MASTERS OF BUSINESS ADMINISTRATION

PROJECT MANAGEMENT

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Session 5 - 19th April 2021

Agenda

Session 5- 5:00 pm to 9:00 pm	
5:00 pm to 6:00 pm	Project Monitoring and Control • The process • Corrective Actions • Tools and Techniques
6:00 pm to 6:10 pm	**Coffee/Tea- Break**
6:10 pm to 7:00 pm	Balancing Time Cost and Quality (TCQ) • Project Crashing • Trade Offs between TCQ
7:00 pm to 7:15 pm	**Coffee/Tea- Break**
7:15 pm to 8:00 pm	Project Tracking- Updating your Gantt Chart • Create a Baseline • Update Tasks • Reschedule Incomplete tasks
8:00 pm to 8:15 pm	**Coffee/Tea- Break**
8:15 pm to 9:00 pm	Look at the Assignment • Reflective- where are we? • What to work on during the weekend?

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THE INFLUENCE OF MONITORING AND CONTROL ON PROJECT MANAGEMENT SUCCESS

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ABSTRACT

This article analyzes monitoring and control techniques and tools and their influence on project management and performance. It researches the current literature, the Bodies of Knowledge approach and the managers' perspective. The article studies the impact of the use of methodologies, techniques and tools on the outcomes of various projects carried out recently by a sample of interviewees.

Through interpretive work the view of the Bodies of Knowledge is reviewed and synthesized. Information from project managers in various sectors is collected in order to analyze the correlation between variables that determine the application of monitoring and control methodologies, techniques and/or tools and variables that determine the success criteria in projects.

The impact of the adoption of techniques and tools was evident on project performance. There was a positive influence of the use of techniques and tools on the results. It was found that some sectors do not use enough methodologies, techniques and tools. The empirical study proved the importance of using these tools as a success factor in project management and performance.

We aim to contribute with an actual approach of the use of techniques and tools in project monitoring and control processes, thus promoting the implementation of both traditional and new tools. The importance of project management is presented in order to increase the interest of researchers in it as a knowledge field applicable to various sectors.

The methodology used to prepare the study is useful in project management contexts and provides a procedure that allows an adequate analysis, data processing and results presentation, both interpretively and graphically.

Keywords: Monitoring and control, project management

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1. INTRODUCTION

The process of monitoring and control (M&C) of projects is a topic of common interest in project management. The purpose of its implementation is to achieve the objectives of the project, causing the least possible difficulty. It is based on observation, systematic measurement of performance, identifying variances, and adoption of corrective / preventive actions as well as changes management. Proposals from professional associations and standard organizations in project management agree that the process of M&C contributes to the minimization of the deviations during execution and to the achievement of better results. This demonstrates the importance of this process in the application of subject, and in the development of studies on techniques, tools and new contributions.

The studies of M&C project management have been motivated by the impact that the process has on their success. In a literature review conducted by Rozones et al (2006), the importance of process control throughout the lifecycle of projects is highlighted and the lack of appropriate methodologies despite the evolution of discipline. Rozones et al emphasizes that many of the causes of project failures can be attributed to the lack of planning and monitoring, highlighting importance of control in the achievement of the aims and improvement the project performance. He classifies them as one-dimensional and multidimensional control systems. One-dimensional systems are not integrated variables, this being their main disadvantage. They are used for specific issues due to their easy usability. Multidimensional systems include the integration of variables.

M&C is especially important in some sectors, for example, studies demonstrate the practical implications in the international development, aid, and disaster recovery, where an effective control process can get the correct implementation of a project (Steinfort, 2010; Steinfort and Walker, 2011). Although the aid sector and international cooperation has not been regarded as a traditional area of intervention of the project management (Ahsan and Gunawan, 2010; P. Crawford and Bryce, 2003; Ika et al., 2010), and the available literature is little and too recent (Steinfort, 2010), thus justifying the contributions that focus on improving processes and monitoring and control applications such projects. In this paper assumed as particular research topic the approach on the consequences of observing techniques, performance measurement and control that are fundamental for self-management methodology and project management, as well as search and choice of factors relevant to the plan, to help simplify tasks and achieve better results in the practice of the project managers (Cicmil et al., 2006; Hodgson and Cicmil, 2006).

Research contributions have set trends for the M&C process, generating the development of methods, techniques, tools, or modifications of the traditional models. Earned value management, for example, is the method most often used in measuring multidimensional systems. It is perhaps the most applied for the M&C. There are a number of publications on the results and modifications of this technique, which reflect the ease of its application, interpretation and implementation. Anbari (2003), suggests that EVM can be used in various types and classes of projects in public and private sectors. Kim et al (2003) confirms the acceptance of earned value in monitoring processes, despite their disadvantages of excluding other aspects such as, among others, quality, technology or design.

In other studies/researches, progressive changes have been made to the EVM in order to improve its implementation. This is the case of Lipke et al (2009), who proposed a method of forecasting final cost and duration of the project, by varying the method to analyze the performance of the calendar (Earned Schedule). Vandevoorde and Vanhoucke (2006) compared the classic indicators of the earned value with a new performance indicator called "earned schedule". They concluded that the use of the modification/change depends on the needs of project managers, and that similar results could be produced for monitoring in early and middle stages. Plaza and Turetken (2009), have designed a spreadsheet as a new version of EVM called EVM/LC. The authors have proposed the tool, looking for a better estimation of the duration and control of projects. Rozenes and others (2004), proposed a multidimensional system to quantify the deviations from the planning phase to implementation phase, which includes aspects such as quality, which cannot be analyzed through other techniques.

Another technique transferred from the area of management into organizations, which has been applied in the M&C project, is the balanced scorecard (BSC). Its function is to detect changes in the market to give rise to organizational changes, and its application in project management allows evaluating the integration of three perspectives: customer, internal processes and learning, and growth. Norrie and Walker (2004) describes the use of the balanced scorecard as a tool for improving the effectiveness of project management, and proposes its use as an extension of the current practices of strategic measurement and improving operational performance of project teams.

The critical chain methodology (CC), which applies the theory of constraints (TOC), is a technique used in organizations operating in multi-projects; it is a method for planning, programming and controlling that recognizes the relationship between activities and resource constraints. This technique is applied for monitoring the progress of projects, the deviations, the schedule and for assisting in correct decision-making (Cohen et al., 2004). The study by Cohen and others has shown that there are advantages in its application. However, provided that it conforms with the needs of the project, it can also be implemented with others tools. Besides the above, traditional techniques such as the Gantt Chart, Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM) are still being studied. Their adaptation to information technology tools have corrected their limitations and promoted a new generation of applications.

Finally, considering that we are trying to analyze the impact of the adoption of methods, techniques and tools of M&C on performance in project management, we have analyzed the criteria normally used to assess such performance. As in other management disciplines that use performance measurement, a discussion has been established in the field of project management on performance assessment and its impact on the project success (Bryde, 2005). Performance assessment is based on the measurement and monitoring of the performance criteria of the projects (Barclay and Osei-Bryson, 2010) and has traditionally been associated with the variables of time, cost and quality (Pillai, Joshi and Rao, 2002; Wi and Jung, 2010).

Although there is divergence of views on what constitutes a "successful project" (Prabhakar, 2008), different authors distinguish between project success, as measured by the achievement of objectives on the final product; and project management success, measured usually in terms of time, cost and quality (Baccarini, 1999; de Wit, 1988). In this regard, Cooke-Davies (2002) states that we should differentiate between success criteria (measures the project will be judged by) and success factors (inputs to the management supporting the success). Project performance is measured by metrics (Luu, Kim and Huynh, 2008; Marques, Gourc and Lauras, 2010), and the process is about setting goals, about the choice of an improvement strategy through success factors, and measurement to establish the difference between what is planned and the results (Toor and Ogunlana, 2008, 2010).

Some studies show that it is impossible to generate a universal list of criteria, since they vary from one project to another (Jha and Iyer, 2007, Marques et al., 2010). Others propose adopting new dimensions that broaden the vision, such as management process quality and meeting stakeholders' expectations (Van Der Westhuizen and Fitzgerald, 2005). In general, most current methods are based on the so-called iron triangle (cost, time and quality) (Wi and Jung, 2010); and other categories are added to this. Other researchers propose traditional categories or some additional (Almahmoud, Doloi and Panuwatwanich, 2012; Cho, Hong and Hyun, 2009, Jha and Iyer, 2007; Ling, 2004; Sohail and Baldwin, 2004). Other proposals suggest categories different from traditional (Cheung et al., 2004; Lauras, and Gourc Marques, 2010; Toor and Ogunlana, 2010). For the preparation of this paper we have used the three traditional categories plus three others taken from the literature described in this section.

The research analyzes and describes the current status of the topic under study, including journal literature, standards and Bodies of Knowledge. An empirical study is carried out to understand the project managers' perspective and adoption of methods, techniques and tools of M&C. The purpose of the empirical phase is to analyze the impact of use of tools and techniques on projects performance.

The question proposed to define the hypothesis in the research is: How can the adoption of techniques and tools be a key factor in project management performance and success?. With this study we aim to provide a contextual framework for applying project management's tools, developed through the analysis of literature and an empirical study. We also seek to confirm the relation between the adoption of these tools and project performance, establishing the variables that affect the results both positively and negatively.

2. Standards and Project Management Methodologies

The bodies of knowledge of project management are developed by organizations, agencies (public or private), professionals and researchers to define and validate the conceptual domain and competencies required for performing adequately in the area. The BOKs contain the most important knowledge (Rozenes et al., 2006), and besides being a guideline, have methods, techniques, tools and skills for their practitioners (White and Fortune, 2002). The fulfillment of the standards is voluntary (Hiyassat, 2000), and its adoption in organizations has increased.

Ahlemann and others (2009), confirm the existence of a large number of standards for project management, issued by organizations, standardization companies and associations in the world. They have common content and principles, and one of the effects of standardization is the creation and maintenance of a market for tools to support the project management practices (Garcia, 2005). Milosevic and Patanakul (2005) argues that increasing the level of standardization in some factors may lead to greater success in managing projects.

The standards should be regarded as an instrument for facilitating the efficient and effective use of resources, since the latter are mobilized through projects in organizations and establish a competitive advantage (Bredillet, 2003). According to Crawford (2004), widely distributed standards have been essential for the growing interest in project management, but it can also be seen as limiting its development and influence. Wirth and Tryloff (1995) compared some bodies of knowledge and standards, and suggested the development of a common international document based on the alternatives available.

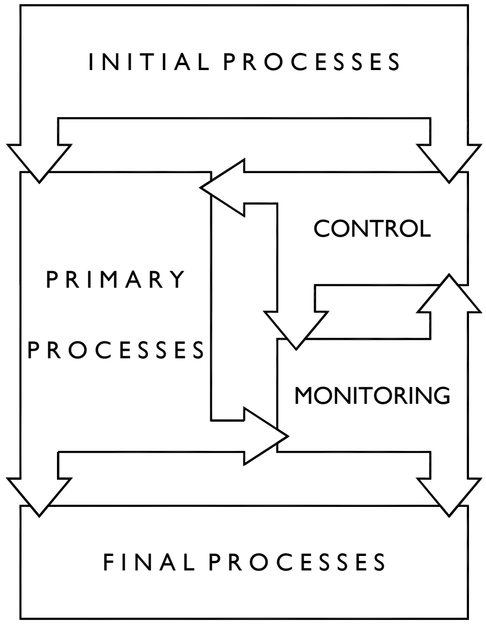


Figure 1. The project management process.

M&C is a project management process commonly referred to by all the BOKs, according to which it represents one of the central and most important processes within their standards. Figure 1 shows a general understanding on the importance of M&C within the processes typically referred to in the standards of project management.

The following sections present the compilation of the approach for realizing the process of M&C projects for each of the bodies of knowledge and internationals standards.

2.1. Project Management Body of Knowledge (PMBOK)

The PMBOK is a standard of the Project Management Institute (PMI) which describes methods, processes, techniques and tools applicable to the management of projects (Pant and Baroudi, 2008). The proposal included in the PMBOK are recognized and accepted worldwide (Barad and Tzvi., 2000; Milosevic and Patanakul, 2005) (Shi, 2011), and its content has been implemented in many sectors (McHugh and Hogan, 2011).

The monitoring and control is an essential process in its approach. This process aims to monitor performance, measure and regulate it in a systematic way to identify changes in planning (Project Management Institute, 2008).

