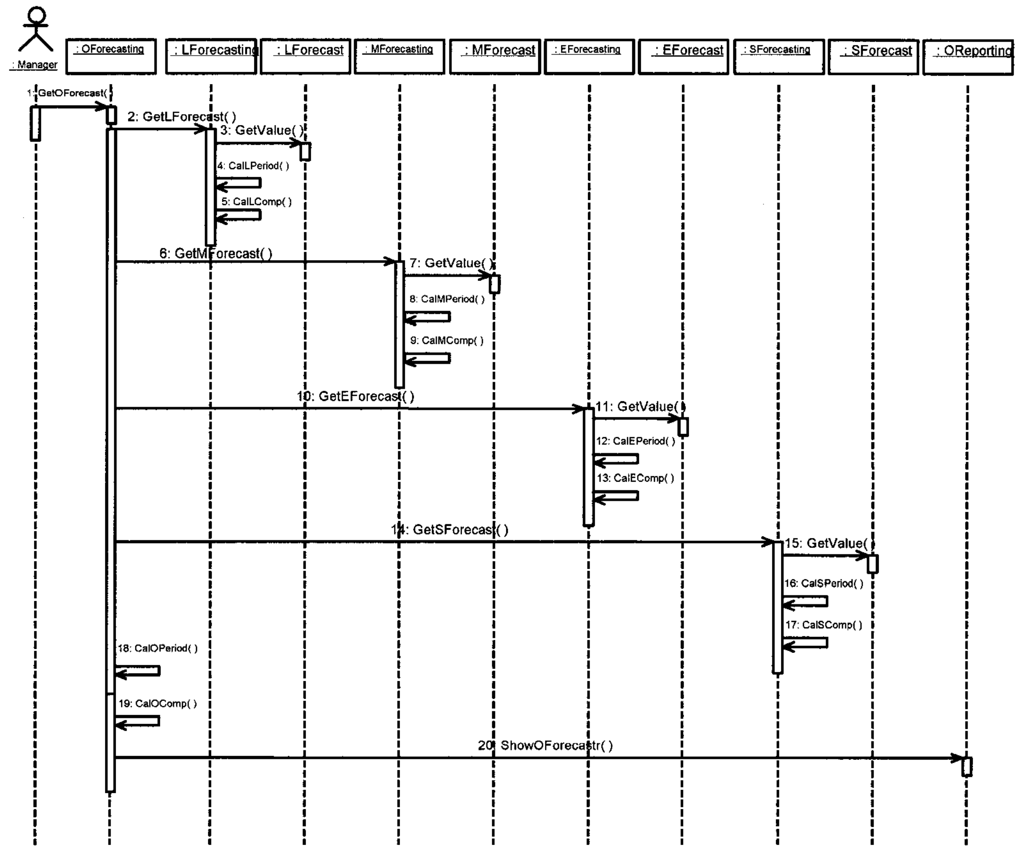


Figure G-14 Sequence Diagram for Control-Object Level Forecasting

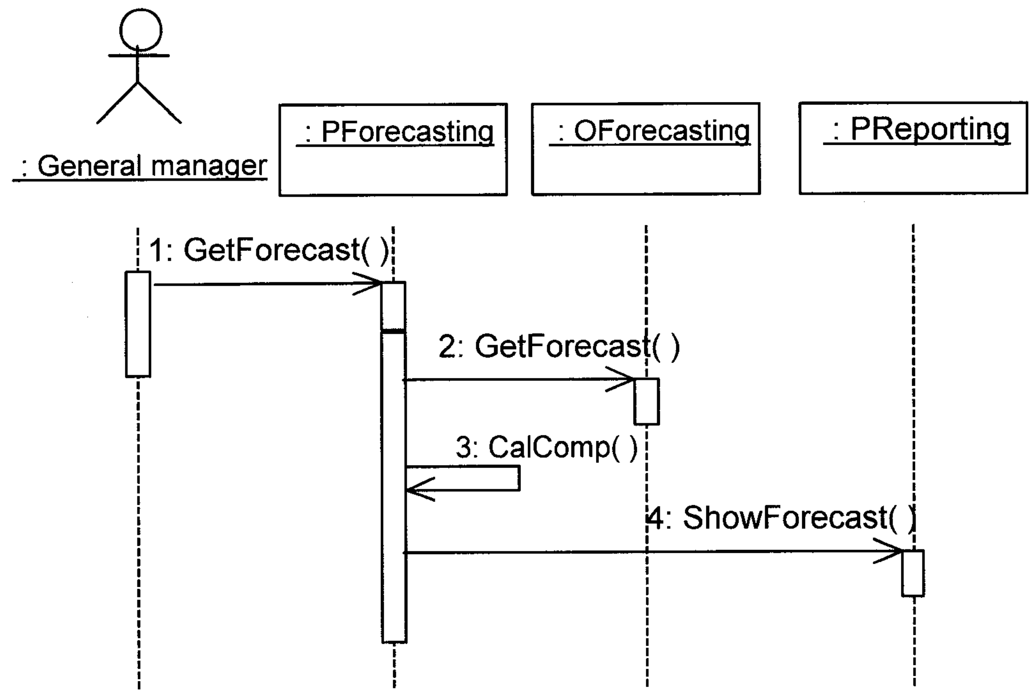


Figure G-15 Sequence Diagram for Project Level Forecasting

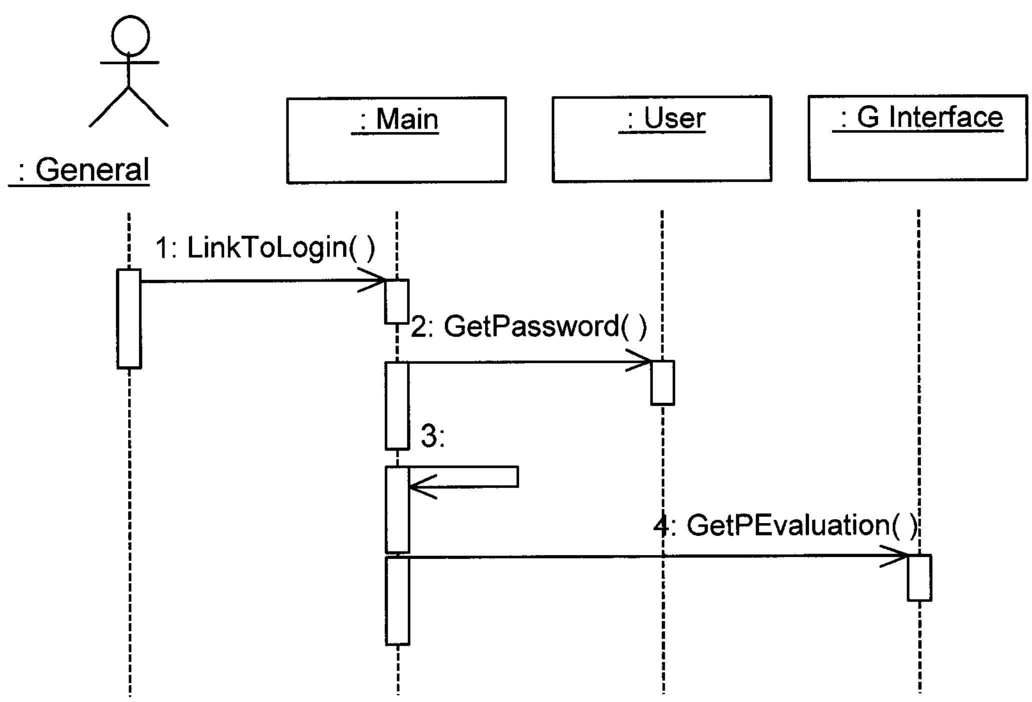
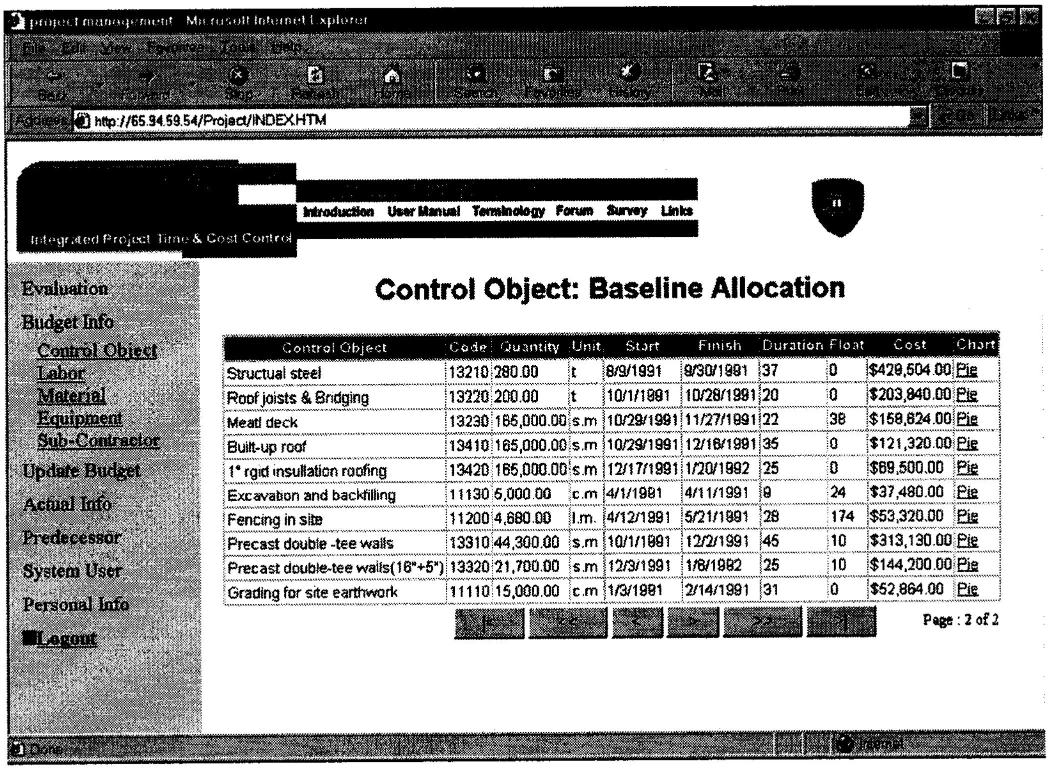


