A Decision-Support Framework for Choosing a Project Delivery System (PDS) in a Multi-Project Environment

By

Ying-Yi Chih

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering — Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor C. William Ibbs, Chair
Professor Glenn Ballard
Professor Sara Beckman

Fall 2010

A Decision-Support Framework for Choosing a Project Delivery System (PDS)

in a Multi-Project Environment

by

Ying-Yi Chih

Abstract

A Decision-Support Framework for Choosing a Project Delivery System (PDS) in a Multi-Project Environment

By

Ying-Yi Chih

Doctor of Philosophy in Engineering-Civil and Environmental Engineering

University of California, Berkeley

Professor C. William Ibbs, Chair

The use of an appropriate Project Delivery System (PDS) can significantly increase the project efficiency and success rate. Designing a PDS however is a difficult task because: (1) decisions are made early in the project planning phase when only limited and imprecise project information is available; (2) decisions involve choosing between a variety of PDSs and consideration of multiple factors (e.g., project characteristics and external environment factors); (3) decisions are made in a multi-project environment with complex project dependencies. Several methods (e.g., guidance, multi-attribute utility analysis, and analytical hierarchy process) have been proposed to help a decision-maker choose a PDS. Nonetheless, project dependencies and possible time/cost trade-offs are frequently ignored in these methods even though they can affect project performance. In addition, these methods provide very little, if any, opportunity to the decision-maker for "designing" a PDS for their needs. This research seeks to overcome these limitations.

This research develops a decision-support framework for designing and choosing a PDS in a multi-project environment. The framework was developed for the specific circumstances of one public agency, which was required by regulations to choose from design-bid-build (DBB), design-build (DB), or construction management at risk (CMR), with limited flexibility to adapt these contractual structures to the specific circumstances of individual projects. That does not materially impact this research, the focus of which is incorporating time/cost tradeoffs and interdependencies in a multi-project environment into the design of PDSs. This framework helps a decision-maker evaluate alternative PDSs (in this case, specifically the DBB, DB, CMR alternatives) with respect to two groups of criteria: performance and general PDS criteria. It also integrates a Net-Present-Value-based (NPV-based) method for objectively determining time/cost trade-off rules and a procedure for systematically evaluating effects of project dependencies on project schedule and cost.

The case study results show that the framework is beneficial to a PDS decision-maker in several ways. First, it guides a decision-maker, step-by-step, in evaluating alternative PDSs. With the information collected and analyzed in the framework, the decision-maker can better justify his/her decisions to others. Furthermore, it helps the decision-maker consider project

dependencies and possible time/cost trade-offs in estimating project timelines and cost distributions in different PDSs. Such consideration can facilitate not only a more realistic project planning but also a more informed PDS decision-making. The proposed framework can also provide the decision-maker opportunities to explore "what if" scenarios in his/her PDS decision-making process. Finally, but not least, the framework also allows the decision-maker to identify the areas where a PDS may perform poorly, and thereby develop proactive management strategies.

The proposed framework has one problem: its application is more time-consuming than some existing PDS selection methods (e.g., a weighted score approach). This longer application time is partially because of the unfamiliarity of decision-makers with the framework, and hence can be improved through proper training. The needs to estimate project timelines and cost distributions in different PDSs and to evaluate effects of project dependencies also contribute to this delay. To ensure a more effective framework implementation in the future, public agencies are suggested to: (1) establish proper documentation and knowledge management systems, (2) develop an effective communication structure, and (3) to provide proper training to enhance the project managers' competence. A strong support from upper-level management is also critical to a successful framework implementation.

Table of Contents

List of Figures

List of Tables

Acknowledgements

My doctoral study would not have been possible without the support and dedication of a number of very special persons. I would like to express my deepest gratitude to my advisor, Prof. C. William Ibbs, for his support and guidance throughout the research. His professional knowledge and experience has inspired me tremendously. He has been a mentor and a continuous source of support, direction, and encouragement.

My sincere appreciation is extended to my dissertation committee members, Prof. Glenn Ballard and Prof. Sara Beckman, for their constructive comments on my research and dissertation. I would also like to thank Prof. Arpad Horvath and Prof. Elizabeth Deakin for their exceptional critiques and suggestions before and during my qualifying exam, and Dr. John B. Miller for his valuable comments on my research proposals. I also appreciate Prof. Iris D. Tommelein and Prof. Robert G. Bea for their care and help during my Ph.D. study.