Eight of the nine knowledge areas interact with the process of M&C, which gives one an idea of the significance of its inclusion in project management and the number of elements that are proposed for use in its application. Moreover, a set of techniques and tools are listed, which can be arranged to benefit the outcome of management activities in this process

Table 1. Techniques / tools for monitoring and controlling in projects PMBOK

Technique/Tool
Expert judgment
Change control meetings
Inspection and audits
Variance analysis
Performance reviews
Project management software
Resource leveling
What-if scenario analysis
Adjusting leads and lags
Schedule compression
Scheduling tool
Earned value management
Forecasting
To-complete performance index
Cause and effect diagrams
Control charts
Flowcharting
Histogram
Pareto chart
Run chart
Scatter diagram
Statistical sampling
Approved change requests review
Communication methods
Reporting systems
Risk reassessment
Risk audits
Technical performance measurement
Reserve analysis
Status meetings
Contract change control system
Procurement performance reviews
Performance reporting
Payments systems
Claims administration
Records management system

According to the PMBOK, the central integration activity in the process of M&C sets monitoring variables into seven areas: work, scope, schedule, cost, quality, risk and procurement project. Once the information is gathered from the above areas, it is compared with the management plan. Furthermore, the project status is communicated through performance reports and change requirements (corrective / preventive actions and defect repair) and is created so that it can be incorporated into the project.

The approach of the standard for the M&C primarily focuses on checking obtained deliverables (scope), dates achieved (schedule) and percentage of completed work (cost), whose parameters should be monitored using performance indicators (KPI). The technique suggested by the PMBOK for this activity is the earned value management (EVM), which is the standard PMI and has been developed as a complement to the PMBOK (Project Management Institute, 2005). EVM indicators provide information on variation in cost and time, and allow to estimate the conclusion/end of the project, which are precisely the essential data in the monitoring approach.

Table 1 has been compiled with techniques and / or tools that could be applied to M&C process according to the PMI. The PMI includes a large group of techniques (qualitative and quantitative) that may be applicable in the process of M&C project. The technique most recommended for the M&C is the Earned value analysis and its use can be supplemented with other techniques such as work to complete performance index, variance analysis, performance reporting, trend analysis, project status meetings, reporting system and project management software.

2.2. Association for Project Management Body of Knowledge (APMBOK)

The body of knowledge from the Association for Project Management (APM) is used as a normative standard of project management. The BOK defines the issues in which APM believes that the professionals of project management should be well informed (Morris et al., 2006; 2000; Willis, 1995), as well as knowledge required for the successful management of projects in various sectors.

In the APM, each group is divided into components to form a structure with a total of 52 parts (Anderson and Merna, 2003; Association for Project Management, 2006). The APM model has a structure similar to the scheme of stages of strategic management, in which the plan conception comes from the direction of the organization, and is implanted through an action plan with activities and projects. Thus, the emphasis in the process of M&C in APM can be seen mostly in the elements called "strategy execution" and "technical", since in the strategic management process is precisely the implementation of the strategy where control and monitoring measures are applied on action plans.

Based on the above, we selected the sections of the model which are related to the M&C project. In section "Executing of the strategy" there is a large number of elements related to the monitoring and control process, such as scope management, scheduling, resource management, budget and costs, and change control. The earned value management technique and reporting information management is also included. It is considered that by definition the process of projects monitoring and control raised by APM is equivalent to the strategic monitoring, since the strategic implementation is carried out mainly through internal projects in organizations.

Likewise, according to APM, verification is based on establishing a work plan, which contains parameters that are initially set as a baseline. Once the actual performance is established with respect to these initial set parameters, the deviations are established and appropriate decisions are taken on this project. Once more, in the process of M&C project

APM model, the ideas promoted by the strategic management theory are replicated, since accordingly the analysis, selection and implementation of the strategy, decisions are implemented through concrete actions. These actions, contained in plans, with deadlines, human, material and financial resources, are projects by definition.

It is considered that the model for project management APMBOK initially covers aspects related to the context of project management, in which strategic approach is evaluated with the opportunity and viability of the project as a business. Therefore, the standard includes aspects prior to the decision to undertake the project (feasibility studies), and subsequent of project management such as managing schedule, budget and changes. The approach to M&C can be found within the topics of strategy execution.

Table 2. Techniques / Tools S&C in projects APM

Technique/Tool
Key performance indicators
Quality management
WBS (Work Breakdown Structure)
OBS (Organizational Breakdown Structure)
CBS (Cost Breakdown Structure)
Earned value management
Gantt Charts
Milestone Charts
PERT
CPM
Precedence diagram
Cash flow
Trend analysis – predictions

It is considered that the APM body of knowledge presents two technical approaches used in the process of M&C: application of traditional techniques (PERT, CPM, precedence, Gantt) and performance-related techniques.

For these latter the earned value management (WBS, OBS, CBS), indicators, trend analysis, predictions and cash flow are incorporated.

The APM techniques may be seen in table 2, which has been summarised and compiled from reports of the APM standard.

2.3. International Competence Baseline (ICB)

ICB is the skills standard outlined by the International Project Management Association (IPMA), an organization of professionals in the management of projects (Söderlund, 2004), ensuring consistent processes in project management (International Project Management Association, 2006).

The model's structure is organized into elements called competencies, which are organized into three groups: technical, behavioural and context. The competence sets represent all elements necessary for proper project management (Anderson and Merna, 2003). According to the ICB (International Project Management Association, 2006), a competence is a collection of knowledge, personal attitudes, skills and relevant experience needed for successful project management.

In the body of knowledge of the IPMA three sets of techniques suggested for the M&C may be identified, The first, relates to the handling of managers and teams (responsibility matrix, groups, decision making and continuous improvement), the second refers to the planning and preliminary organization of good control (critical path, planning time, budgets, scenarios), and the third, the techniques that can be incorporated with the earned value (cost control, reporting, auditing, performance, budget control).

Table 3. Techniques / Tools S&C in projects ICB

Technique/Tool	
	Decision models
	Responsibility matrix
	Deliverable design and control methods
	Critical path planning
	Time contingency ‘buffers’ or ‘float’
	Time planning methods and time control methods
	Cost control methods
	Earned value
	Project reporting system
	Financial audits
	Control cycles
	Change management
	Continuous improvement
	Scenario planning
	Key performance index
	Budget planning and budget control

Although this classification is not explicit in the standard ICB, it is considered to be a classification very appropriate for the application of the process, since it is complemented by three key aspects: team responsible for the M&C process, M&C planning and performance verification.

The techniques that have been collected may be seen in table No. 3, whose structure has been compiled from information included in the ICB. It is considered that the proposal of ICB presents specific actions related to the process of M&C projects, which can be applied easily if implemented through specific methodologies on specific types of projects. Similarly, the inclusion of specific aspects of project managers’ behaviour makes the proposal unique and ensures that the processes are supported by personal skills and implementation of techniques.

2.4. International Standard Organization 10006 (ISO 10006)

The version of standard ISO 10006:2003 has been published by the International Organization for Standardization and provides guidelines for quality management in projects (West, 2002), and recommendations for successful management processes of these (Rutešić et al., 2005). The document has been prepared based on the 1994 version of ISO 9001 and does not constitute a guide to the global project management (Anderson and Merna, 2003), but provides at least a starting point for meeting management requirements and can be very helpful for people involved in such activities (West, 2002). At present the new version is being developed and has not yet been published.

We analyzed the sections of the standard that suggest one or further processes related to implementation of control activities in the project. The selected sections are: management responsibility, resource management, product realization and measurement, analysis and improvement. According to the standard, measuring performance should be based on the management plan and verification of the state indicators of project progress (The International Organization Standardization, 2003). It also states that performance reports and corrective actions are the instruments of control of project management.

The ISO 10006 standard includes the essential elements of control of the projects illustrated by the referred "iron triangle" (time, cost and scope), plus other additional important elements such as contracts, communications and information. Although the description of the application precludes drawing many practical details, we distinguish other elements of measurement, process analysis and improvement as related to the continuous improvement of the organization which runs the project.

Table 4. Techniques / Tools ISO 10006

Technique/tool			
	Work breakdown structure		Quality auditing
	Measurement and control progress		Statistical methods
	Plan for remaining work		Control charts
	Measuring project performance (KPI)		Flowcharting
	The timings of reviews		Brainstorming
	Regular reviews of the project schedule		Pareto chart
	Progress review meetings		Trend analysis
	Inspection and auditings		Contingency plans
	Control of documents and records		Earned value analysis

Table 4 shows the tools and techniques suggested for the M&C process in ISO 10006, whose structure has been developed from its reports. It can be seen that a group of qualitative techniques transferred from the quality management is included, and others related to the measurement of project progress and performance.

2.5. Projects in Controlled Environments (PRINCE2)

Prince2 is a structured method project management, developed by the OGC, Office of Government Commerce UK (McManus and Wood-Harper, 2003).

The use of PRINCE project management has been intensively promoted (L. Crawford et al., 2006), and is recognized internationally as the standard, frequently used in some countries (Fortune et al., 2011), becoming one of the three most frequently requested along with the PMI and APM (Whitty and Maylor, 2009).

The method uses a process approach to guide the flow of project management activities, so that it is possible to distinguish which activities are directed at monitoring processes and / or control of the project. In the distribution it can be observed that one of the principles is the "manage by stages"; one of the thematic approach of "progress" and the processes of monitoring and/or control are managing stage boundaries, controlling a stage and managing product delivery.

Likewise, in PRINCE2, those project management variables which are subject to M&C are: cost, schedule, quality, scope, risk and benefits.

The progress approach according to the method is carried out by measuring the achievement of planned goals and objectives, and involves comparing the progress of the variables to be controlled at specific decision points. The output of the progress measurement provides the completion of corrections and approval of additional working to complete the project.

The project management approach in frequently controlled stages indicates the importance given to aspects of M&C.

This approach provides two types of monitoring progress: events-based approach (late stage, end of year) useful for monitoring purposes, and time-based approach (monthly, periods, etc.) useful in monitoring and presentation report (Office of Government Commerce, 2009).

Management products that are presented as advantageous for establishing and executing progress controls are the project plan, stage plans, exception plan and work packages. It can be seen that dividing activities into stages allows to carry out actions for reviewing and correcting reports in small cycles, which leads to frequent and reviewed feedback during the whole project life cycle.

It is considered that with the distribution of management processes in PRINCE, a project manager can easily identify the activities that relate to monitoring and / or controlling, as well as the sequence for implementation.

The division into management segments with continuous assessment may improve the outcome of the process, since it induces the responsible person to have permanent contact to the milestones and boundaries among each of the stages.

Table 5 presents the techniques and tools for M&C proposed in PRNCE2, whose structure has been compiled from the information included in the standard. These are applied with the topic of progress control, stage control process and stage management boundaries. According to the standard, with progress measurement it is possible to assess the achievement of the plan objectives. It is evident that the earned value technique, as in other bodies of knowledge, is once more recommended. Similarly guidance techniques can be classified into three periods: before the decision to carry out the project (feasibility), planning stage and progress assessment stage, the latter being the main focus of the present research.

Table 5. Techniques PRINCE2

The critical chain technique
Gantt charts
Spread sheets
Product checklist
Critical path diagram
Review lessons
Risk checklists
Risk prompt lists
Brainstorming
Risk breakdown structure
Risk models
Expected monetary value
Milestone chart
S-curve
Earned value management

2.6. Comparing of Standards and Methodologies

It is considered that standards have common contributions, which supports the development of a proposal to integrate the perception of monitoring and control in the subject of project management into a single instrument. As a result of this group Table 6 shows techniques / tools groups for each standard, assigned to variables traditional. Table 6 has been prepared with information, structured and summarized throughout this document, from reports of each of the standards

It is considered that the monitoring and control variables classification performed in accordance with the guidelines of each of the standards, indicates that most of its proposals agree on the importance of applying the monitoring process on the variables representing the axis of the management of a project (scope, time, cost or quality). Likewise, most applicable tools and techniques recommended, focus their application in these variables. Therefore, these techniques support the achievement of the objectives with each management variable, supporting them with their implementation in specific cases.

Despite this, gaps can be seen in representation and applications; techniques for monitoring and control of other variables that are not part of the axis of project management, but they support their successful development, such as risk, communications, purchasing, documentation, among others. In such cases, recommended techniques and / or tools are scarce, with little applicability, and without contributions to the standards, which in turn represents a future line of research for the subject.