Figure G-16 Sequence Diagram for Login User

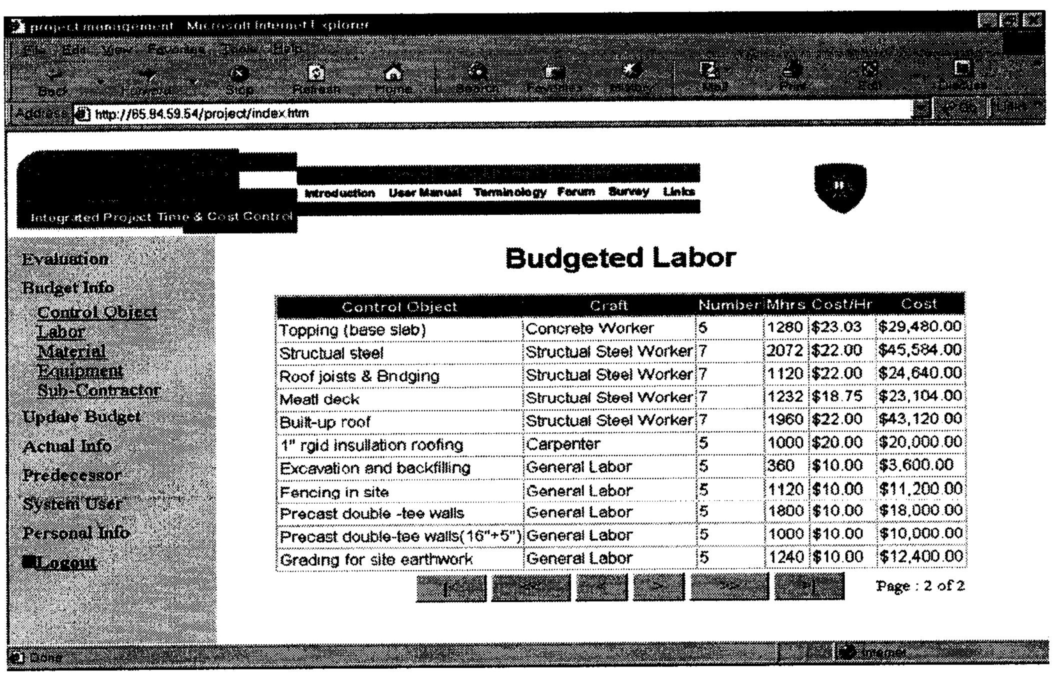
Appendix (H) Planned and Actual Data



Control Object: Baseline Allocation

Control Object	Code	Quantity	Unit	Start	Finish	Duration	Float	Cost	Chart
Structual steel	13210	280.00	t	8/9/1991	9/30/1991	37	0	$429,504.00	Pie
Roof joists & Bridging	13220	200.00	t	10/1/1991	10/28/1991	20	0	$203,840.00	Pie
Meatl deck	13230	165,000.00	s.m	10/29/1991	11/27/1991	22	38	$158,824.00	Pie
Built-up roof	13410	165,000.00	s.m	10/29/1991	12/16/1991	35	0	$121,320.00	Pie
1" rgid insullation roofing	13420	165,000.00	s.m	12/17/1991	1/20/1992	25	0	$69,500.00	Pie
Excavation and backfilling	11130	6,000.00	c.m	4/1/1991	4/11/1991	9	24	$37,480.00	Pie
Fencing in site	11200	4,680.00	l.m.	4/12/1991	5/21/1991	28	174	$53,320.00	Pie
Precast double -tee walls	13310	44,300.00	s.m	10/1/1991	12/2/1991	45	10	$313,130.00	Pie
Precast double-tee walls(16"+5")	13320	21,700.00	s.m	12/3/1991	1/8/1992	25	10	$144,200.00	Pie
Grading for site earthwork	11110	15,000.00	c.m	1/3/1991	2/14/1991	31	0	$52,864.00	Pie

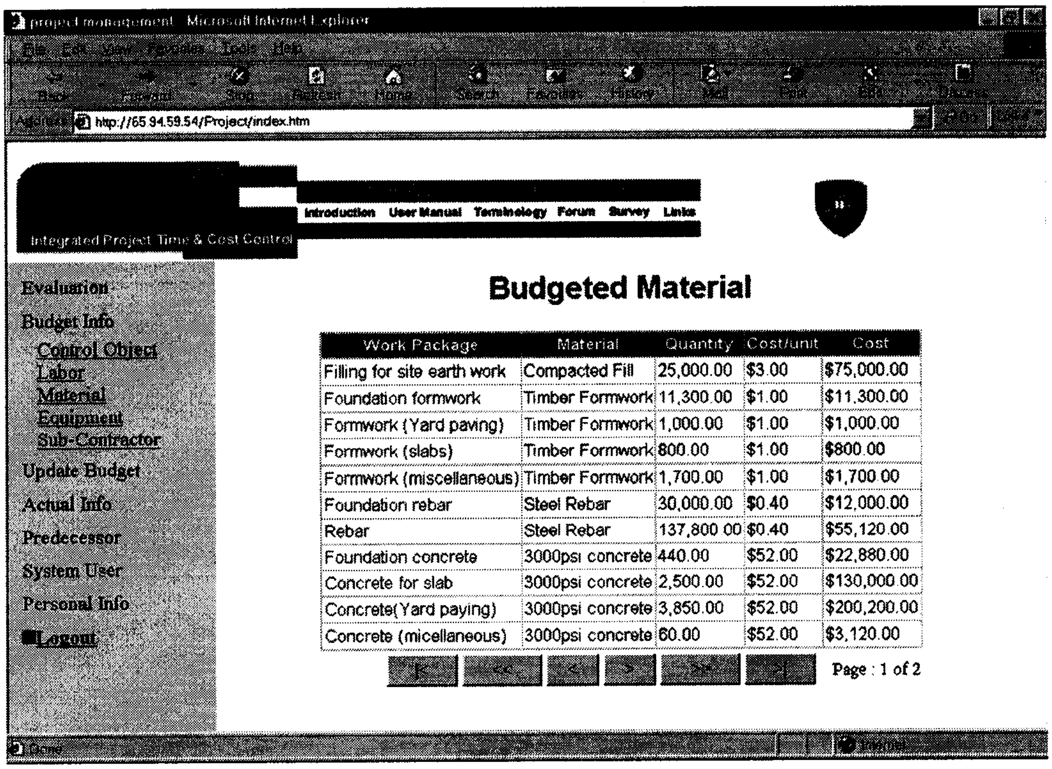
Figure H-1 Control-Object Schedule Data



Budgeted Labor

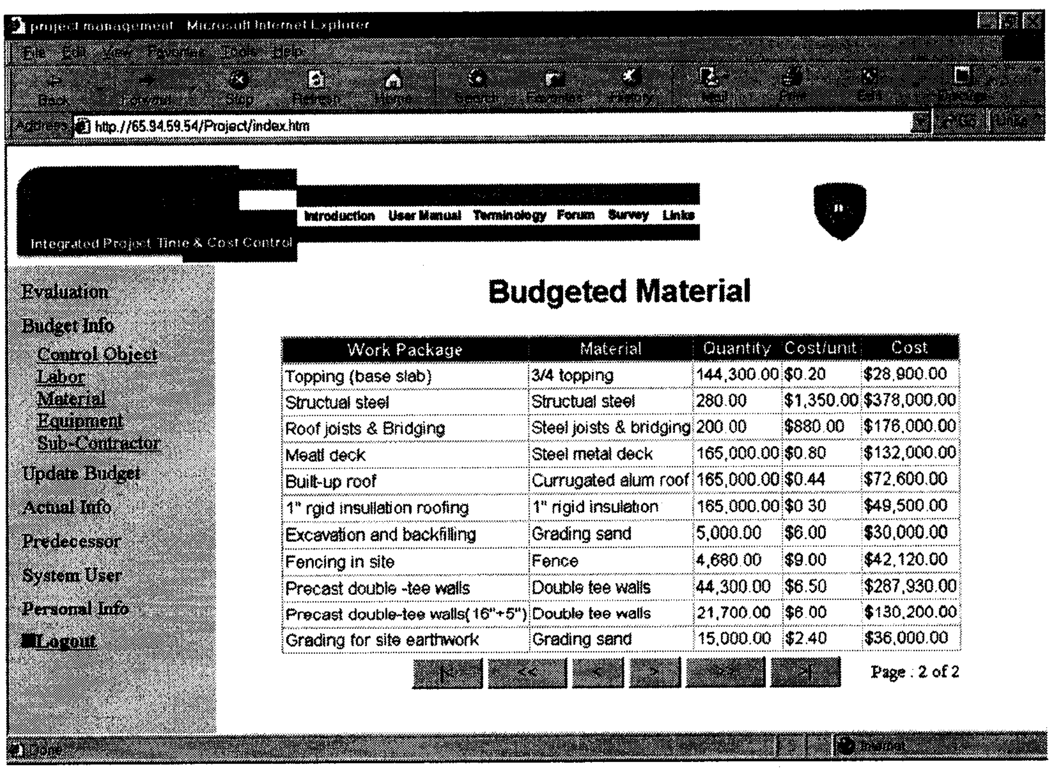
Control Object	Craft	Number	Mhrs	Cost/Hr	Cost
Topping (base slab)	Concrete Worker	5	1280	$23.03	$29,480.00
Structual steel	Structual Steel Worker	7	2072	$22.00	$45,584.00
Roof joists & Bndging	Structual Steel Worker	7	1120	$22.00	$24,640.00
Meatl deck	Structual Steel Worker	7	1232	$18.75	$23,104.00
Built-up roof	Structual Steel Worker	7	1960	$22.00	$43,120.00
1" rgid insullation roofing	Carpenter	5	1000	$20.00	$20,000.00
Excavation and backfilling	General Labor	5	360	$10.00	$3,600.00
Fencing in site	General Labor	5	1120	$10.00	$11,200.00
Precast double -tee walls	General Labor	5	1800	$10.00	$18,000.00
Precast double-tee walls(16"+5")	General Labor	5	1000	$10.00	$10,000.00
Grading for site earthwork	General Labor	5	1240	$10.00	$12,400.00