I also owe gratitude to Prof. Yaw-Kuang Chen at National Cheng Kung University in Taiwan. Prof. Chen has been my teacher and mentor for the past ten years. I am fortunate to be his student. I would also wish to thank Prof. Fu-Shainn Lee at Kun Shan University in Taiwan and Miss Rina Gerevitz for their continued assistance and encouragement during my studies in the United States.

I am grateful for the scholarship that I received from the Ministry of Education, Taiwan in the early two years of my Ph.D. study. I would also like to thank Mr. Kuan-Ting Chen and Mr. Chia-Chang Chang and their colleagues for their comments and assistance in my data collection process.

I would like to extend my thanks to my colleagues at Berkeley, especially Long Duy Nguyen, Min Liu, Martin Chandrawinata, Sebastien Humbert, Tarun Singh, Tai-Lin Huang, and Zofia Rybkowski, for our valuable discussions and interaction. Thanks the CEE Department staff, especially Ms. Shelley Okimoto, for their assistance and my Taiwanese seniors and friends at Berkeley for their continuous help and support.

Finally, I would like to convey my most sincere gratitude to my family. I am especially grateful to my parents, Chin-Long Chih and Shu-Chen Lin, for their unconditional love, sacrifice, and patience while I pursue my dream. Thanks to my brother, Wei-Cheng Chih, for his support to our family while I am away.

Abbreviations

AHP : Analytical hierarchical process
BOT : Build-operate-transfer
C : Cost
CC : Cost certainty
CBR : Case-based reasoning
CMR : Construction management at risk
CO : Complexity
DB : Design-build
DBB : Design-bid-build
DBO : Design-build-operate
DBOM : Design-build-operate-maintain
DOTs : Department of Transportation
FL : Flexibility
HBLRTS : Hudson-Bergen Light Rail Transit System
QL : Quality
MAUT : Multi-attribute utility theory
MAVT : Multi-attribute value theory
MCDA : Multiple criteria decision analysis
MCDM : Multiple-criteria decision-making
PC : Price competition
PD : Project dependency

PDS : Project delivery system
PPSSM : Project procurement system selection model (PPSSM)
PR : Point of responsibility
RT : Risk transfer
SMARTS : Simple multi-attribute rating technique with swing weights
T : Time
TC : Time certainty
TTV : Total time value
UTA : Utility theory additive
UTV : Unit time value
NPV : Net present value
VE : Value engineering
VPDSA-IF : Virtual project delivery system adviser for infrastructure facilities

Chapter 1
Introduction

1.1 Background

A Project Delivery System (PDS) defines the process by which the finance, design, construction, operation, maintenance and decommissioning of a project are executed and the roles and responsibilities of the parties involved in a project (Love et al. 1998; Miller et al. 2000; Construction Industry Institute 2003). The use of an appropriate PDS can significantly increase the efficiency and the success rate of a construction project (Naoum 1994; Rwelamila and Meyer 1999; Luu et al. 2003a; Oyetunji and Anderson 2006). For example, the construction project cost is estimated to be reduced by an average of 5% with an appropriate PDS (Contractual 1982). Designing a PDS is however a difficult task for a number of reasons.

First, a PDS decision is usually made early in the project planning phase when only limited and imprecise project information is available. That information scarcity involves goals, timing, budget, etc. of the project, roles of the participants, the surrounding economic environment, and so forth. Second, even though it the literature often speaks of selecting a PDS, it would be more accurate to speak of designing a PDS. Contractual structures such as DBB or DB are but the tip of the iceberg in the number of decisions that must be made that ultimately define a PDS. PDSs may vary in several aspects. A PDS that can achieve certain project objectives better than others may also perform worse on some other objectives. For instance, even though DB can generally deliver a project in a timelier manner than DBB, its level of price competition is lower. This means that no single contract structure or PDS is appropriate for all types of projects under all circumstances. Third, the PDS decision needs to consider various factors (e.g., client's time, cost and quality objectives, project characteristics and external environment) (Alhazmi and McCaffer 2000; Ambrose and Tucker 1999; Luu et al. 2003a), and no single set of criteria can be employed to determine a PDS for a specific project. Finally, but not least, the decision is made in a multi-project environment, where there exist complex interdependencies among projects. These project interdependencies may hinder a PDS's abilities to achieve its expected benefits; and therefore should be taken into account in the PDS decision-making process. This need considers project interdependencies which further compound the difficulty in making a PDS decision.

The importance and difficulties associated with the PDS decision-making indicate that a systematic approach is needed to help a decision-maker evaluate and choose a PDS and to reduce the possibility of an inappropriate PDS being used.