Table 6. Techniques/tool for control of projects into project management standards

TECHNIQUE/TOOL ON MONITORING AND CONTROL					
Variables	PMI	APM	ICB	ISO	PRINCE2
Scope	Inspection, Variance analysis			Measurement and control progress	
Time	Performance reviews, Variance analysis, Project management software, Resource leveling, What-if scenario analysis, Adjusting leads and lags, Schedule compression, Scheduling tool	WBS (Work Breakdown Structure), OBS (Organizational Breakdown Structure), Gantt Charts, Milestone Charts, PERT, CPM, Precedence diagram,	Responsibility matrix, Critical path planning, Time contingency 'buffers' or 'float', Time planning methods and time control methods	The timings of reviews, Work breakdown structure	Activity-on-node technique, The critical chain technique, Gantt charts, Spreadsheets, Critical path diagram, Milestone chart, Estimating techniques, Product checklist
Costs	Earned value management, Forecasting, To-complete performance index, Performance reviews, Variance analysis, trend analysis, Project management software	Earned value management, CBS (Cost Breakdown Structure), Cash flow, Trend analysis – predictions, Key performance indicators	Cost control methods, Earned value, Budget planning and budget control, Key performance index, Project reporting system	Earned value analysis, Flowcharting, Measuring project performance (KPI), Plan for remaining work	
Quality	Cause and effect diagrams, Control charts, Flowcharting, Histogram, Pareto chart, Run chart, Scatter diagram, Statistical sampling, Inspection, Approved change requests review	Quality management		Pareto chart, Control charts, Trend analysis, Statistical methods, Inspection and auditings, Quality auditing	Pareto analysis
Risk	Risk reassessment, Risk audits, Variance and trend analysis, Technical performance measurement, Reserve analysis, Status meetings			Regular reviews of the project schedule, Progress review meetings	Risk checklists, Risk prompt lists, Risk models, Risk breakdown structure
Communications and procurements	Forecasting methods, Communication methods, Reporting systems. Contract change control system, Procurement performance reviews, Inspections and audits, Payments systems, Claims administration, Records management system			Control of documents and records	

3. Research Methods

For the study we used qualitative and quantitative strategies in order to determine the use of monitoring and control techniques and tools, and to evaluate the relation between their use and project success. The preliminary step was conducting a review and interpretive work (analytical-descriptive) of the literature and bodies of knowledge. Once the review was completed, we designed a questionnaire, structured in three parts, which aimed to collect empirical data about the managers interviewed, the use of techniques and tools, and their relationship with performance measured by success criteria in projects.

The first part of the questionnaire had three open questions, the rest of the questions were closed. The first part, with ten questions, gathered general information on the managers interviewed. The second part had three questions that gathered information on methodologies, techniques and tools in order to assess the level of their use. Finally, data was collected on the frequency of application and submission of progress reports according to the size of the project, procedures, use of indicators and variable measurement during monitoring and control reports. Results were presented individually, indicating the ones with the highest use of techniques and tools and seeking the relation that may exist between their use and project performance. The third and last part of the questionnaire consisted of three questions that explored the final performance of a project carried out by the manager interviewed and that had recently been completed.

To this end, and based on the literature review, we chose six performance criteria that are considered relevant in determining success (time, cost, quality, activities, scope and stakeholders' satisfaction). The variables that determine performance were linked with the results on the use of techniques and tools, assessing whether there was any correlation.

People with experience in the area were selected to avoid crowding the questionnaire and to clarify the language used in questions and thus improve the understanding of the statements contained therein. A questionnaire was sent to project managers registered in a database of a public university. The information obtained from 280 questionnaires was analyzed and described.

The application of techniques and tools was analyzed, describing their adoption in general and determining which had greater applicability. Finally, through a correlation analysis, the influence of the adoption of techniques and tools on project results was established; variables with the greatest correlation were shown and results discussed.

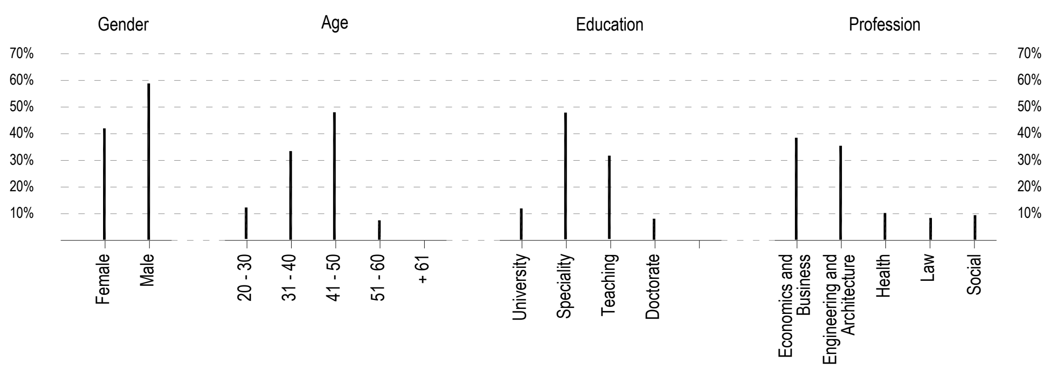
4. Analysis and Discussion of Results

Using information collected through the questionnaire, we analyzed various topics of interest in order to answer the question and hypothesis presented in this research. Overall results of the sample were classified by variables (gender, age, education level, profession and occupation) to determine whether any of these had an impact on performance aspects. Other variables such as number of managed projects, project type, and number of people in the team were used to characterize the elements that determined the type of projects in the sample.

We identified the frequency of using the variables for each technique and tool for project monitoring and control, gathered from the analysis of literature and standards. In addition we assessed the relation between each tool or technique and the variables assigned to measure project performance.

The most used tool in the work of project managers was identified. With the last part of the questionnaire we characterized the type, the measurement frequency and the final percentage of completion of each project. The variables that determine the performance were related to the variables identified for techniques and tools, assessing whether there was correlation between them and project performance.

From the overview analysis it can be seen that most managers interviewed were male, 59% male and 41% female. About half of the study population was between 41 to 50 years, and the remaining were mostly those between 31 and 40, which guaranteed, in principle, that the interviewed managers had professional experience. The most prevalent education level was specialization and expertise, which indicates that most had a post-graduate degree and only a minority had only professional studies (11%). Profession and occupation of professionals were mostly in the area of Economics and Business, and Engineering; which confirms that these areas are the most applicable for project management. Figure 2 shows the main results of the sample's overview.



Executed project´s types

1. Research and/or development	42%
3. Information technology and communication	16%
5. Organizational development	37%
6. Product/service development	48%
7. Marketing / Publicity	13%
8. Production	18%
12. Education	5%
13. International cooperation	23%

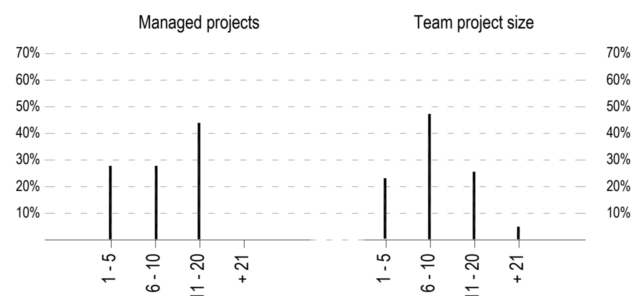


Figure 2. Sample's overview results.

The types of projects implemented were varied and allowed more general characterization in terms of typology. The number of managed projects and team size indicate that the selected sample had experience in the area. In addition, the managers interviewed had mostly been in charge of medium-sized teams, which also indicates that the projects managed were of considerable size. It can be seen that the types of projects most executed by the managers were research and development, organizational development and product and service development. This means that the projects were carried out mostly in areas of Economics and Engineering, corresponding to the education characteristics of the sample.

With regard to the adoption of methodologies, we can find a large number adopted from the PMBOK; although in general there was a low use of methodologies. It can be seen that the PMBOK had high acceptance and use (approximately 35% of the sample) whereas other standards' were generally low (between 2% and 12%). The other most used methodology was PRINCE2, which coincides with results of studies described in the literature, where PMBOK and PRINCE are said to be the most used methods in some European countries. Approximately 35% of managers did not often use methodologies developed from the mentioned standards, in some cases because they did not use any procedures at all, and in others because they used in-house methodologies or techniques. Figure 3 shows a chart comparing the results of adopting methodologies by the managers who were part of the study.

With respect to the use of monitoring and control techniques of projects, generally one can see a use of more traditional tools like the Gantt chart (21%); and in other cases, the use of newer techniques such as performance indicators (11%) and earned value (10%). It is also interesting to note that a considerable proportion of the sample (11%) do not normally use any technique for project monitoring and control. Figure 3 shows the most general and representative results of the use of techniques. Not included are those techniques that, taken from the reviewed standards, were placed in the questionnaire but whose adoption result was very low (between 0 and 1%).

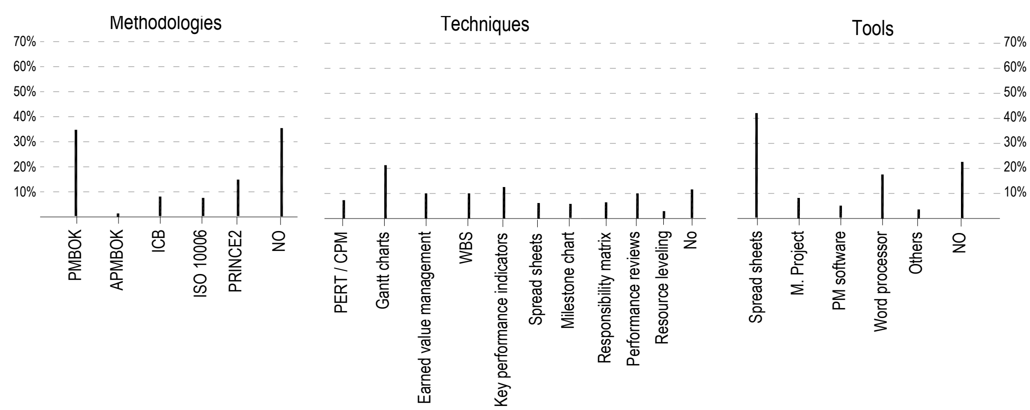


Figure 3. Adoption of methodologies and techniques/tools for monitoring and control.

With respect to the use of tools, it is remarkable the considerable and widespread use of the spread-sheet as a monitoring and control tool. This may be because it is the IT tool for project planning and budgeting. Likewise, it is possible to note the use of word processing, probably due to the application of templates; and a considerable proportion of managers who did not use any monitor and control tools. Other tools like Microsoft Project or other software applications were used in a low proportion (5% and 8% respectively). Figure 3 shows the overall results of adoption of tools. Not included are those with very low results of tool adoption, although they were included in the questionnaire. It can be noted that the lack of knowledge of tools is higher than that of techniques, indicating the existence of different systems other than computers' to manage projects. Among the tools classified as "other" are applications such as spring project, free software and in-house tools.

With the descriptive statistical analysis we studied the correlations between variables pertaining to the use of methodologies, techniques and tools and the projects performance criteria. In the correlation analysis only those variables with the highest percentage of use (methodology, technique, or tool) were taken into account.

Regarding the use of methodologies, a positive correlation with performance was generally found. The strongest positive correlation occurred between the use of methodologies and the project scope, especially the PMBOK standard. That is, the more methodologies are used the better the project scope results are. Another variable with strong positive correlation was between the use of methodologies and project cost and time, that is, generally the use of methodologies improves key variables of project management results.

The correlation results can be seen in the diagram of Figure 4. Although the correlation with other performance variables (quality, activities and stakeholders) was not as representative as for the rest, one can see that the correlation remained positive. This indicates that although there are variables that are affected more than others, managers who used project management methodologies found better results.

Regarding the correlation between the use of techniques and tools and performance, the variables with the strongest positive correlation were cost, activities, time and scope of projects. In this case the activities were affected by the use of techniques and tools, indicating that with these, control on operational execution was improved, so were the results. The other variables (quality and stakeholders) showed positive correlation; and like with the use of tools, although not strong, maintained some degree of influence on the results.

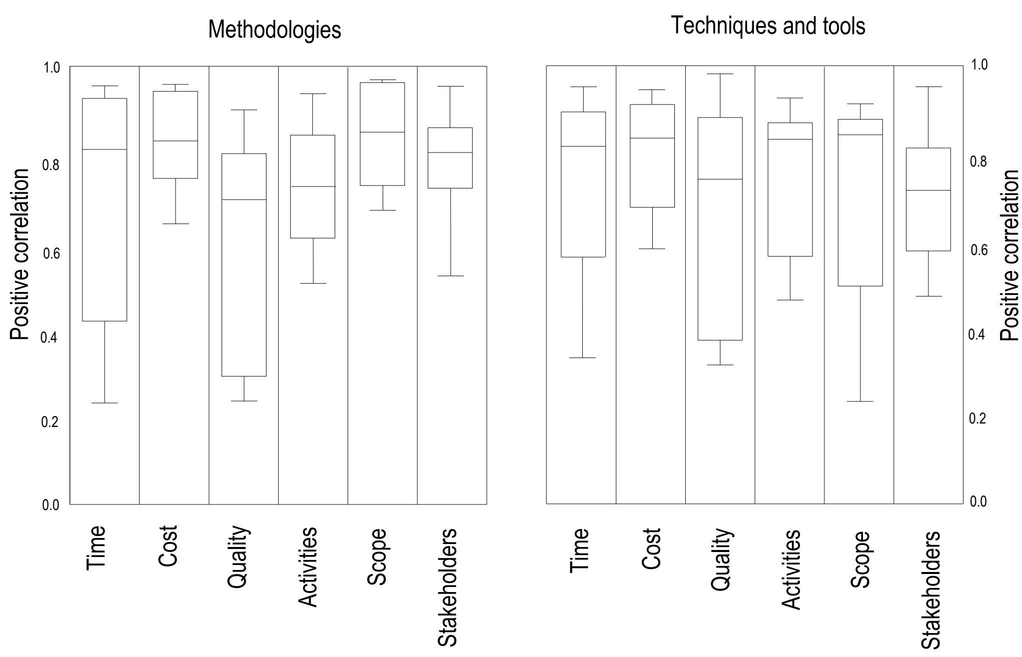


Figure 4. Correlation between variables and project performance.