Figure H-2 Control-Object Budgeted Labor Data



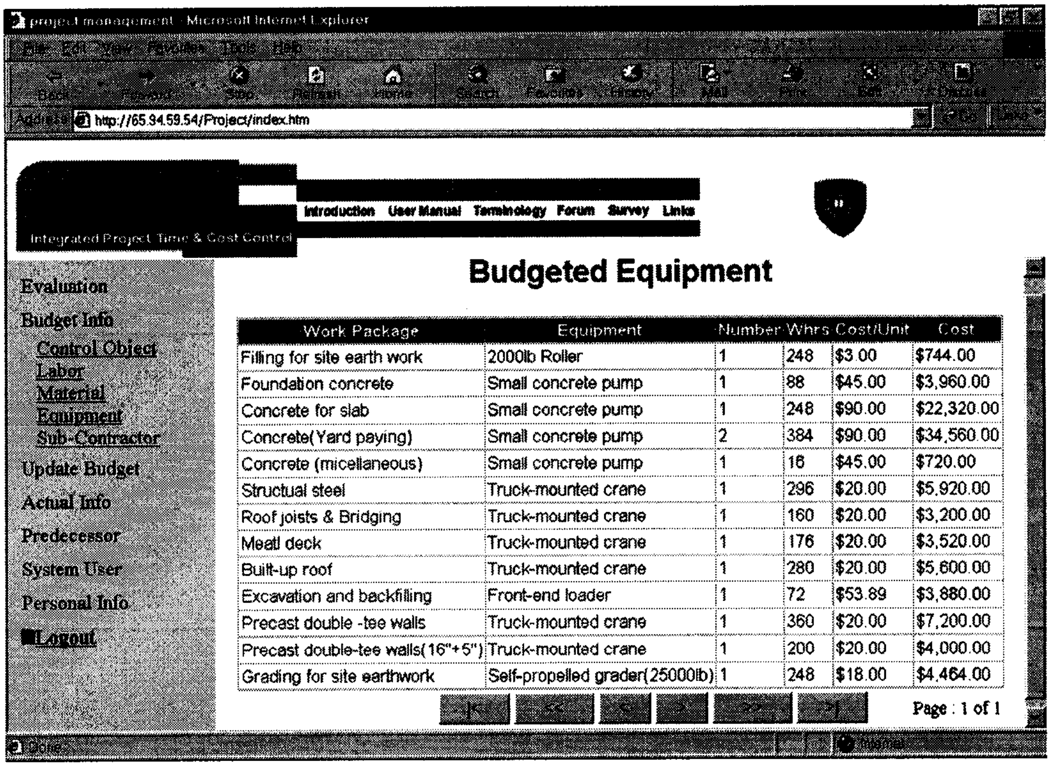
Work Package	Material	Quantity	Cost/unit	Cost
Filling for site earth work	Compacted Fill	25,000.00	$3.00	$75,000.00
Foundation formwork	Timber Formwork	11,300.00	$1.00	$11,300.00
Formwork (Yard paving)	Timber Formwork	1,000.00	$1.00	$1,000.00
Formwork (slabs)	Timber Formwork	800.00	$1.00	$800.00
Formwork (miscellaneous)	Timber Formwork	1,700.00	$1.00	$1,700.00
Foundation rebar	Steel Rebar	30,000.00	$0.40	$12,000.00
Rebar	Steel Rebar	137,800.00	$0.40	$55,120.00
Foundation concrete	3000psi concrete	440.00	$52.00	$22,880.00
Concrete for slab	3000psi concrete	2,500.00	$52.00	$130,000.00
Concrete(Yard paying)	3000psi concrete	3,850.00	$52.00	$200,200.00
Concrete (micellaneous)	3000psi concrete	60.00	$52.00	$3,120.00

Figure H-3 Control-Object Budgeted Material Data



Work Package	Material	Quantity	Cost/unit	Cost
Topping (base slab)	3/4 topping	144,300.00	$0.20	$28,900.00
Structual steel	Structual steel	280.00	$1,350.00	$378,000.00
Roof joists & Bridging	Steel joists & bridging	200.00	$880.00	$176,000.00
Meatl deck	Steel metal deck	165,000.00	$0.80	$132,000.00
Built-up roof	Currugated alum roof	165,000.00	$0.44	$72,600.00
1" rgid insullation roofing	1" rigid insulation	165,000.00	$0.30	$49,500.00
Excavation and backfilling	Grading sand	5,000.00	$6.00	$30,000.00
Fencing in site	Fence	4,680.00	$9.00	$42,120.00
Precast double -tee walls	Double tee walls	44,300.00	$6.50	$287,930.00
Precast double-tee walls(16"+5")	Double tee walls	21,700.00	$6.00	$130,200.00
Grading for site earthwork	Grading sand	15,000.00	$2.40	$36,000.00

Figure H-4 Control-Object Budgeted Material Data (Continue)



Budgeted Equipment

Work Package	Equipment	Number	Whrs	Cost/Unit	Cost
Filling for site earth work	2000lb Roller	1	248	$3.00	$744.00
Foundation concrete	Small concrete pump	1	88	$45.00	$3,960.00
Concrete for slab	Small concrete pump	1	248	$90.00	$22,320.00
Concrete(Yard paying)	Small concrete pump	2	384	$90.00	$34,560.00
Concrete (micellaneous)	Small concrete pump	1	16	$45.00	$720.00
Structual steel	Truck-mounted crane	1	296	$20.00	$5,920.00
Roof joists & Bridging	Truck-mounted crane	1	160	$20.00	$3,200.00
Meatl deck	Truck-mounted crane	1	176	$20.00	$3,520.00
Built-up roof	Truck-mounted crane	1	280	$20.00	$5,600.00
Excavation and backfilling	Front-end loader	1	72	$53.89	$3,880.00
Precast double -tee walls	Truck-mounted crane	1	360	$20.00	$7,200.00
Precast double-tee walls(16"+5")	Truck-mounted crane	1	200	$20.00	$4,000.00
Grading for site earthwork	Self-propelled grader(25000lb)	1	248	$18.00	$4,464.00

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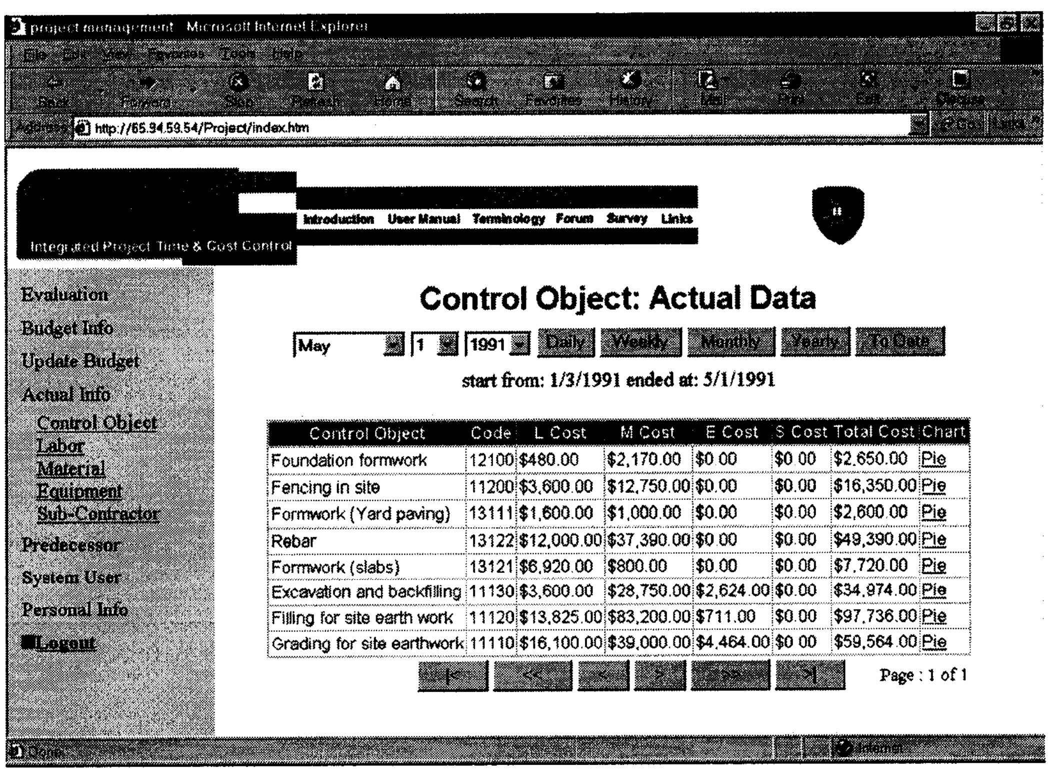
Figure H-5 Control-Object Budgeted Equipment Data