1.2 The Need for Research

Even though choosing a PDS is a critical task with significant influence on project success and efficiency, in practice such decisions tend to be made intuitively or, in general terms, not in a structured way (Cheung et al. 2001; Luu et al. 2003a). The PDS selection process often starts with a lack of understanding of the decision situation, minimum knowledge of alternative PDSs, and very little idea of how to evaluate them and make a final choice (Masterman 2002). Such an unstructured decision-making process may result in an inappropriate PDS being selected. This can impede the realization of certain benefits associated with the chosen PDS and lead to project failure (Rwelamila and Meyer 1999).

In response to this problem, researchers have proposed several theoretical methods (to be discussed in more detail in Chapter 2) for evaluating PDSs in a systematic way. These PDS selection methods vary in their concepts, complexity of implementation and levels of information required. They are also different in the ways in which a decision-maker's preferences are elucidated, expressed and measured. Despite these differences, existing PDS selection methods share three similar limitations. First, they inadequately consider project dependencies in their PDS evaluation processes, if not ignore them entirely. In addition, they do not allow a decision-maker to explicitly consider possible time/cost trade-offs. Finally, these methods provide very little, if any opportunity for the decision-maker to "design" a PDS to best satisfy project objectives. These three limitations are discussed below and they have inspired this research work.

Inadequate consideration of project dependencies. In the construction industry most projects are undertaken in a multi-project environment of some sort (Kometa et al. 1995; Chinyio et al. 1998). There exist different types and degrees of interdependencies among the projects, which may hinder a PDS's abilities to achieve its expected benefits.

Consider an example where a project's implementation is dependent on information from another project (the information resource interdependencies). In this example, even though DB is expected to deliver the project faster, if the other project cannot deliver necessary information in the same timely manner, the project delivery speed will be significantly delayed.

In most of available PDS selection methods, the new project is considered in isolation when determining the PDS to use. The currently available PDS selection methods do not (if at all) address the project interdependencies in their PDS evaluation processes. As a result, a PDS may be selected based on the unrealistic expectations of its associated benefits (e.g., overly optimistic and unrealistic schedule and cost estimations). Such unrealistic expectations can be the main causes for project delay and cost overruns in later project implementation phases (Chang 2002; Odeh and Battaineh 2002).

Miller and Evje (1999) is one key paper that attempts to tackle the PDS decision-making problem from the multiple-project point of view. They argue that a PDS should be determined based on the feasible financial configuration of the project portfolio, but not on that of an individual project. Although this study partially addresses the issue of project interdependencies, it is limited to consideration of resource interdependency focusing only on the capital resource. Other types of resources (e.g., the agency's personnel) and other types of project interdependencies are not discussed.

Lack of an explicit consideration of possible time/cost trade-offs. Time and cost are the two primary concerns in choosing a PDS because the project owners need to meet certain mandatory constraints (Touran et al. 2009). For example, a project has to be completed within a certain amount of budget and by a specified deadline. Time and cost are highly interrelated (Feng et al.

1997; Li and Love 1997) and trade-offs between them can also play a critical role in the PDS decision-making process.

Consider an example where a PDS is found to be performed better than others on most objectives except that the estimated total project cost under this PDS will exceed the budget limit. In this case, the PDS will be considered as an infeasible option. This may change however if time/cost trade-offs are considered. A decision-maker can choose to trade cost with time to meet the budget limit. This adjustment will make the PDS a feasible option for further consideration and this may allow other benefits associated with the PDS to be materialized. The time/cost trade-off analysis also gives the decision-maker the flexibility to consider different project scheduling and cost planning circumstances given the same PDS. These analysis results are useful in making an informed PDS decision. The available PDS selection methods however do not adequately address this time/cost trade-off issue.

Lack of opportunity to "design" a PDS. All currently available PDS selection methods help decision-makers evaluate a set of given PDS alternatives and choose one among them. Decision-makers are not given the opportunity to design, to a certain degree, a PDS for their needs and project objectives. This limitation has caused two problems in the PDS decision-making. First, a PDS can have many variants and it is impossible for a method to include all possible PDS alternatives. As a result, a decision-maker may be forced to choose from a set of limited alternatives. In addition, the given alternatives may not be able to meet decision-makers' needs and project objectives as each PDS decision-making situation is unique.

To sum up, a PDS decision in practice is still not made in a structured way, and currently available PDS selection methods are limited in their capability to consider project dependencies and possible time/cost trade-offs, and to enable the design of a PDS in the PDS decision-making process. These limitations have inspired this research.