The diagram in Figure 4 shows the overall results of the correlation between the use of techniques and tools and performance of projects managed by the interviewees. Figure 4 shows the average rate of correlations. The left part illustrates the correlation between the use of methodologies and all performance variables of the study. The results of this correlation are positive, indicating that their adoption affected project performance. Of all parameters assessed, the most influenced were cost and scope.

The right part of Figure 5 illustrates the correlation between the use of techniques and tool and performance variables. The results of this correlation are also positive, indicating that their adoption improved performance. The parameters most correlated with performance were cost, activities and scope.

CONCLUSION

The monitoring and control is considered as the action of checking frequently progress in project implementation. The influence of its proper implementation over on the criteria for project success generates interest in learning and applying instruments, techniques or tools that keep stable all the variables that affect performance. This paper analyzes the adoption of monitoring and control methodologies, techniques and tools; and their influence on project management performance. According to the review and interpretation of literature and Bodies of Knowledge and application of the questionnaire, this research provides empirical evidence to establish whether the adoption of techniques and tools and the use of methodologies developed from representative Bodies of Knowledge influences project results.

The results showed that project management literature and Bodies of Knowledge do treat with monitoring and control techniques and tools adequately. However, in terms of adoption, there was a low rate of use, prevailing traditional ones. Managers' poor training was one of the causes for the outcomes, which resulted in limited applicability. However, Bodies of Knowledge and standards were proved to be known, so probably the issue is about applying their guidelines.

It is considered that standards such as PMBOK and PRINCE2 structure detailed application monitoring and control, in part because they assume that this is a process in the distribution of process groups. PMBOK includes actions to monitor the status of the project, analyzing the impact on the management plan, performance report and relevant decision making. However, documentation systems have to be used as formats and / or templates to transform the totality of the standard and increase its usefulness in the effective implementation of projects.

With regard to techniques and tools that are included in the bodies of knowledge and standards, traditional techniques are suggested but supported by computer tools or software management systems. This validates the usefulness of these techniques still in force and the need to include information technology as support for project managers. Similarly the technique of earned value management is perhaps the most popular today, and suggested by all standards.

The frequency of use of methodologies, techniques and tools shown by the sample managers was low. However, their adoption affected project performance with greater or lesser impact. There was not general consensus about the most used technique or tool, since there were not significant differences in their use. It was found that there was more adoption of traditional management techniques applied in project management. The techniques most correlated with performance were related to the use of key performance indicators, such as earned value, or review systems.

Although satisfaction and adoption of more known and used traditional tools were high, they were not the ones that generated better results on project performance. The adoption of newer techniques and tools could generate a considerable improvement in project performance, thus promoting new strategies for the development of the discipline.

It is considered that the methodology used to prepare the study is useful in project management contexts and provides a procedure that allows an adequate analysis, data processing and results presentation, both interpretively and graphically. It is suggested that the methodology could be used in similar studies to relate the success factors in a project to it's performance and outcome.

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Table 6. Techniques/tool for control of projects into project management standards

TECHNIQUE/TOOL ON MONITORING AND CONTROL					
Variables	PMI	APM	ICB	ISO	PRINCE2
Scope	Inspection, Variance analysis			Measurement and control progress	
Time	Performance reviews, Variance analysis, Project management software, Resource leveling, What-if scenario analysis, Adjusting leads and lags, Schedule compression, Scheduling tool	WBS (Work Breakdown Structure), OBS (Organizational Breakdown Structure), Gantt Charts, Milestone Charts, PERT, CPM, Precedence diagram,	Responsibility matrix, Critical path planning, Time contingency 'buffers' or 'float', Time planning methods and time control methods	The timings of reviews, Work breakdown structure	Activity-on-node technique, The critical chain technique, Gantt charts, Spreadsheets, Critical path diagram, Milestone chart, Estimating techniques, Product checklist
Costs	Earned value management, Forecasting, To-complete performance index, Performance reviews, Variance analysis, trend analysis, Project management software	Earned value management, CBS (Cost Breakdown Structure), Cash flow, Trend analysis – predictions, Key performance indicators	Cost control methods, Earned value, Budget planning and budget control, Key performance index, Project reporting system	Earned value analysis, Flowcharting, Measuring project performance (KPI), Plan for remaining work	
Quality	Cause and effect diagrams, Control charts, Flowcharting, Histogram, Pareto chart, Run chart, Scatter diagram, Statistical sampling, Inspection, Approved change requests review	Quality management		Pareto chart, Control charts, Trend analysis, Statistical methods, Inspection and auditings, Quality auditing	Pareto analysis
Risk	Risk reassessment, Risk audits, Variance and trend analysis, Technical performance measurement, Reserve analysis, Status meetings			Regular reviews of the project schedule, Progress review meetings	Risk checklists, Risk prompt lists, Risk models, Risk breakdown structure
Communications and procurements	Forecasting methods, Communication methods, Reporting systems. Contract change control system, Procurement performance reviews, Inspections and audits, Payments systems, Claims administration, Records management system			Control of documents and records	

Theory of the Triple Constraint – a Conceptual Review

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Abstract – **Projects are generally undertaken because they are part of the plans to meet business needs and charter organizations to new levels of performance. Projects are however constrained by conflicting demands and competing priorities within the project environment. Neglecting to manage these constraints accurately and effectively may be sufficient to condemn a project even if all other project management activities are performed to a high standard of excellence. The aim of this paper is to improve the interpretation of the triple constraint and its dynamics and indicate how this may advance the delivery of project success. An integrated model is proposed to facilitate the strategic management of the triple constraint trade-offs as a function of the project higher purpose.**

Keywords - **Project management, triple constraint, trade-offs, scope, time, cost**

I. INTRODUCTION

Products and solutions need to be constructed faster, cheaper and better. Around the world mission-critical projects are being launched all the time involving significant capital investments and high-risk ventures. Projects are becoming the way of the working world. What makes project delivery successful is however a topic of much academic debate, and depends by whom and against which value system the project is being evaluated. It is generally agreed that to be considered successful, a project must be fit for purpose (add strategic value) and it must have achieved its delivery targets [1], [2].

In reality it is not always considered practical to deliver all the project targets exactly as planned. Trade-offs need to be considered and priorities must be set in order to realize strategic decisions. The project management body of knowledge (PMBOK®) endorses that every project is governed by the triple constraint, which reflects a framework for evaluating these competing demands [3], [4], [5].

A. Introducing the triple constraint

The triple constraint is a critical project management concept that originates from the basis for undertaking a project and provides direction for framing the project. The triple constraint constitutes one of the primary building blocks of the project plan and is paramount to the monitoring and controlling process group [3], [4], [6], [7], [8], [9].

Although the triple constraint theme has various interpretations, the literature shows a general agreement that project scope, time and cost comprise the three key triple constraint variables [1], [3], [4], [6], [10], [11], [12]. Project time addresses the scheduling and duration of the project, cost addresses the budget and resources of the project, and scope addresses the requirements and work of the project. A time-constrained project is bounded by the completion agenda, whereas a cost-constrained project is bounded by the scheduling of expenditure. Scope-constrained projects are bounded by the performance criteria of the deliverables. Project quality constitutes an integral dimension of project management and is supported by the triple constraint [3], [4], [6], [7], [10], [11], [13], [14].

The project management triangle (Fig. 1) is a useful model to illustrate the consequences of change on the triple constraint to key project stakeholders. The triangle reflects the fact that the three constraints are interrelated and involve trade-offs – one side of the triangle cannot be changed without impacting the others. Project quality takes root in all three variables of the triple constraint and is affected by balancing the three factors [4], [10].

It may easily be argued that triple constraint affairs reside at the kernel of the most essential determinations surrounding projects.

B. Introducing the research rationale

According to research by the Gartner Group, only 16% of information technology (IT) projects are completed within the desired time frame and budget and achieve the desired results. More than 30% of projects are cancelled and over 50% of projects will experience cost overruns. Less than 30% of the projects companies employ to change their businesses are successful [1].

The current literature in the project management domain suggests that there exists a lack of appropriate (and consistent) scholarship on the triple constraint and its dynamics [7]. The term 'triple constraint' did not even appear in the initial issues of the PMBOK® Guide glossary or index.

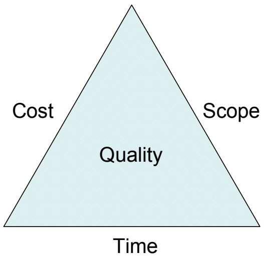

Fig. 1. Project management triangle.

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This knowledge gap results in project managers not being able to effectively prioritize and exploit the triple constraint trade-offs. It is proposed that a thorough comprehension of the triple constraint dynamics is paramount to effective project management.

Another problem is that project managers often create an illusion of tangible progress by relying heavily upon traditional on-time, on-budget and on-target measures – yet this tactic fails to address the strategy ambiguity or establish appropriate project goals [15].

It has also become commonplace in many projects to view the triple constraint trade-offs as organizational problems that have a definitive solution ('either/or' choices) – yet this tactic fails to effectively negotiate the triple constraint and leads to destructive conflict. Collins & Porras discovered that instead of being oppressed by the 'Tyranny of the Or', highly visionary companies liberate themselves with the 'Genius of the And' – the ability to embrace both extremes of a number of dimensions at the same time [16]. This conjecture is supported by the Polarity Management™ philosophy [17].

Without the effective management of the triple constraint as an interrelated system, projects run the risk of becoming separated from purpose. A mechanism is needed on how to manage this seemingly contradictory task when it comes to constraint trade-offs. The premise is that if these constraints are managed properly, organizations will be successful in delivering projects and meeting organizational goals.

This paper examines the notion behind the project management triangle and power structure of its constraints. An integrated model is proposed for managing relative flexibility within the triple constraint towards a beneficial outcome in terms of project success.

II. RESEARCH METHODOLOGY

The basic structure of the research process used in the study is presented in Fig. 2.

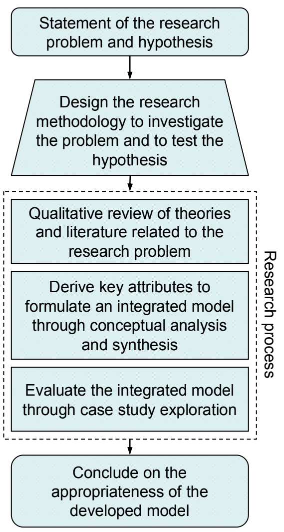

Fig. 2. Research process.

The type of study associated with this paper is primarily non-empirical defined through an extensive literature study, conceptual analysis and construction of an integrated model using secondary data. Theory building in the research occurred through retroductive and deductive strategies. Conceptual explication was used to derive the model through analysis and integration of concepts discovered through the literature study.

The research undertook basic case study analysis as a mechanism to demonstrate that the derived model is valid and useful, which also introduced an empirical element into the research design. The results from the case study analysis have been generalized to refer back to the project management body of knowledge in terms of applicability.

The integrated model presented in this paper is highly conceptual. The emphasis in the study was on qualitative reasoning both in definition, explanation and application, rather than an emphasis on empirical and other quantitative techniques. The findings of the research study should thus be considered as preliminary rather than conclusive, pending further research.

III. THEORETICAL FRAMEWORK

A substantial range of literature has been considered in the study with reference to more than 100 sources representing authoritative knowledge across the fields of project management [7]. This section provides an overview of some of the key concepts surrounding the triple constraint, and concludes with a consolidated triple constraint model.

A. Dynamics of the triple constraint

The triple constraint continuously faces conflicting demands and competing priorities within the project milieu. For example, if the project is working to a fixed level of scope then the cost of the project will largely be dependent upon schedule availability. Similarly, when the project time is fixed, the scope of the end product will depend on the budget or resources available.

Project management researchers and authors widely recognize that the inherent trade-off dynamics of the triple constraint can be described by the following three key relationships [3], [9], [12], [18]:

$$S\uparrow \;\alpha\; T\uparrow \; C\uparrow \qquad (1)$$

$$T\downarrow \;\alpha\; S\downarrow \; C\uparrow \qquad (2)$$

$$C\downarrow \;\alpha\; S\downarrow \; T\uparrow , \qquad (3)$$

where the up-arrow (↑) implies an increase, the down-arrow (↓) implies a decrease, and S, T, and C refers to scope, time and cost respectively.

Relationships (1), (2) and (3) denote that any triple constraint variable can be delivered at the expense of one or both of the remaining two variables. Further analysis signifies that when there is pressure on the triple constraint, at least one of the variables needs to be flexible in order to validate a quality balance [7], [11].

The dynamics of these relationships can be illustrated in a variety of ways through manipulation of the project management triangle. For example, if both the schedule and budget of the project are negatively affected as a result of an increase in project scope, the relationship may be graphically illustrated as shown in Fig. 3.