Control Object: Actual Data

start from: 1/3/1991 ended at: 5/1/1991

Control Object	Code	L Cost	M Cost	E Cost	S Cost	Total Cost	Chart
Foundation formwork	12100	$480.00	$2,170.00	$0.00	$0.00	$2,650.00	Pie
Fencing in site	11200	$3,600.00	$12,750.00	$0.00	$0.00	$16,350.00	Pie
Formwork (Yard paving)	13111	$1,600.00	$1,000.00	$0.00	$0.00	$2,600.00	Pie
Rebar	13122	$12,000.00	$37,390.00	$0.00	$0.00	$49,390.00	Pie
Formwork (slabs)	13121	$6,920.00	$800.00	$0.00	$0.00	$7,720.00	Pie
Excavation and backfilling	11130	$3,600.00	$28,750.00	$2,624.00	$0.00	$34,974.00	Pie
Filling for site earth work	11120	$13,825.00	$83,200.00	$711.00	$0.00	$97,736.00	Pie
Grading for site earthwork	11110	$16,100.00	$39,000.00	$4,464.00	$0.00	$59,564.00	Pie

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Figure H-6 Control-Object Actual Performance Data

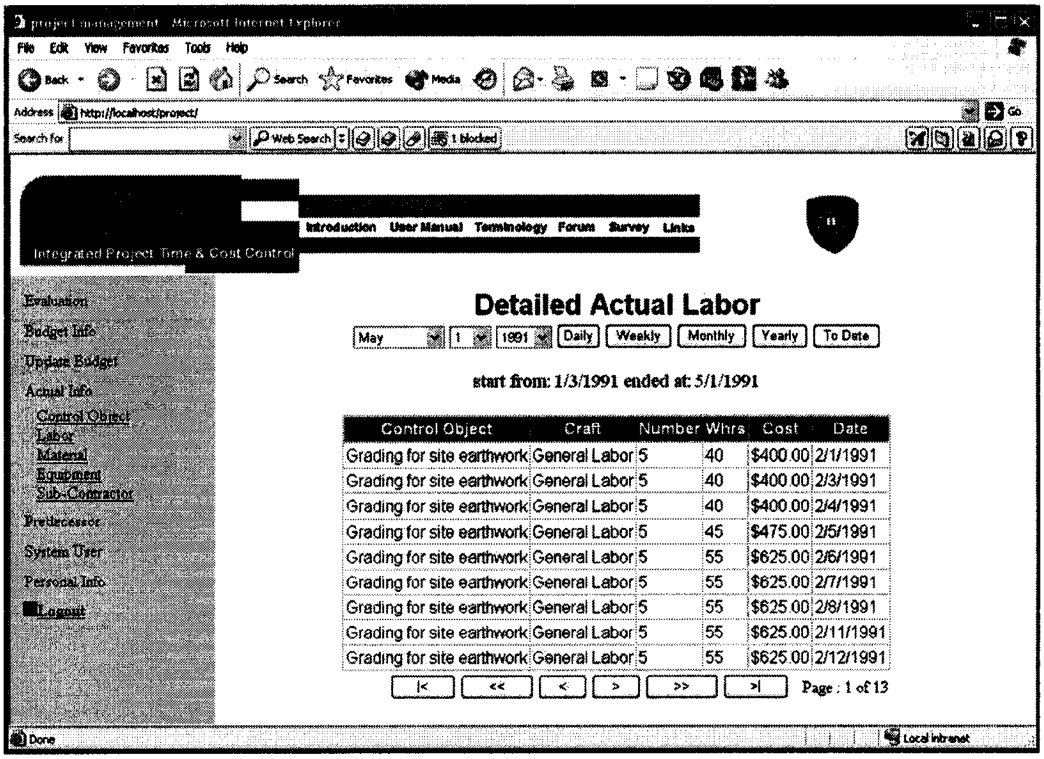


Figure H-7 Actual Labor Cost

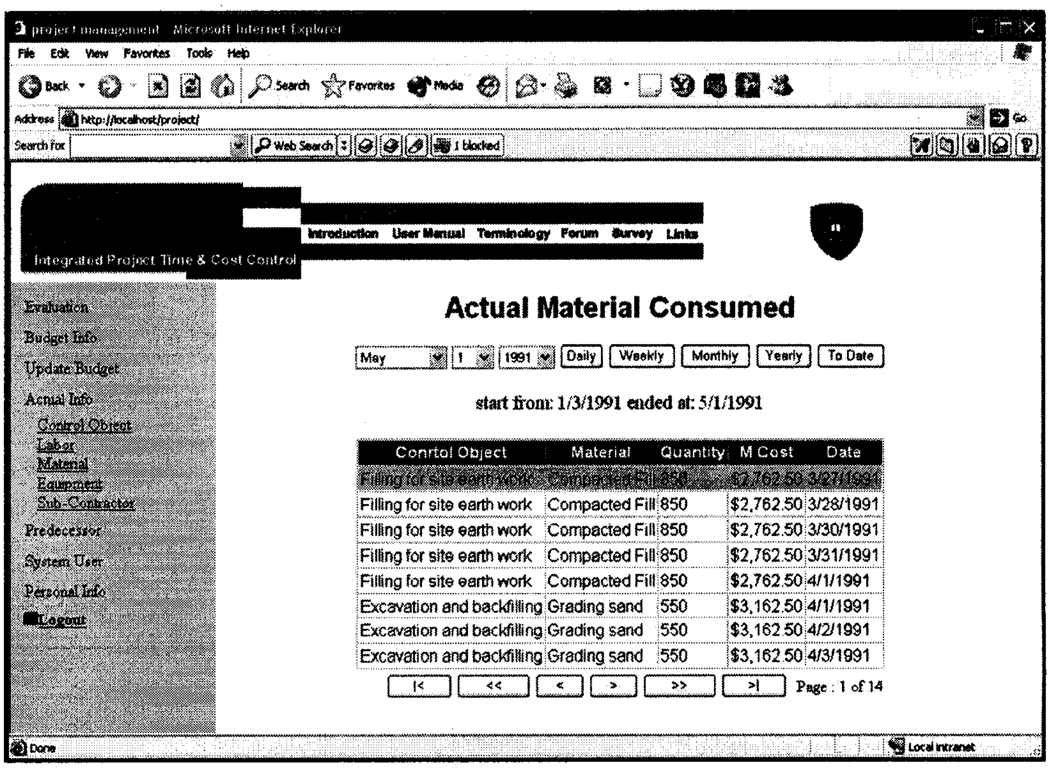


Figure H-8 Actual Material Cost

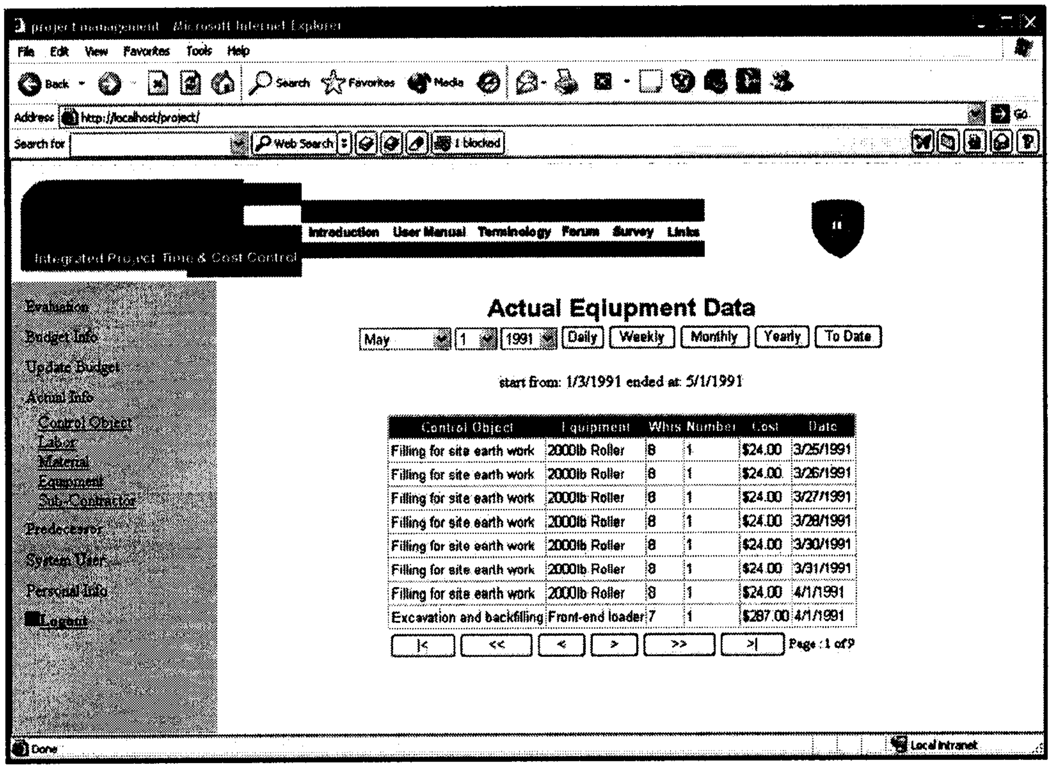
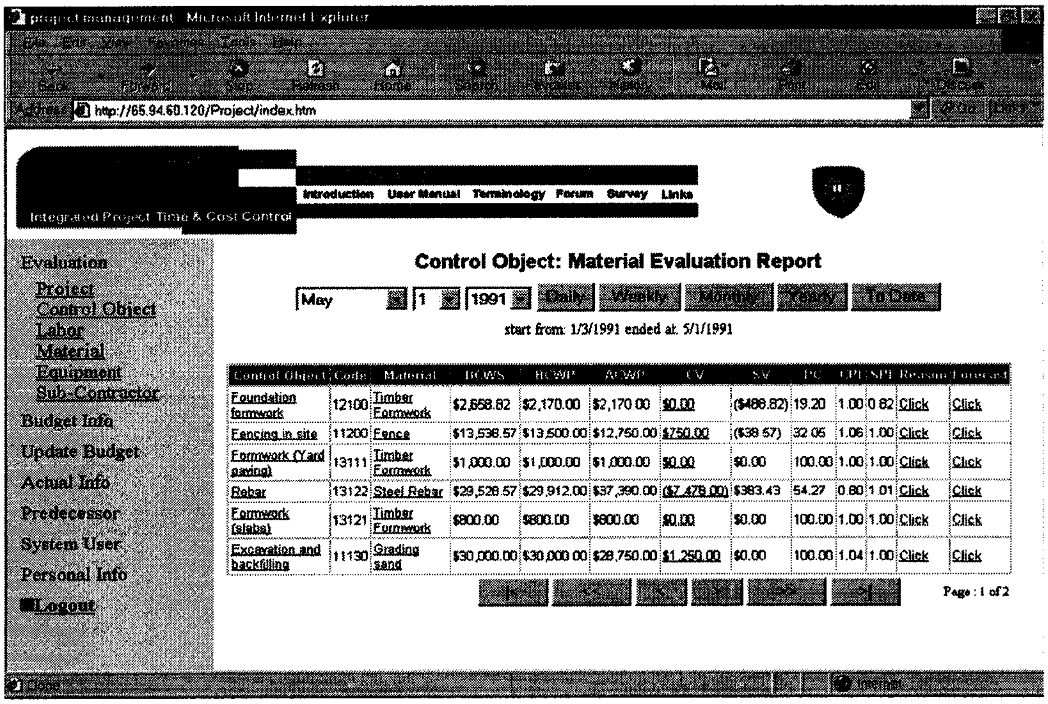