1.3 Problem Statement

Most, if not all, currently available methods evaluate PDSs on the basis of their expected capabilities to satisfy clients' objectives. They do not properly consider factors (e.g., project dependencies) that may affect project performance in their PDS evaluation processes. Consequently, a PDS may be selected for an unrealistic expectation of its benefits. Once the chosen PDS is used, the project may encounter unexpected difficulties.

More realistic project programming and an understanding of potential operational difficulties thereby taking appropriate decisions are two critical project success attributes (CIRC 2001; Iyer and Jha 2005). With this in mind, this research aims at developing a decision-support framework that can facilitate a more realistic PDS decision. In this framework, project performance under different PDSs and factors that may affect project performance (especially on time and cost) are evaluated. Three layers of factors to be addressed in the framework include: (1) possible time/cost trade-offs; (2) project dependencies (between internal and external projects); and (3) external factors (e.g., regulation approval). Figure 1.1 illustrates this research focus. Even though it is not possible, nor operationally feasible, to consider all factors and to accurately estimate their impacts on project performance, a consideration of these factors, even partially, can still facilitate a more realistic project planning and an informed PDS decision-making.

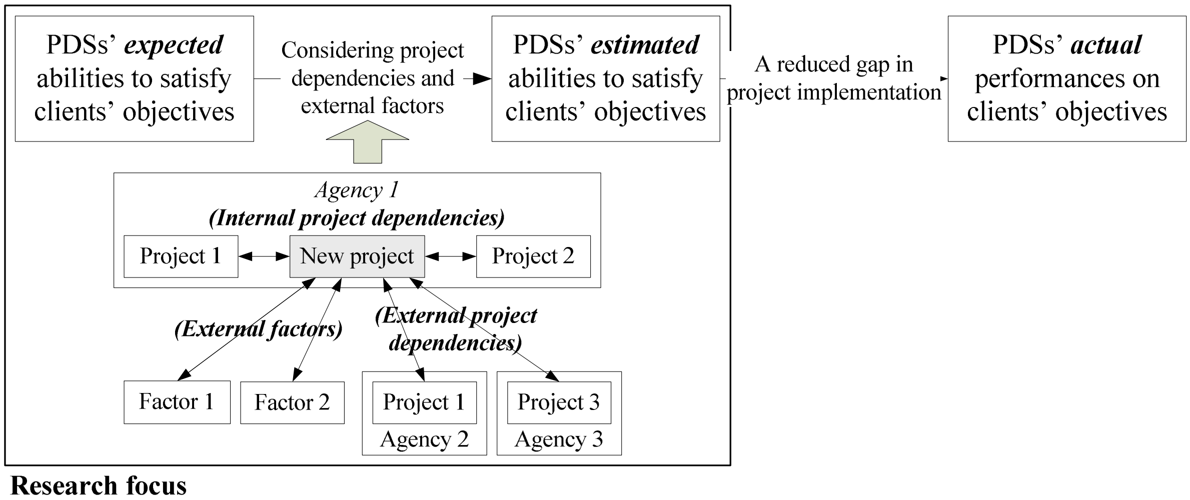


Figure 1.1 Research focus

1.4 Research Objectives

This research aims at developing a decision-support framework to help a decision-maker design and choose a PDS among the regulation-authorized alternatives (e.g., DBB, DB and CMR) in a multi-project environment. The specific objectives of this study include:

a. To review and synthesize literature on alternative PDSs and available selection methods, and to provide a comprehensive understanding of a PDS decision-making problem;
b. To develop a method for determining time/cost trade-off rules given different PDSs in the project planning phase;
c. To develop a procedure for evaluating the impacts of project dependencies on a new project's estimated schedules and costs under different PDSs;
d. To propose an integrated framework for evaluating PDSs with respect to a set of criteria, while taking into account project dependencies and possible time/cost trade-offs; and
e. To illustrate and evaluate the proposed framework through a case study and provide suggestions for future framework implementation.

1.5 Scope of Work

The framework is developed mainly for decision-makers in the public sector. Choosing a suitable PDS is a decision facing decision-makers in both the public and private sectors. A decision-maker in the private sector usually has clear objectives (e.g., profit maximization) in making his/her PDS decisions. He/she also has greater flexibility in his/her choices of PDSs and PDS decision-making processes. A decision-maker in the public sector, on the other hand, needs to consider several criteria (e.g., efficiency and equity) other than the project's profitability. In addition, the decision-maker's choices of PDSs are constrained by regulations. The decision-support framework developed in this research is mainly for decision-makers in the public sector. However, the use of the framework by decision-makers in the private sector is not precluded.