Fig. 3 is only one of many possible ways of how to illustrate these dynamic relationships. The illustrations also depend on which factors are fixed and which are flexible. It should be highlighted that the changes are not always symmetric, i.e. if two variables need to increase, one may increase proportionally more than the other – for example, more resources may need to be added in order not to exceed the deadline by too much.

The important consideration is that a connected triangle must be maintained at all times. Fig. 4 illustrates that it is not possible to maintain the triple constraint as a triangle when all three variables are pursued simultaneously [9].

B. Good, fast, or cheap? Pick two

Within the project management and consulting environment, the adage 'good, fast or cheap - pick two' is commonly encountered. Good, fast and cheap respectively refer to the three key elements of the triple constraint namely the extent of work (scope), the schedule (time) and the budget (cost). The notion is that projects are generally constrained to choose two of the three elements and sacrifice the other in order to gain the chosen two.

The 'good, fast or cheap - pick two' impression is a manifestation of the 'Tyranny of the Or' – the rational view that cannot easily accept paradox, that cannot live with two seemingly contradictory forces or ideas at the same time [16]. This concept pushes people to believe that things must be either A or B, but not both. That is to say, in terms of the triple constraint, one can choose either good-and-fast, or good-and-cheap, or fast-and-cheap; but critically not all three (Fig. 4).

The 'good, fast or cheap - pick two' trade-off can be demonstrated with an adaptation of Barker & Cole's seesaw model as illustrated in Fig. 5. If pressure is put on timescales (fast) then costs can be expected to go up; alternatively, if pressure is put on costs (cheap) then timescales can be expected to go up. From the seesaw example it is clear that, with the scope of work (good) remaining pivotal, the project cannot be delivered simultaneously fast and cheap as well; one of the elements has to be flexible [5], [7].

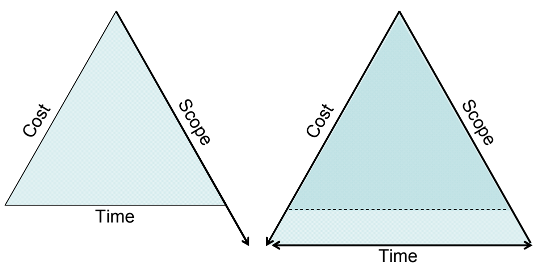

Fig. 3. The triple constraint relationship S↑ α T↑ C↑.

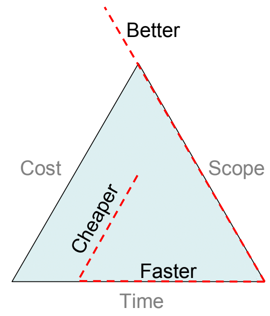

Fig. 4. Better, faster, cheaper – is this really possible?

The following analogy may be drawn between the 'good, fast or cheap - pick two' permutations and the key triple constraint relationships [7]:

1) Relationship 1, S↑ α T↑ C↑, implies that the effect of increasing scope (S↑), or effort (pressure) to achieve scope, necessitates an increase in time (T↑) and/or cost (C↑). If cost remains unchanged, then the project can be delivered good (because S↑) and cheap (because C fixed as planned) but not fast (because T↑);

2) Relationship 2, T↓ α S↓ C↑, implies that the effect of reducing time (T↓), or effort (pressure) to achieve time, necessitates a reduction of scope (S↓) and/or an increase in cost (C↑). If scope remains unchanged, then the project can be delivered fast (because T↓) and good (because S fixed as planned) but not cheap (because C↑);

3) Relationship 3, C↓ α S↓ T↑, implies that the effect of reducing cost (C↓), or effort (pressure) to achieve cost, necessitates a reduction of scope (S↓) and/or an increase in time (T↑). If time remains unchanged, then the project can be delivered cheap (because C↓) and fast (because T fixed as planned) but not good (because S↓).

C. Supporting factors of the triple constraint

Within the context of this paper the three prime elements of scope, time and cost are considered central to the triple constraint. Project management literature, however, sporadically indicates quality and performance as an adjunct to or substitute for scope, and occasionally designates customer satisfaction and project risk as ancillary constraints [7].

Project scope encapsulates capability and grade attributes. Quality and grade are not the same. Grade refers to the set of attributes on which the quality of a product will be judged [19]. Quality constitutes an uncompromising and inherent objective of the project specification that takes root in all three properties of the triple constraint.

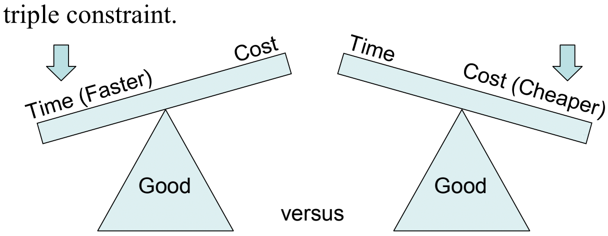

Fig. 5. Good-and-fast vs. good-and cheap.

A lower-grade material, for example, is not necessarily a lower-quality material, as long as the grade of material is appropriate for its intended use. Performance is an operational assessment metric for the triple constraint in terms of project accomplishment, which should be continuously monitored and controlled throughout the project. Performance and quality are hence not substitutes for scope [4], [9], [14], [19].

Customer satisfaction is fulfillment of the consumer requirements, expectations and needs, and constitutes a performance measure in terms of quality or excellence. Risk impacts the performance of the triple constraint, which may precipitate change in terms of the triple constraint trade-off dynamics [6], [10], [11], [20].

This paper presents a classic interpretation of the triple constraint, focusing on the 'big three' of scope, time and cost without adding or subdividing.

D. Power structure of the triple constraint

One of the challenges project managers face is the iterative and infringing requirements of the customer. A good starting point is thus to understand the customer's priorities in order to identify the most important aspect of the project and obtain an optimum balance between the constraints [5], [9].

Dobson's theory on the Hierarchy of Constraints defines a project by listing the triple constraint variables in order of flexibility [6]. Dobson proposes that exploitation of flexibility in the weaker (more flexible) constraints can be used as a tool to meet the absolute requirement of the driver (least flexible) constraint in order for the project to succeed. The driver constraint is derived from the *raison d'être* of the project and is the constraint that has to be met otherwise the project fails. There can only be one project driver at any given time. The weak constraint has the greatest flexibility, but is not necessarily the least important. The middle constraint normally has a small amount of flexibility and can either be very close to the driver in importance to the project mission, or may sometimes have flexibility more akin to the weak constraint.

It is important to note that flexibility, and not importance, serves as the ranking criterion. Importance is the relative merit of the constraints considering the long-term value of the project. Flexibility is the extent to which the project manager can manipulate the constraints in order to successfully deliver the project [6].

It is presupposed that the effective management of the triple constraint power structure and its dynamics is central to project success. Details pertaining to trade-off strategies and exploitation considerations are documented in [7].

E. Key attributes of the triple constraint

The following fundamental characteristics were consolidated in support of the physiology of the consolidated triple constraint model [7]:

1) Effective projects bring form and function to ideas or needs, and yield beneficial change or added value.

2) The higher purpose of a project is fundamentally the driver of the project.

3) The triple constraint constitutes a balance of the three interdependent project elements of scope, time and cost as a function of the project higher purpose.

4) The concepts of quality, customer satisfaction, performance and risk have an impact on the triple constraint, but do not inherently constrain the project.

5) The cause and effect of new or changing triple constraint requirements are constantly negotiated during all phases of a project.

6) Change within the triple constraint is compensated through proportional trade-offs.

7) Failure to deliver all three triple constraint variables on target does not necessarily imply project failure.

8) Flexibility is an indispensable triple constraint requirement in order to accommodate shifts in project emphasis, and to ensure a beneficial project outcome.

9) The three key triple constraint relationships signify that at least one of the triple constraint variables must be constrained (otherwise there is no baseline for planning), and at least one of the variables must have capacity for exploitation (otherwise quality may be affected).

10) The triple constraint can be prioritized into a power structure by ranking the variables into a hierarchy of flexibility (capacity for exploitation).

11) The power structure derives from the project objectives and higher purpose and may be influenced by environmental change.

12) Capitalizing on the pliability of the two more flexible constraints can be used as a mechanism to achieve the essential demands of the primary triple constraint variable (the driver).

F. Consolidated triple constraint model

The integrated model was realized through conceptual synthesis of the key derived triple constraint attributes discussed in the previous section. The matured model is presented in Fig. 6. The consolidated model has been dubbed the TRIJECT model (an acronym created from the titles 'TRIple constraint' and 'proJECT management').

The project management triangle, which constitutes the heart of the TRIJECT model, is supported by the two more flexible constraints (time and cost in this instance) and forms the foundation of the triangle. The primary triple constraint variable (scope in this instance) aligns the triangle with the project higher purpose. The triangle projection is dynamic and can pivot about its axis to accommodate change within its power structure. The triple constraint hierarchy may be influenced by the project environment, which impacts the higher purpose and objectives of the project. The model embodies three dimensions, in which each facet of the triple constraint may drive the project.

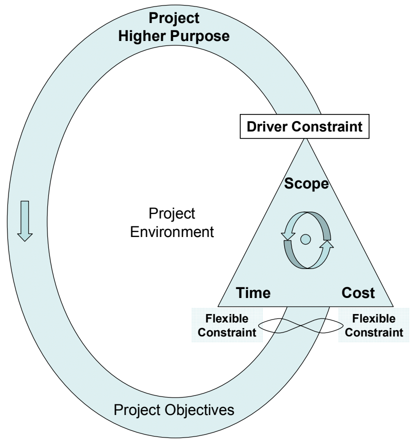

Fig. 6. TRIJECT model.

The central presence of quality is signified by the outline shape of the TRIJECT model, which, using some imagination, resembles a capital letter 'Q'.

The rationale of the TRIJECT model is based on the achievement of the primary triple constraint variable through the exploitation of the two more flexible constraints and alignment with the project higher purpose.

The continuous cycle implied by the model represents the ongoing and interrelated nature of this process as change is introduced into the system. Monitoring and controlling hence manifest a requisite part of this cycle. The model also accounts for the ancillary issues such as 'the why' of the project and change within the project environment as well as quality and control.

In practice the TRIJECT model is expected to overlap and interact dynamically with the project management process groups. Details pertaining to the proposed protocol and application of the consolidated triple constraint model are documented in [7].

IV. CASE STUDY ANALYSIS

Evaluation of the TRIJECT model was limited to the exploratory review of the theoretical model and protocol against a simplified case in order to facilitate a conceptual understanding of the integrated model in practice. The observed case was the building project of the Smithsonian Institution, National Air and Space Museum (NASM) [6], [7]. There is no claim that this case is representative of the general project management milieu.

A. Case paraphrases and system definition

The NASM project mission, essentially, was to build a world-class aviation and space museum for a budget of approximately USD 40 million and open it on July 4, 1976. The project mission statement satisfies the triple constraint, which is defined as follows:

1) Time constraint = July 4, 1976
2) Cost constraint = USD 40 million
3) Scope constraint = World-class museum.

A key part of the Smithsonian's ability to get congressional funding unlocked for the project involved the national focus on the upcoming Bicentennial celebrations. National attention would be focused on Washington, D.C., and the National Mall during the festivities, and the President of the United States would be on hand to cut the ribbon. The consequences of missing the Bicentennial would have been hugely humiliating for the Smithsonian and for the NASM team. The time constraint has therefore been assigned in the lead position as the driver for this project. Before settling on the primary triple constraint variable, the critical question of why this project is being undertaken needs to be reviewed.

The term 'world-class' may constitute a variety of potential meanings, each with different consequences for time and cost. For example, how many air and spacecraft should hang in the new building, or how complicated should the audiovisual exhibits be. The distinction between the work of the NASM and the project of the NASM needs to be considered. The project ends, but the work is ongoing. What must be done to meet the demands of opening day is only a prelude to the indefinite lifespan of the open museum. It can therefore be argued that the scope constraint, although probably the most important, is also the most flexible (weak) constraint for this project.

The USD 40 million federal appropriation is a definite number, but not an exact one. Major construction projects often have a contingency reserve of up to 10% of the budget for change orders and other problems. Considering flexibility and following the process of elimination, cost may thus be identified as the middle constraint for this project.

B. Case investigation and system analysis

The triple constraint compromise to manage was identified as the trade-off between the exploitation of the USD 40 million budget (the cost constraint), and the requirements / features that constitute a world-class museum (the scope constraint). The success of this project was driven by the deadline (the time constraint) to open the museum on the nation's Bicentennial celebration July 4, 1976 in order to attain national focus (the higher purpose). With the project mission and triple constraint power structure defined, the TRIJECT model for the NASM project can be delineated as shown in Fig. 7.