Figure H-9 Actual Equipment Cost

Appendix (I) Sample of the Generated Reports



Control Object: Material Evaluation Report

May 1 1991 Daily Weekly Monthly Yearly To Date

start from: 1/3/1991 ended at: 5/1/1991

Control Object	Code	Material	BCWS	BCWP	ACWP	CV	SV	PC	CPI	SPI	Reason	Forecast
Foundation formwork	12100	Timber Formwork	$2,658.82	$2,170.00	$2,170.00	$0.00	($488.82)	19.20	1.00	0.82	Click	Click
Fencing in site	11200	Fence	$13,538.57	$13,500.00	$12,750.00	$750.00	($38.57)	32.05	1.06	1.00	Click	Click
Formwork (Yard paving)	13111	Timber Formwork	$1,000.00	$1,000.00	$1,000.00	$0.00	$0.00	100.00	1.00	1.00	Click	Click
Rebar	13122	Steel Rebar	$29,528.57	$29,912.00	$37,390.00	($7,478.00)	$383.43	54.27	0.80	1.01	Click	Click
Formwork (slabs)	13121	Timber Formwork	$800.00	$800.00	$800.00	$0.00	$0.00	100.00	1.00	1.00	Click	Click
Excavation and backfilling	11130	Grading sand	$30,000.00	$30,000.00	$28,750.00	$1,250.00	$0.00	100.00	1.04	1.00	Click	Click

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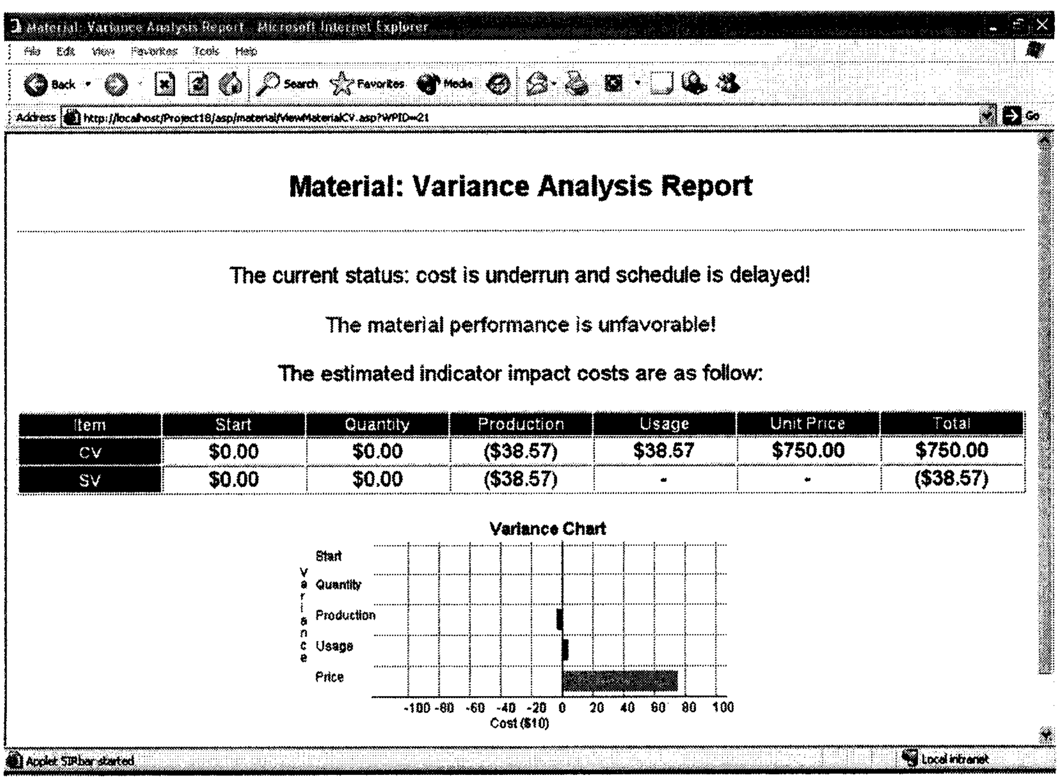
Figure I-1 Material Performance Evaluation Report



Material: Variance Analysis Report

The current status: cost is underrun and schedule is delayed!

The material performance is unfavorable!

The estimated indicator impact costs are as follow:

Item	Start	Quantity	Production	Usage	Unit Price	Total
CV	$0.00	$0.00	($38.57)	$38.57	$750.00	$750.00
SV	$0.00	$0.00	($38.57)	-	-	($38.57)