Exploitation of the project budget (C↑) alleviates the pressure to rollback on the museum's scope requirements, and supplements the effort to ensure that the deadline for opening the museum is met (more money and resources can be spent to get the same or more work accomplished within a limited period of time). The cost constraint includes both cash and non-cash resources. Exploitation of the project scope (S↓), on the other hand, alleviates the pressure to add additional cost and resources to the museum budget, but also supplements the effort to ensure that the deadline for opening the museum is met. Exploiting flexibility in the scope constraint should however not compromise quality, i.e. the museum's world-class criteria, which Congress values. One mechanism for exploiting the scope of the museum building program is to downsize selected objectives and quality metrics that do not add customer value.

Because it was simpler to exploit the 'world-class' scope requirements than it was to exploit the congressional budget, the system was initially located in the right half of Fig. 8, i.e. the flexibility of project scope outweighed the flexibility of project cost. The kinetics of Fig. 8 constitute a reverse congruency with respect to Fig. 5, focusing on exploitation causality rather than on constraints. The risk for the NASM case is that excessive manipulation of the scope requirements may eventually result in the benefits of this effort to disperse as the system moves into its downside (R-). This may put the project at risk to not deliver a world-class aviation and space museum, with inadequate artifacts and exhibits. As these disadvantages are being experienced, an increasing awareness may develop towards the advantages of budget exploitation (L+). This awareness may shift the focus of manipulation by sliding the exploitation weight up the seesaw from R- to L+. Accordingly, excessive manipulation of the budget requirements may again transition the system into its downside (L-). The consequent risk is that the project may be completed substantially over budget, and the project schedule may also be expected to slip due to the restoration of additional artifacts and the incorporation of complex exhibits. What is called for is a dynamic mechanism that may equilibrate the system as exploitation weight shifts and trade-offs are compromised during the project.

C. Case discussion and system guidelines

In order to effectively manage the exploitation trade-off, the project manager needs to consider each of the benefits in the upper quadrants and define how to gain or maintain these advantages. A risk strategy is also required. The flexibility in the weaker constraints is not unlimited since there is always a minimum that must be achieved. The project manager needs to consider each of the disadvantages in the lower quadrants and define indicators that will alert the project team when the project dips into the red zone of over focusing the exploitation effort.

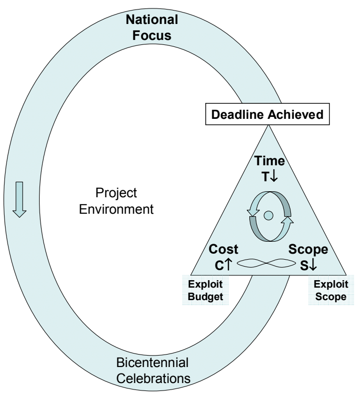

Fig. 7. TRIJECT model for the NASM case.

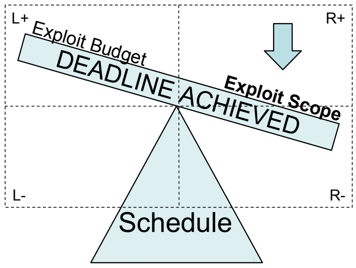

Fig. 8. System diagnosis of the NASM case [17].

The following considerations have been identified for obtaining and sustaining the positive results of the L+ quadrant of the NASM case: Find out what degree of budget overrun will be acceptable; Find out if contingency funds are available; Investigate if additional staff and equipment can be borrowed; Determine which costs will not be charged to the project; Establish how political influence can be achieved in order to pursue budget flexibility; Examine the consequences that the various interpretations of the 'world-class' requirement may have on the project; Identify the air and spacecraft which posses overwhelming historical significance; Discern how time and cost of artifact restorations can be optimized; Determine the appropriate requirement and level of complexity for the museum's audiovisual exhibits; Take the law of diminishing returns into consideration.

Retrospectively, the considerations to obtain and sustain the positive results of the R+ quadrant include: Establish effective and proven practices to efficiently manage and control the project budget; Identify those aspects of the project scope requirements that are not quality related; Target areas for exploitation where scope creep is detected; Reach a common understanding with the stakeholders on the importance they place on the delivery of each scope requirement, and ascertain the could-have's and would-have's; Ensure that the 'world-class' criterion is not dismissed due to excessive artifact and exhibit cutbacks; Investigate where initial objectives may be downsized, for example lowering the planned number of air and spacecraft for opening day; Determine quality metrics that do not add customer value, for example trimming back on complicated audiovisual exhibits.

The following red zone indicators (early warnings) have been identified for when the project falls in the L- quadrant of the NASM case: Resistance from Congress regarding the increased project cost; Spending additional money and resources have reached the point where it no longer adds value to the project schedule, i.e. recognizing the law of diminishing returns; Artifact restorations and audiovisual exhibits fall behind schedule. The red zone indicators for when the project falls in the R- quadrant include: The 'world-class' requirement of the museum comes into question; Criticism regarding the appropriateness of artifacts and degree of exhibits.

The project team needs to monitor these dynamics within the triple constraint power structure throughout the project life cycle. The timely identification of divergences from the project higher purpose followed by the appropriate corrective actions is crucial.

The NASM project might have benefited more by sustaining the positive results of both upper quadrants (green zone) and minimizing the time spent in the lower quadrants (red zone) – thus, delivering the project fast as well as relatively good and cheap (Fig. 9). A possible solution that effectively addresses this challenge is proposed in [17].

V. CONCLUSION

The study of the triple constraint is believed to be one of the most overlooked fundamentals of project management. As a result of the various perspectives and interpretations across literature that surround the project management triangle and triple constraint, the need for a unified model has been identified. The TRIJECT model supports an understanding of finite resources and facilitates a mechanism for managing the competing triple constraint requirements. The model encourages the creative exploitation of the triple constraint to improve project performance by considering the relative flexibility between the key elements. The goal of the model is to maintain the focus of the triple constraint power structure on the project higher purpose.

The case study presented has demonstrated that the integrated model may furnish the instruments that enable project teams to manage their work in line with the absolute requirements for project success. It should be taken in consideration that every project will experience its own unique limitations to exploitation capacity, which needs to be assessed through appropriate 'cost' vs. value impact analyses. Projects should however aim to always deliver to a much greater extent in terms of value than the sacrifice of the exploitation effort.

An integrated framework is suggested in [17], which evolves the strategic management of the TRIJECT model using Polarity Management™ techniques. Supporting quantitative studies may be justified to conclude the real world pertinence of these conceptual models.

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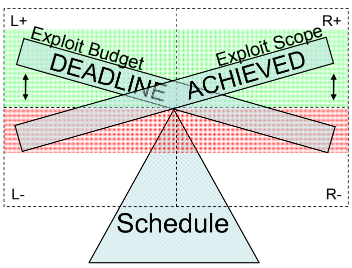

Fig. 9. Effective management of the NASM case [17].

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Time, cost and quality trade-off in project management: a case study

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In 1996, Babu and Suresh proposed a framework to study the trade-off among time, cost and quality using three inter-related linear programming models. This paper describes our attempt to apply the method to an actual cement factory construction project. The purpose is to evaluate the practical applicability of the method by highlighting the managerial insights gained, as well as pointing out key problems and difficulties faced. As consequence, the paper helps practicing project engineers to have realistic expectations of the method. It also provides suggestions to overcome some practical problems if the method is to be applied in real industrial projects. © 1999 Elsevier Science Ltd and IPMA. All rights reserved

Keywords: critical path method (CPM), time, cost, quality trade-off, case study

Introduction

The critical path method (CPM) provides not only an excellent way of calculating the shortest completion time and the critical activities for a project, but also a framework to analyze the time/cost trade-off. In practice, however, one of the critical measures of project success is the quality of its performance that may be affected by attempt to crash the completion time with additional budget[1,2]. In this context, the traditional CPM method is inadequate to help the project manager make informed decisions on project progress and performance. Many attempts have been recorded in the literature to improve the method since its inception in the late 1950s[3]. However, most of this research either focused on improving the efficiency of the project-crashing algorithm[4–8], or on relaxing on the assumption of the linear relationship between cost and time factors[9–11]. In 1996, Babu and Suresh[12] proposed a new method to study the tradeoff among time, cost and quality using three inter-related linear programming models. Their approach is based on the linear relationship among the project cost, the quality measure and the project completion time. The method is illustrated with a small textbook example taken from Hillier and Lieberman[13].

This paper describes an attempt to apply the Babu and Suresh method to an actual cement factory construction project in Thailand. With the purpose of evaluating the practical applicability of the method, the basic assumptions are investigated, major problems in estimating input parameters are pointed out, and the resulting managerial insights are highlighted. As consequence, the paper helps practicing project engineers to have realistic expectations of the method. It also provides suggestions to overcome various practical problems if the method is to be applied in real industrial projects. This research also validates with real data most of the conceptual findings by Babu and Suresh in their original work.

Review of Babu and Suresh cost–time–quality trade-off models

Babu and Suresh developed their method by assuming that the project activities and their precedence relationships are determined. Each activity has a normal time of completion and a crash time of completion. Associated with the normal time are normal cost and normal performance quality, and with crash time are crash cost and crash quality. It is assumed that the cost and quality of an activity vary as linear functions of the completion time. Given individual activity completion times, the total project completion time can then be calculated using the traditional CPM method. The total cost is simply the sum of individual activity costs, and the total project quality is measured by the average of the individual activity quality measures.

Babu and Suresh suggest three optimization models as a framework to analyze the trade-off among the cost, time and quality factors of a project. In order to formulate these models in the familiar linear programming (LP) format, the activity-on-arc (AOC) network convention and the following notation will be used:

M: Number of events
N: Number of activities

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Y_i: Earliest time of event i (i = 1,2,...,M)
X_{ij}: Duration of activity (ij) (X_{ij} and Y_i are decision variables)
t_{ij}: Normal time for activity (i,j)
t'_{ij}: Crash time for activity (i,j) ($t_{ij} \geq t'_{ij} \geq 0$)
c_{ij}: Normal cost for activity (i,j)
c'_{ij}: Crash cost for activity (i,j) ($c'_{ij} \geq c_{ij} \geq 0$)
q_{ij}: Normal quality for activity (i,j)
q'_{ij}: Crash quality for activity (i,j) ($q_{ij} \geq q'_{ij} \geq 0$).

Notice that a dummy activity can be indicated by letting $t_{ij} = t'_{ij} = 0$. The constraints common to all the LP problems can then be summarized as follows:

(a) The project is started at time zero.

$$Y_1 = 0 \tag{1}$$

(b) Each activity completion time X_{ij} is bounded from above by the normal time, and from below by the crash time:

$$t_{ij} \geq X_{ij} \geq t'_{ij} \tag{2}$$

(c) For each activity (i,j),

$$Y_i + X_{ij} - Y_j \leq 0 \tag{3}$$

The objective function for the first LP model is the project completion time that is simply the earliest time of the last 'finish' event:

$$TF = Y_M$$

For the second model, the objective function is the total cost of the project. By assuming the linear relationship of the activity cost and completion time, the total project cost is estimated as a linear function of the individual activity times:

$$CF = \sum_{(i,j)} (A_{ij} + B_{ij} \times X_{ij}),$$

where $B_{ij} = (c'_{ij} - c_{ij})/(t_{ij} - t'_{ij})$ and $A_{ij} = c'_{ij} - B_{ij} \times t'_{ij}$ are the slope and intercept of the cost curve for activity (i,j). For the third model, the objective function is the project's overall quality that is calculated as the average of the individual activity qualities, that is

$$QF = \sum_{(i,j)} (A'_{ij} + B'_{ij} \times X_{ij}),$$

where $B'_{ij} = (q_{ij} - q'_{ij})/(t_{ij} - t'_{ij})$ and $A'_{ij} = q'_{ij} - B'_{ij} \times t'_{ij}$ are the slope and intercept of the quality curve for activity (i,j).

Thus, assuming that T' and Q' are the lower bounds for project completion time TF and average quality QF, and C' is the upper bound for total cost CF, the models can be simply written as:

Model 1: Minimize TF subject to (1–3) and $CF \leq C'$ and $QF \geq Q'$;
Model 2: Minimize CF subject to (1–3) and $TF \leq T'$ and $QF \geq Q'$;
Model 3: Maximize QF subject to (1–3) and $CF \leq C'$ and $TF \leq T'$.

For different budget levels and the quality tolerances, the first model yields the corresponding shortest completion times, and thus provides a framework for the trade-off analysis by considering project completion time as a function of budget and quality constraints. In a similar way, the second model searches for the lowest cost to complete the project as a function of completion due dates and quality tolerance allowed, while the third model yields maximum overall project quality subject as a function of budget constraints and completion due date.