Figure I-2 Estimated Impact-Cost for Material

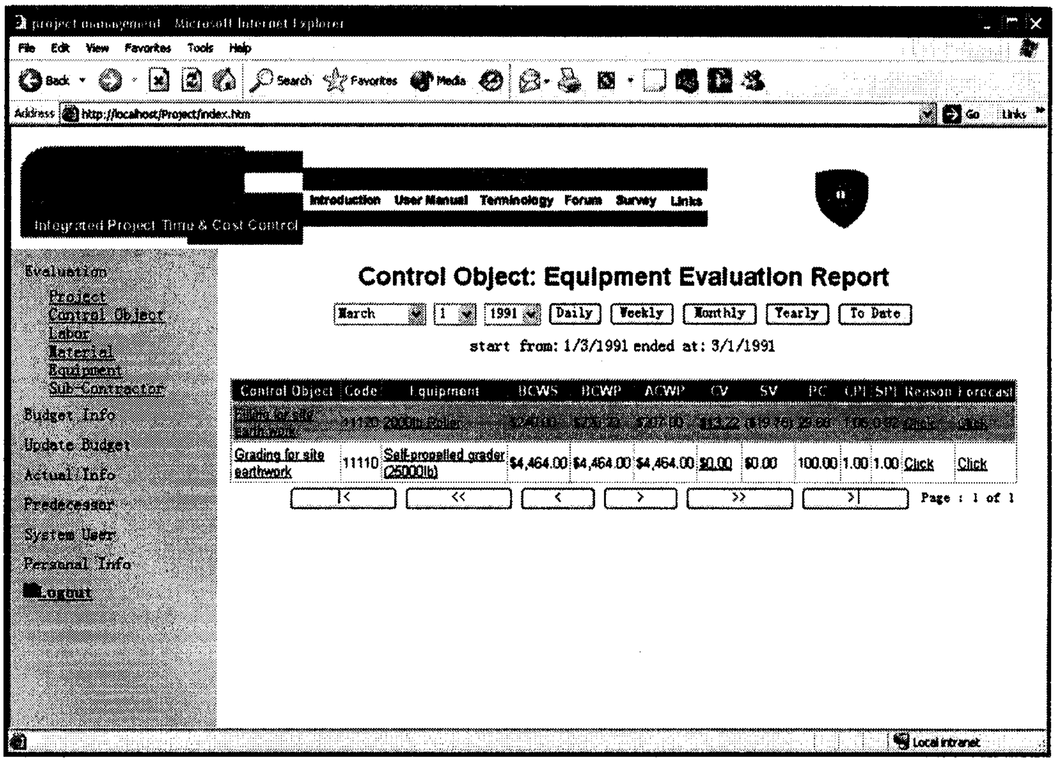


Figure I-3 Equipment Performance Evaluation Report

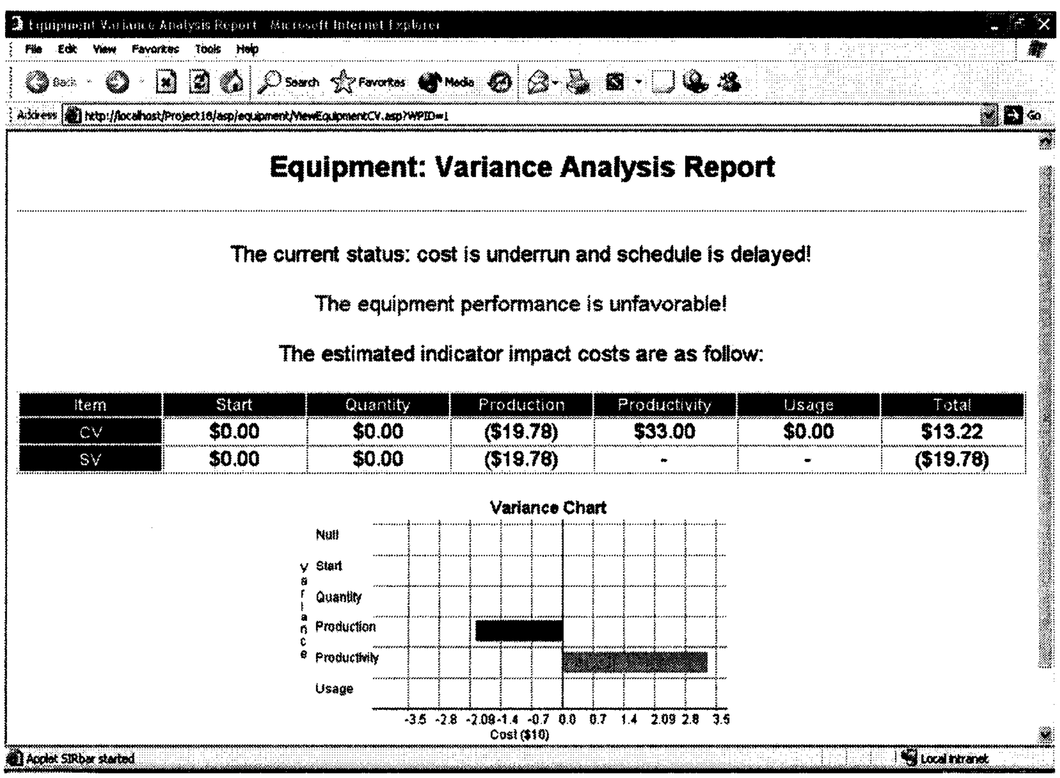


Figure I-4 Estimated Impact-Cost for Equipment

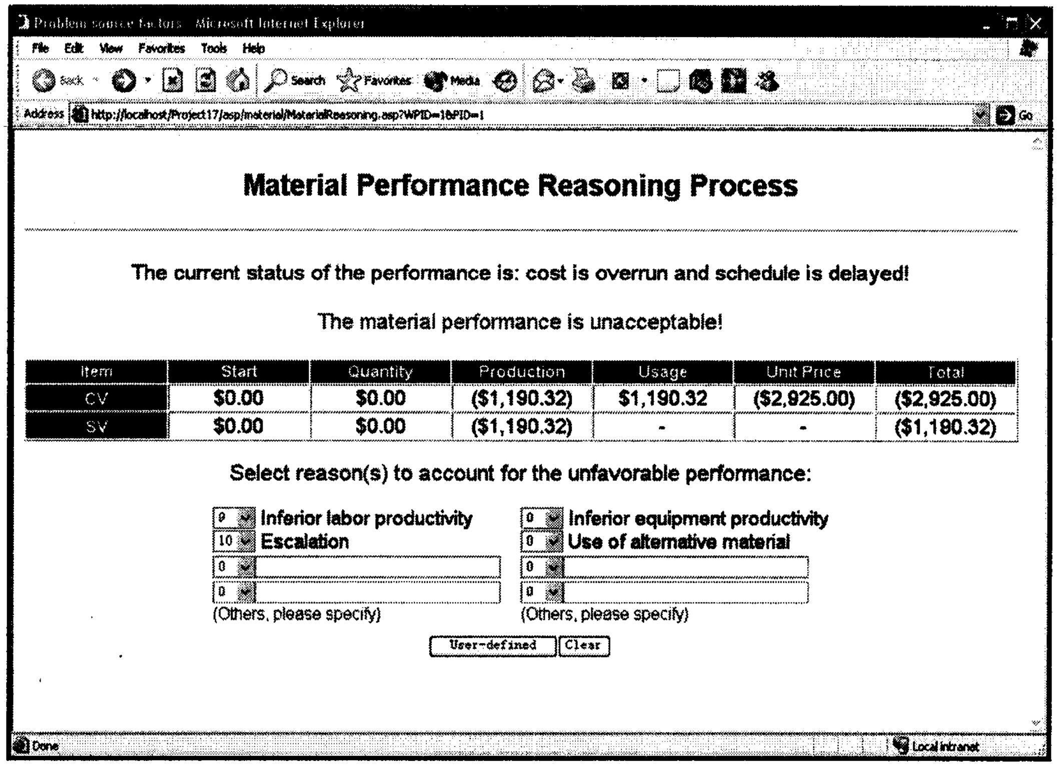


Figure I-5 User-Specified Factors for Material Performance

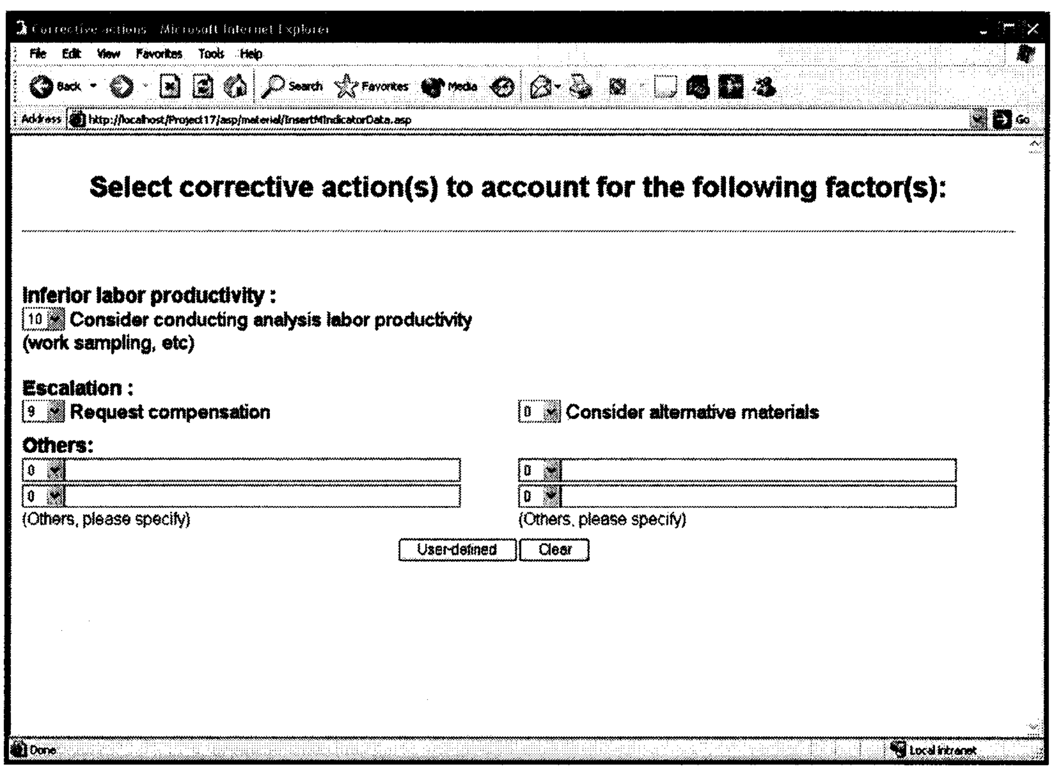