Case study and parameter estimation

TPI Polene Public Company Limited (TPIPL) is located about 134 km north of Bangkok, Thailand. The company currently operates three cement factories with an annual capacity of 9 million tons per annum. The fourth factory is now under construction and is expected to be in operation by 1998, which will bring the total cement capacity to 12.3 million tons per annum. The total cost for this new construction project is estimated to be baht 9.6 billion (or roughly US$375 million). The scope of work for the whole project is large and complex with 35 different sub-projects and more than 1000 separate activities. Partly because of this complexity, and partly due to the fact that the completion of the project is subject to a large number of exogenous factors, both economical and political, beyond the control of the top management, it was decided to focus this research on only one of its sub-projects. The sub-project chosen is one of erecting the Dopol pre-heater tower, which is the most time consuming and problematic sub-project in the whole factory construction project. In fact, the pre-heater tower erection is so important that its schedule is used by project engineers as the benchmark to adjust the schedule of all other sub-projects. It is believed that using this sub-project in evaluating the practical value of the method will not affect the validity of the conclusions.

The activities of the sub-project to erect the Dopol pre-heater tower can be grouped into 52 work packages under four main categories: civil work (leveling, excavation, foundation and construction), mechanical work (fabrication, erection, refractory and cold test run), electrical work (power distribution, substation and transformer, MCC control, cable rack installation, power supply) and automation (Plc cabinet, safety and local control). Each work package consists of numerous related specific activities that are normally carried out under a single supervisor or subcontractor. The work packages are identified so that activities of different work packages do not use the same resources at the same time, and therefore can be scheduled relatively independently. Care is taken that completion time and cost of individual work packages can be estimated relatively easily and accurately. The list of these work packages and their brief description is given in *Table 1*.

Estimating the relevant input parameters for work packages was probably the most time consuming task in applying the Babu and Suresh method to the sub-project under study. The work was done in close consultations with site managers. Below is described the way these parameters were estimated as well as the difficulties encountered.

Table 1 Works on Dopol preheater tower and the estimates parameters

Work-package	Brief description of work	t_{ij} (days)	t'_{ij} (days)	c_{ij} (million baht)	c'_{ij} (million baht)	q'_{ij}
A	Procurement of Rebars	33	22	5.50	8.25	0.90
B	Procurement of steel section, plates, pipes, etc.	33	22	58.40	87.60	0.90
C	Excavation	33	22	0.50	0.75	0.90
D	Foundation	33	22	6.50	9.75	0.95
E	Concrete columns to first floor (188 m)	22	15	3.40	5.10	0.95
F	Concrete floor and beams to first floor	22	15	3.50	5.25	0.95
G	Concrete columns to second floor (200m)	22	15	2.50	3.75	0.95
H	Fabrication of beams, steel floor and staircase (second floor)	44	29	1.09	1.63	0.83
I	Fabrication of kiln inlet and transaction piece	75	50	1.84	2.76	0.83
J	Erection of kiln inlet and transaction piece	75	50	1.10	1.65	0.85
K	Installation of beams, steel floor and staircase (second floor)	44	29	1.95	2.93	0.85
L	Fabrication of beams, steel floor and staircase (third floor)	55	37	2.22	3.34	0.83
M	Installation of steel structure to 3rd floor (217 m)	55	37	4.00	6.00	0.85
N	Erection of 1st stage cyclones and ducts between 3rd and 4th floors	30	20	1.80	2.70	0.85
O	Fabrication of 1st stage cyclones and ducts (3rd floor)	30	20	1.08	1.61	0.83
P	Refractory works (kiln inlet, transaction pieces, column ducts)	40	27	2.85	4.28	0.90
Q	Electrical works in 1st, 2nd and 3rd floors	40	27	2.50	3.75	0.70
R	Fabrication of beams, steel floor and staircase (4th and 5th floors)	55	37	3.15	4.73	0.83
S	Erection of beams, steel floor and staircase for 4th and 5th floors (251 m)	55	37	5.68	8.51	0.85
T	Erection of 2nd stage cyclones and transfer ducts	40	27	1.65	2.48	0.85
U	Fabrication of 2nd stage cyclones and transfer ducts	40	27	2.75	4.12	0.83
V	Refractory works at 1st stage cyclones and ducts	44	29	2.54	3.81	0.90
W	Fabrication of beams, steel floor and staircase (5th and 6th floors)	55	37	1.99	2.99	0.83
X	Erection of beams, steel floor and staircase (5th and 6th floors)	55	37	3.59	5.38	0.85
Y	Erection of 3rd stage cyclones	30	20	0.80	1.20	0.85
Z	Fabrication of 3rd stage cyclones and ducts	30	20	1.34	2.01	0.83
AA	Refractory works at 2nd stage cyclones and ducts	44	29	2.54	3.81	0.90
AB	Electrical and instrument cabling 4th and 5th floor	22	15	1.50	2.25	0.70
AC	Installation of 2 Poldos-feeding equipment in 1st floor	30	20	1.20	1.80	0.85
AD	Installation of shock blowers (M.E) in floors 1,2 and 3.	30	20	1.25	1.88	0.85
AE	Fabrication of beams, steel floor and staircase (6th and 7th floors)	55	37	1.59	2.39	0.83
AF	Erection of beams, steel floor and staircase for 6th and 7th floors (268 m)	55	37	2.87	4.30	0.85
AG	Erection of 4th stage cyclones on 6th floor	30	20	0.69	1.04	0.85
AH	Fabrication of 4th stage cyclones etc.	30	20	1.16	1.73	0.83
AI	Refractory works at 3rd stage cyclones and ducts	44	29	3.25	4.88	0.90
AJ	Electrical and instrument cable racks etc. (6th floor)	22	15	1.50	2.25	0.70
AK	Fabrication of beams, steel floor and staircase (7th and 8th floors)	72	48	1.54	2.31	0.83
AL	Erection of beams, steel floor and staircase for 7th and 8th floors (291 m)	72	48	2.77	4.16	0.85
AM	Erection of 5th stage cyclones on 7th floor	40	27	0.62	0.93	0.85
AN	Fabrication of 5th stage cyclones and ducts	40	27	1.04	1.55	0.83
AO	Refractory works on 4th stage cyclones and ducts	44	29	3.25	4.88	0.90
AP	Fabrication of ladder, platform, stairs,beams for 8th floor	55	37	1.23	1.85	0.83
AQ	Erection of steel structures for 8th floor	55	37	2.22	3.33	0.85
AR	Erection of 6th stage cyclones on 8th floor	40	27	1.19	1.79	0.85
AS	Fabrication of 6th stage cyclones on 8th floor	40	27	1.98	2.97	0.83
AT	Refractory works on 5th stage cyclones and ducts	44	29	1.66	2.49	0.90
AU	Fabrication of second gas duct	165	111	3.55	5.32	0.83
AV	Refractory work on 6th stage cyclones completed	66	44	3.26	4.90	0.90
AW	Electrical and instrument cables on 7th floor	30	20	1.50	2.25	0.70
AX	Installation of local instruments	88	59	5.23	7.85	0.85
AY	Insulation for gas ducts and 6th stage cyclones connection	66	44	2.28	3.62	0.85
AZ	Readying for test run	5	3	0.50	0.75	0.85

Normal time cost and quality parameters

The time and cost parameters under assumed normal conditions were easiest to estimate. In fact, the normal completion time of activity was taken from the existing project schedule that had been prepared by project engineers with care taken to all technical details. For the purpose of studying the inter-relationship among the cost, time and quality dimensions of the project in crashing the activities, all fixed costs of equipment and materials procurement, and the overhead were excluded from these cost parameters. In fact, all site managers and engineers believed that these costs, although being a major part of the total cost, were not affected by decisions of crashing the project activities. Thus the cost data used in the calculations (see also *Table 1*) include only the variable costs of which labour cost is the major component. Since the relative quality reduction due to crashing activities is the focus of interest in this research, the performance quality expected under the normal conditions is assumed to be at 100% level for each activity. This assumption reflects the research objective of investigating only the impact of the time/cost factor, and not any other influence, on the project's overall quality.

Crashing time, cost and quality

Most of the work at the pre-heater tower is labour intensive with relatively clear definition. As it is typical for construction sites in Thailand, the number of workers working 6 days a week at the project is already at the maximum due to the limited work area. Thus, according to the managers, the only way activities can be accelerated is through using overtime. Since the maximum overtime allowed is 4 hours on top of the regular 8-hour working day, activities may be crashed on average at a ratio of 2:3. These crash times were then adjusted for each of the 52 work-packages taking into account the possibility that workers may sometimes be asked to work on Sunday also, and that some work would permit less hours of overtime due to lighting conditions and safety reasons. The results are the maximum crash times t'_{ij} used in the LP models. Site managers also believed that when activities need be crashed, the cost increase is mostly due to the double rate for overtime. As consequence, they had no problem in accepting the assumption of linear relationship between cost escalation and time crashed which is fundamental in the Babu and Suresh method.

The estimation of the quality reduction due to crashing was more difficult and elaborate. There were two major obstacles in arriving at an acceptable measurement of quality reduction. First, and not surprisingly, it was found that the practicing managers and engineers were very sensitive to the idea that the quality of the project could be compromised at all by crashing. Second, the quality of an activity can be usually measured only by subjectively using managers' judgement. In a few cases when quality can be determined quantitatively and objectively using technical specifications, these specifications were to be adhered to rather strictly, and the quality measure was not noticeably affected by the use of overtime. The common reaction was that 'quality reduction due to overtime is negligible and cannot exceed 2–3%, even if the maximum amount of overtime is used'. With the objective of arriving at workable estimates of quality reductions in project activities due to crashing, the following principles were agreed:

1. In interpreting the results of the models, it is not the absolute value of the quality measure that is relevant, but the relative quality values of the individual activities when crashing is performed.
2. These relative values should reflect two considerations:
   - Some works (such as painting works) are more prone to the measurable quality reduction when crashed;
   - Some works (such as welding or electrical works) are so important and critical that a minor reduction in quality may seriously compromise the whole project performance.

     In both cases, crashing should induce a relatively large reduction in the quality measures of the activities.
3. If a work-package has more than one activity then its quality is measured as the weighted average of the individual activities' quality where the weights are proportional to the contractual values of the activities.

Based on this common framework, the researchers and the managers together compared the individual activities to estimate the relative quality reductions due to crashing. The last column of *Table 1* is the result of this time consuming process. The numbers in that column indicate the relative, and at times subjective, assessment of the quality of the individual project activities when maximum crash is performed. It is presumed then that the quality measure will decrease as a linear function of activity completion time from the normal value of 1.00 to this lower bound.