Figure I-6 User-Specified Actions for Material Performance

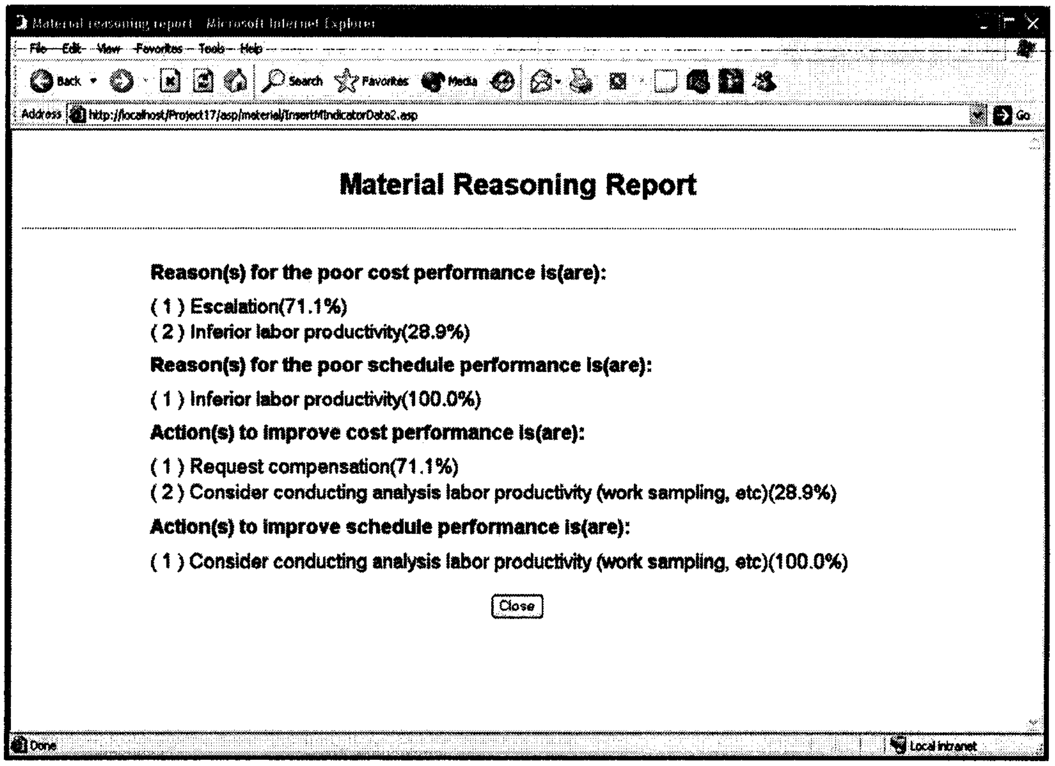


Figure I-7 Material Reasoning Report

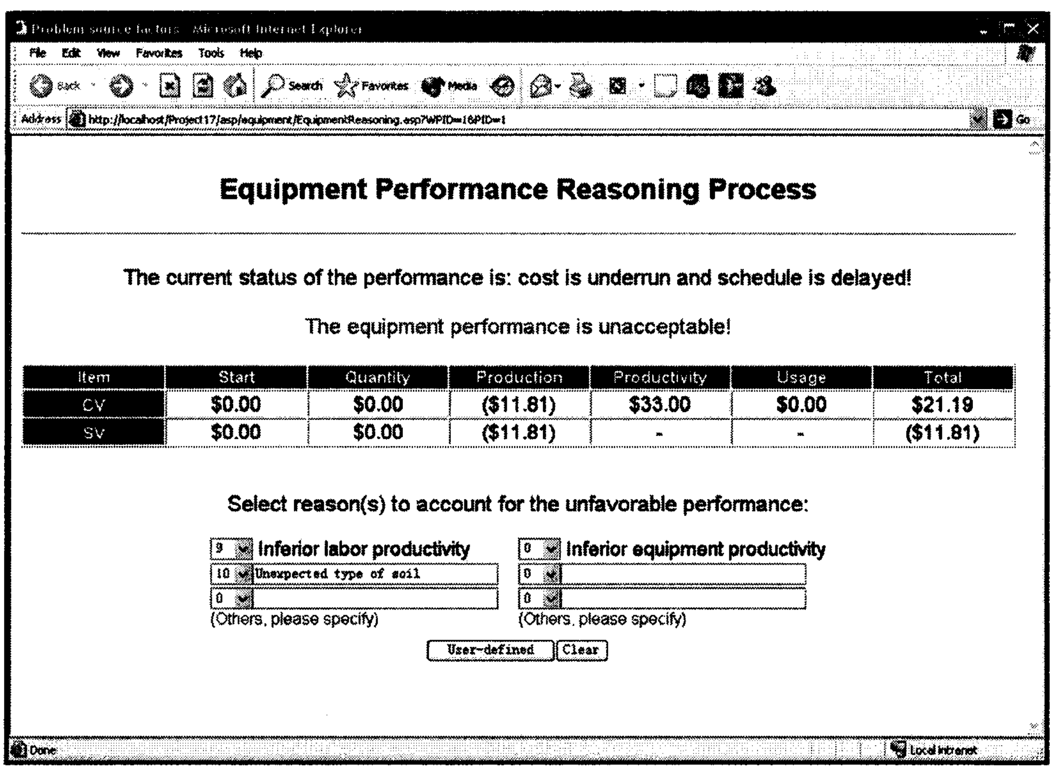


Figure I-8 User-Specified Factors for Equipment Performance

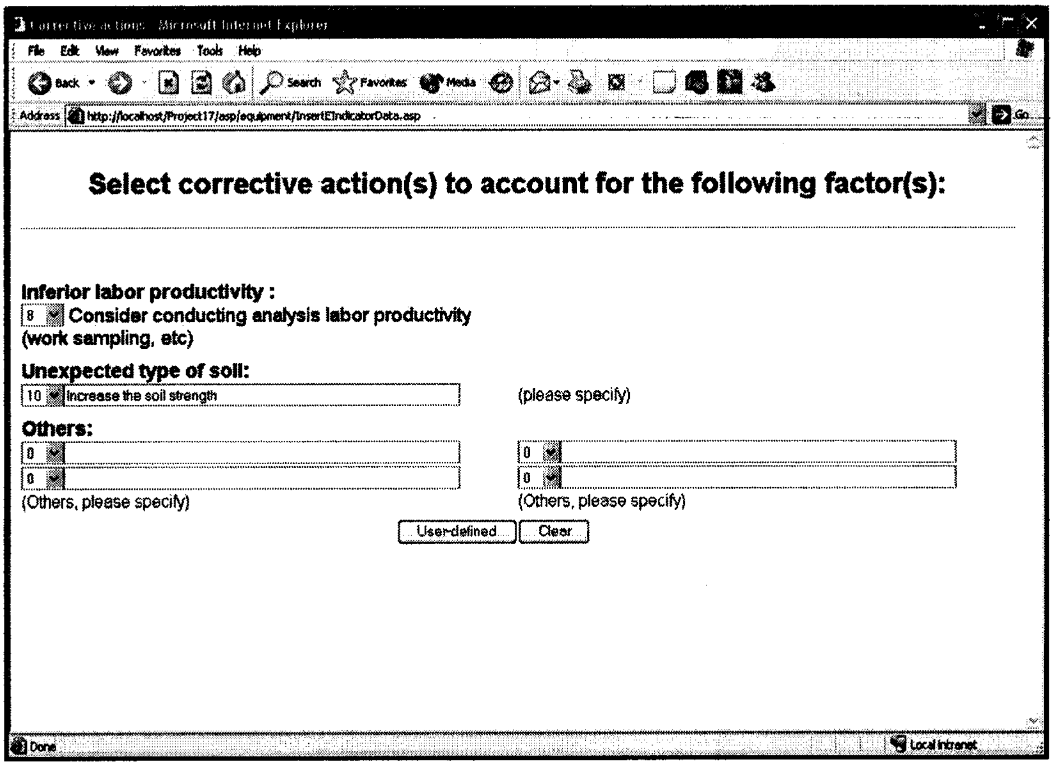


Figure I-9 User-Specified Actions for Equipment Performance

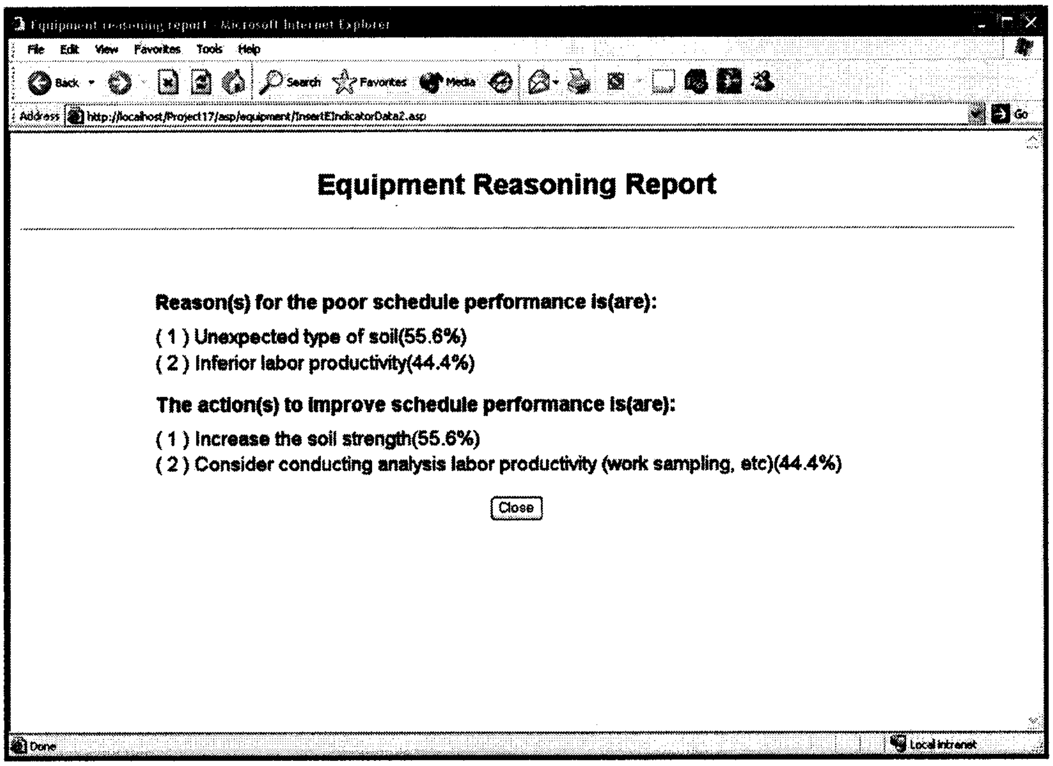