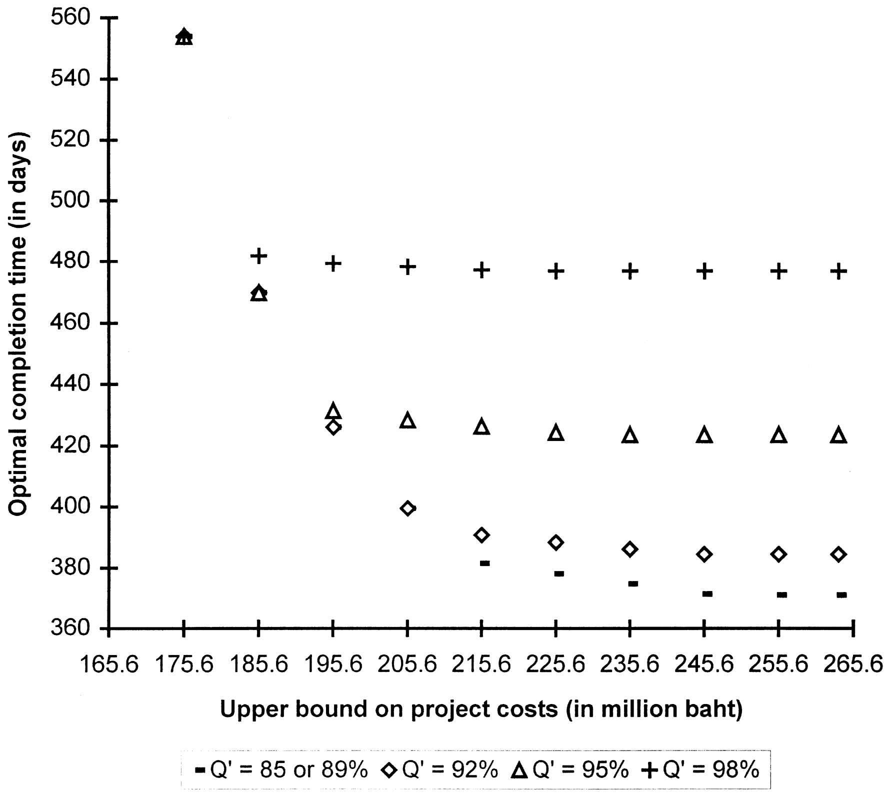

Figure 1 Optimal completion time when costs and quality are bounded

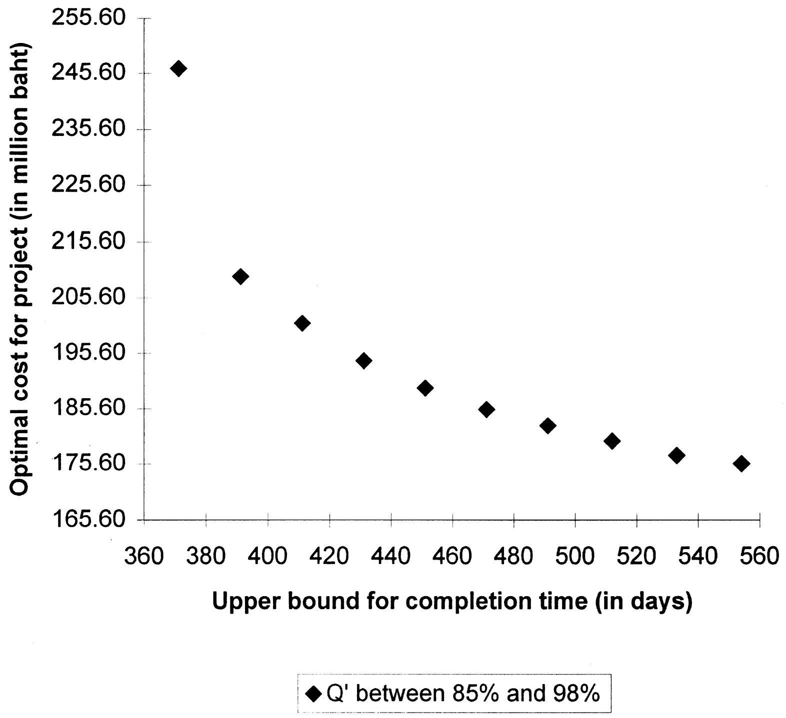

Figure 2 Optimal cost when completion time and average quality are bounded

Analysis of computational results

Once the parameters are estimated, the computation of the three models, using software LINDO (version 5.1), is simple since the size of the LP problems is relatively small (104 variables and 231 constraints for each model). All these problems were solved repeatedly using different values for the goal constraints in cost, time and quality. The maximum budget varied with increments of 10 million baht—except for the last increment—from the normal cost of 175.60 million baht to the maximum crash cost of 263.60 million baht. The lower bound for completion time was allowed to change in increments of 20 days—or 21 days for the last three increments—from the maximum crash time of 371 days to the normal time of 554 days.

Five different quality levels were considered in the models: 85%, 89%, 92%, 95% and 98%.

The computational results of the three models are summarized in *Figures 1–3* and *Tables 2–4* which bear much similarity to the corresponding results obtained by Babu and Suresh with their textbook example. In particular, the following major findings can be noted:

- For each given quality level, there exists a budget threshold beyond which there would be of little value to increase budget in the hope of expediting further project completion. These thresholds are given in *Figure 1* as 185.60 million baht at a 98% quality allowance, 195.60 million baht at a 95% quality allowance, and 215.60 million baht at a 92% quality allowance. The corresponding completion times are 482 days, 431 days and 391 days, respect-

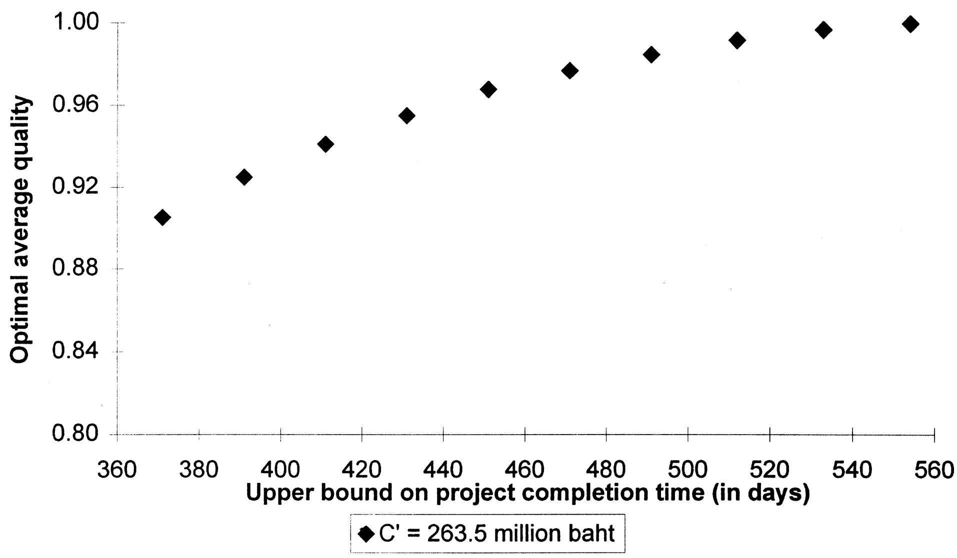

Figure 3 Optimal average quality when cost and completion time are bounded

Table 2 Optimal completion time (in days) when costs and quality are bounded

Upper bound on project costs (million baht)	Lower bound on project quality 0.85	0.89	0.92	0.95	0.98
175.6	554	554	554	554	554
185.6	470	470	470	470	482
195.6	426	426	426	431	479
205.6	400	400	400	428	478
215.6	381	381	391	426	477
225.6	378	378	388	424	477
235.6	375	375	386	424	477
245.6	371	371	385	424	477
255.6	371	371	385	424	477
263.6	371	371	385	424	477

Table 3 Optimal project cost when completion time and average quality are bounded

Upper bound on completion time (in days)	Lower bound on project quality 0.85	0.89	0.92	0.95	0.98
371	246.48	246.48	INF	INF	INF
391	209.42	209.42	214.50	INF	INF
411	200.97	200.97	200.97	INF	INF
431	194.21	194.21	194.21	196.26	INF
451	189.32	189.32	189.32	189.32	INF
471	185.41	185.41	185.41	185.41	INF
491	182.48	182.48	182.48	182.48	182.49
512	179.67	179.67	179.67	179.67	179.67
533	177.08	177.08	177.08	177.08	177.08
554	175.60	175.60	175.60	175.60	175.60

ively. At the lower quality levels of 89% and 85%, the thresholds are not as sharp as with the higher quality tolerances.

- If the average quality requirement is decreased, these budget thresholds, which can be interpreted as the practical limiting costs for crashing, will increase, which in turn allows for a further reduction in project completion time.
- Project cost is almost independent of the quality requirement and therefore, the cost/time curves in *Figure 3* coincide for all quality levels. This fact is not surprising because the performance quality at each activity was assumed to be a function of the time factor only.
- There is a critical value for project completion time, beyond which it would be extremely expensive to crash further. *Figure 2* indicates that this critical value is around 400 days.

In order to help managers to gain better insight of the trade-off among time, cost and quality factors of the project, the output of Model 1 is re-organized by quality requirements. Wherever an increase in budget is not accompanied by a reduction in completion time, only the minimum budget required for that time is recorded. The results are summarized in *Tables 5* and *Figure 4*. It is now clear that managers may not expect to crash the project completion time below 482 days without compromising the high quality level of 98%

Table 4 Optimal average quality when cost and completion time are bounded

Lower bound on completion time (in days)	Upper bound on project costs (in million baht) 175.6	185.6	195.6	205.6	215.6	225.6	235.6	245.6	255.6	263.6
371	INF	INF	INF	INF	INF	INF	INF	0.91	0.91	0.91
391	INF	INF	INF	INF	0.92	0.92	0.92	0.93	0.93	0.93
411	INF	INF	INF	0.94	0.94	0.94	0.94	0.94	0.94	0.94
431	INF	INF	0.95	0.95	0.95	0.96	0.96	0.96	0.96	0.96
451	INF	INF	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
471	INF	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
491	INF	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
512	INF	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
533	INF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
554	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 5 **Trade-off among optimal cost, time and quality level**

Optimal duration (in days)	Minimum cost (in million baht)	Quality level
554	175.6	0.98
482	185.6	
479	195.6	
478	205.6	
477	215.6	
477	225.6	
470	185.6	0.95
431	195.6	
428	205.6	
426	215.6	
424	225.6	
424	235.6	
426	195.6	0.92
399	205.6	
391	215.6	
388	225.6	
386	235.6	
384	245.6	
381	215.6	0.85–0.89
378	225.6	
375	235.6	
371	245.6	
371	255.6	

or running to an exceedingly high cost. Similarly, if 95% average project quality is the performance that can be accepted, then trying to complete the project in less than 431 days may be very expensive.

Assessment of the method and conclusions

The linear programming models proposed by Babu and Suresh are conceptually easy to understand, and computationally easy to solve. All managers and engineers are interested in the possibility of incorporating performance quality in the time and cost scheduling. The results obtained, when presented using proper graphics, provide insightful information that can help the managers in making trade-off decisions. At the early stage of the cement factory construction project when the research was conducted, the goal of completing the construction in time was the most important for the managers. Thus, Model 1 was judged as the most relevant and interesting. However, it is possible to foresee a situation where Model 2 becomes prominent, especially when some cost overrun has occurred in the project and the task of minimizing expenditures is of the top priority. In any case, the two models 1 and 2 are dual in the linear programming sense, and can always be considered together with quality levels as parameters. Model 3, although playing a rather symmetric role with the other two, is less appealing to practical managers and engineers. The main objection to this model is that the quality measurements are sometimes too subjective and inaccurate to be considered as an objective function in an LP formulation. At the same time, it can be observed that, while all managers, understandably, are sensitive to the issue of quality reduction due to crashing work, they are also reluctant to consider improving an already acceptable quality level at extra expenses or by delaying the project completion.

As already pointed out by Babu and Suresh, the solutions of the models support the common intuition regarding effects of time, cost and quality in project management. The most valuable finding to managers participating in the research, and probably a surprising one for some, is the recognition of the existence of the different budget thresholds for the time/cost curve at different quality levels. These thresholds, not mentioned by Babu and Suresh, are explicitly presented in *Figure 4*, and judged as most useful in helping managers making trade-off decisions.

The managers involved in this research consider as reasonable the assumption of linear relationship between cost and time. The fact that crashing this particular project was practically possible only through overtime not only made the assumption readily accep-

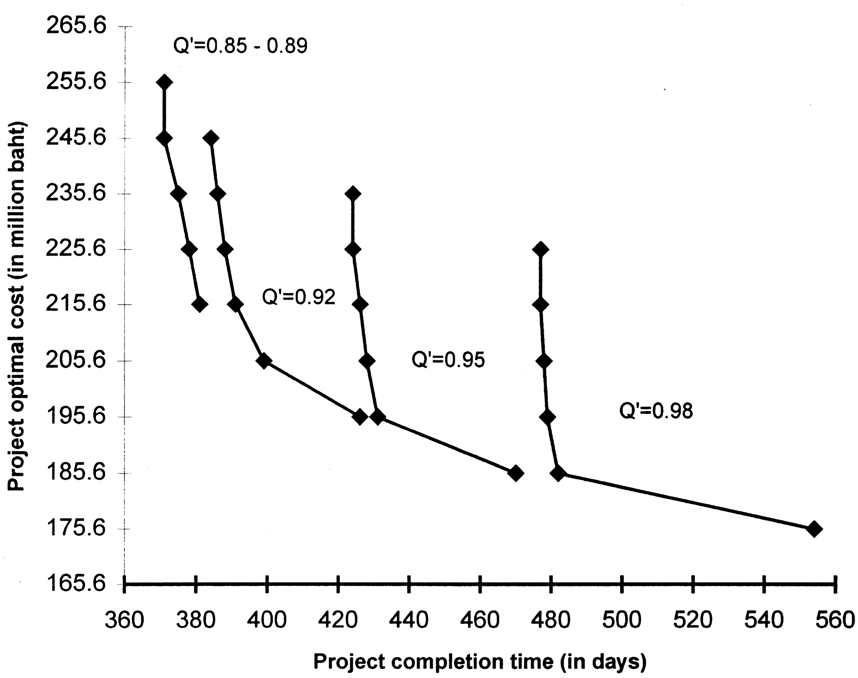

Figure 4 Trade-off among optimal cost, time and quality requirement

table, but also facilitated estimating the necessary parameters. The linearity assumption between quality and time is more problematic. In fact, the most difficult, and probably most controversial, task in applying the method in the case project was to assess the quality reduction associated with crashing. In the current research, this is achieved, to a certain degree of satisfaction of both the researchers and practitioners, through the framework outlined in the chapter on parameter estimation. Even then, it is recognized that the quality measures at best reflect only relative performance levels of different activities with different crashing decisions. The difficulty also highlights a major limitation of the method: in all practically justifiable measurements of quality, only a very small portion bears direct relation with crashing decisions. Thus, the quality factor considered in the models accounts for only a small, and unfortunately usually not the most relevant, part of the performance of managerial interest. This leads to an interesting research question of finding a more holistic measurement for performance quality, and a more realistic model to describe the relationship among quality of individual activities, and therefore of the whole project, and the budget and time allowed.

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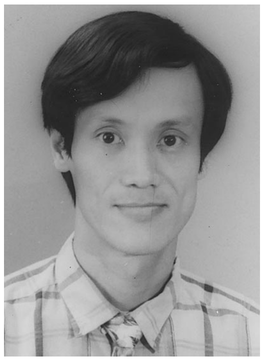

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