Figure I-10 Equipment Reasoning Report

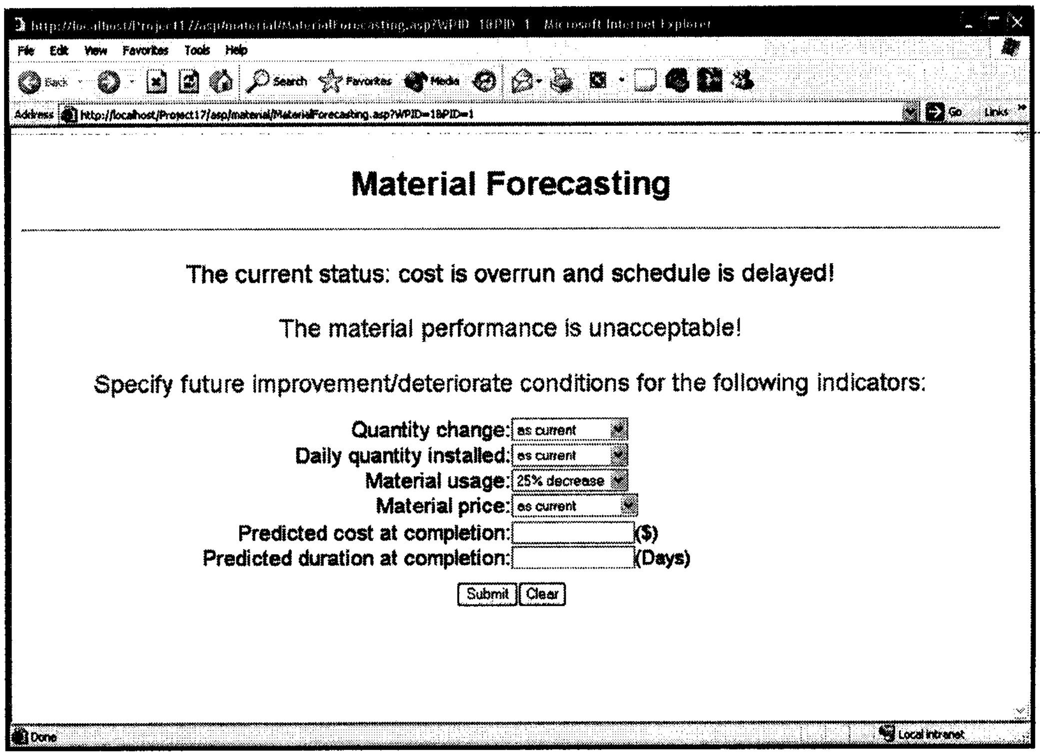


Figure I-11 Material Forecasting

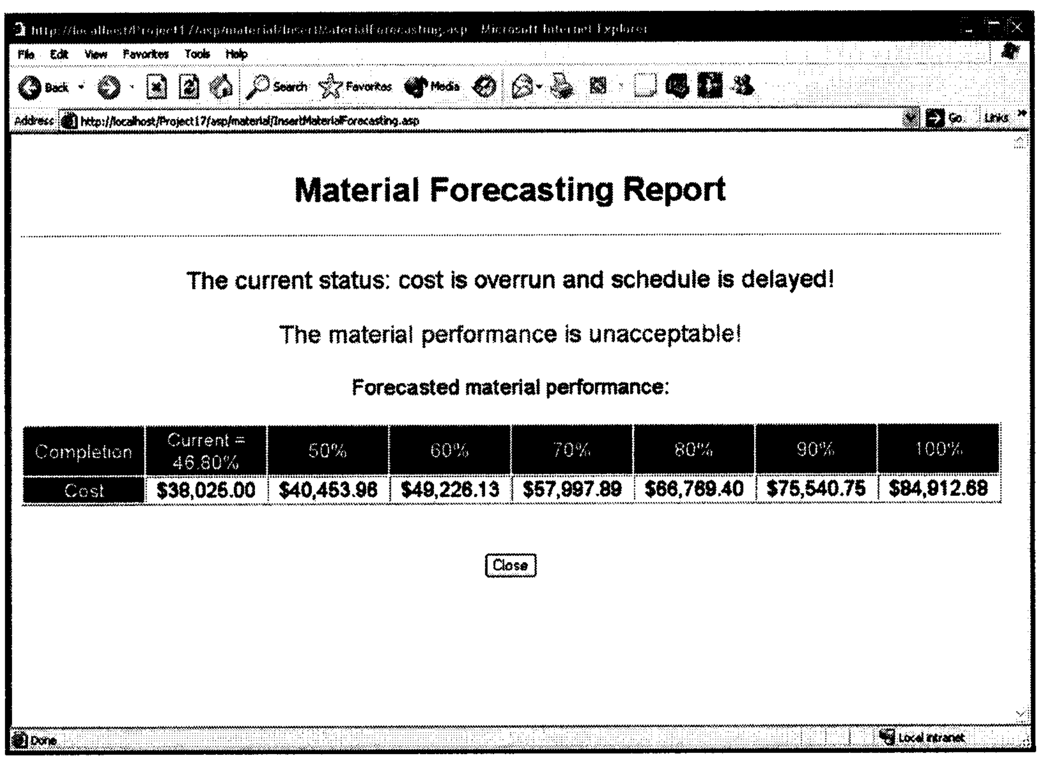


Figure I-12 Material Forecasting Report

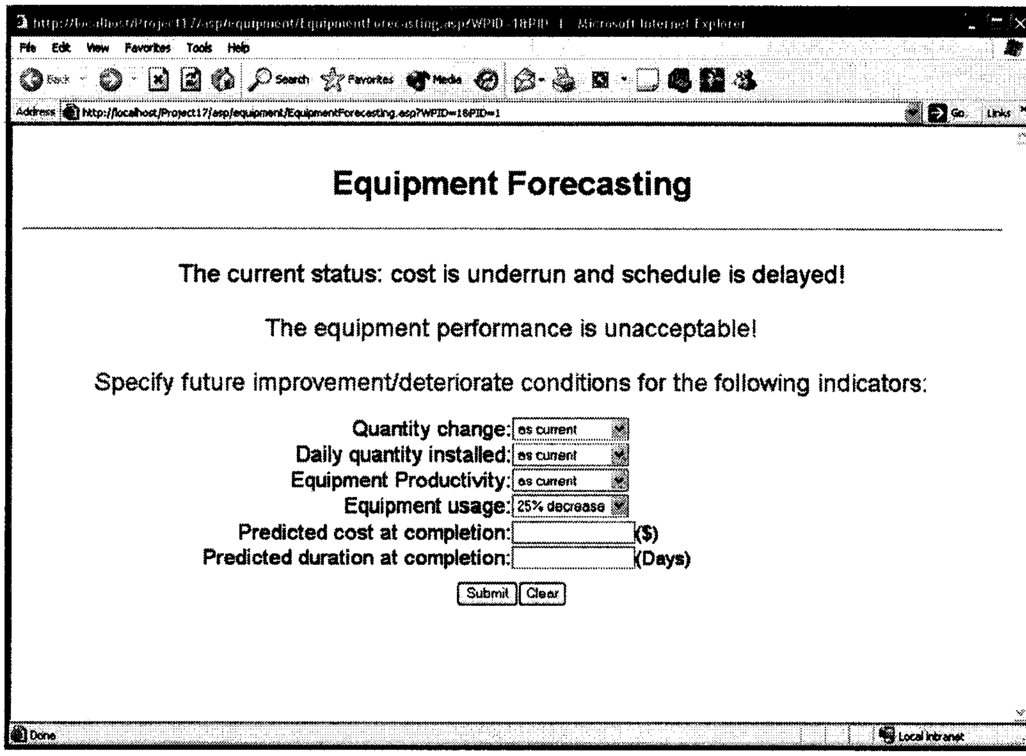


Figure I-13 Equipment Forecasting

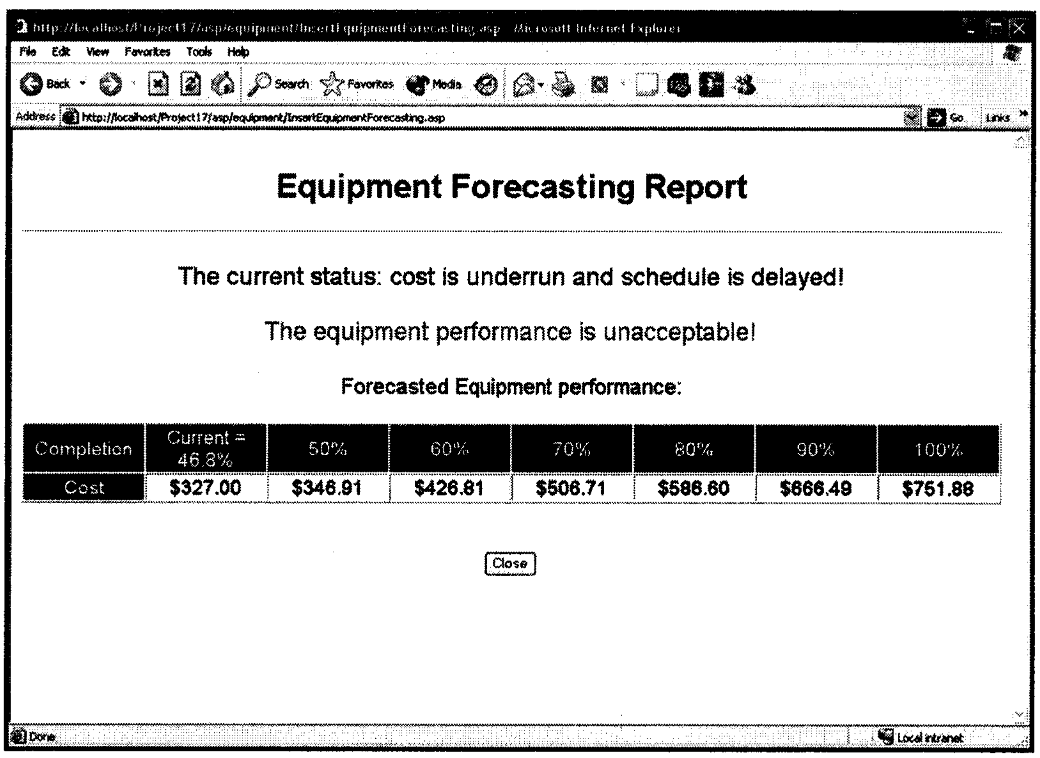


Figure I-14 Equipment Forecasting Report