The framework assists in choosing among public-funded PDSs. Researchers may define PDS differently. Given the restrictions in the case study, in this research, a PDS is defined as a framework that defines how project phases are integrated and by whom the project phases are implemented (Miller 1998); in other words, a contract structure and a PDS are assumed to be one and the same. This is acceptable in the context of this research because of the case study restrictions; namely, that the public agency was required to select from DBB, DB, and CMR, with little flexibility to adapt these contract structures for specific circumstances of individual projects (as described below). The choice of these three PDS alternatives, used in the sense described above, is consistent with the Construction Industry Institute (CII) viewpoint that there are three fundamental PDSs: DBB, DB and CMR.

The specific case study is a wastewater treatment plant project in Taiwan (referred to as the Case Project herein). The Case Project's project manager was required to choose a PDS from two regulation-authorized PDSs, namely, DBB and DB. In Taiwan, the term CMR is not used. A similar form is called professional construction management (PCM), where a PCM team is hired to assist the public agency in project implementation. Unlike CMR, PCM cannot be used alone. It needs to be used together with DBB and DB. In other words, the Case Project's project manager had four PDS alternatives: DBB, DBB (with PCM), DB and DB (with PCM). Due to the regulation constraints, the project manager was not allowed to use PDSs other than these four alternatives. He was also not allowed to change the basic forms of these four alternatives. However, making minor adjustments to these four alternatives to best meet project objectives was permitted.

1.6 Structure of the Dissertation

This dissertation has eight chapters and references, as described below:

Chapter One: Introduction. This chapter introduces research background, need for research, research problems, research objectives, and research scope.

Chapter Two: Literature Review. This chapter presents literature review on project planning, alternative PDSs, currently available PDS selection methods and multi-attribute decision analysis. A definition of the PDS decision-making problem including its characteristics, affecting factors and decision-making process are also presented.

Chapter Three: Research Methodology. This chapter presents the research methodology including the research framework, date collection techniques, data reliability and quality control measures, and framework verification and validation methods.

Chapter Four: A PDS Decision-Support Framework: an Overview. This chapter provides a step-by-step description of the proposed decision-support framework. Framework requirements are outlined and how the proposed framework meets these requirements is also discussed.

Chapter Five: A NPV-based Method for Deriving Time/cost Trade-Off Rules. This chapter proposes a NPV-based method for deriving time/cost trade-off rules. Previous research on the application of NPV to project scheduling and time/cost trade-off analysis is first reviewed. Characteristics of the time/cost trade-off decisions in the project planning phase are then discussed. Next, basic concepts, assumptions and steps of the NPV-based method are described. Finally, an illustrative example is presented.

Chapter Six: Procedure to Evaluate Project Dependencies. This chapter presents a procedure to evaluate impacts of project dependencies on the new project's estimated schedules and costs in different PDSs. Basic concepts, assumptions and steps of the procedure are described and an illustrative example is provided.

Chapter Seven: Framework Application. This chapter illustrates the application of the proposed framework to a wastewater treatment plant project in Taiwan. The case study data collection process and the limitations of the data collection are also described. Furthermore, suggestions for future framework implementation are presented.

Chapter Eight: Conclusions and Recommendations. This chapter discusses the findings and limitations of this research and provides recommendations for future research directions.

Chapter 2
Literature Review

2.1 Introduction

This chapter presents the review of literature relevant to this research. First, literature on project planning is reviewed in Section 2.2. Section 2.3 introduces alternative PDSs with a focus on their characteristics, advantages and disadvantages and defines a PDS decision-making problem. Section 2.4 reviews several available PDS selection methods and discusses their limitations. Concepts and issues involved in Multiple Criteria Decision Analysis (MCDA) are examined in Section 2.5. Finally, a summary of the literature review is given in Section 2.6.

2.2 Project Planning

2.2.1 The importance of project planning

The project life cycle can be divided into separate phases including: conceptual planning, design, procurement, construction, operation/maintenance, and eventual retrofit (or demolition) (Barrie and Paulson 1992). Among these phases, the project planning phase plays the most critical role to the success of a project (Barrie and Paulson 1992; Dvir et al. 2003). Decisions made at this phase can have a tremendous impact on the successful execution of other later project phases. As a project progresses toward completion, the level of influence of a project phase on project performance decreases, as conceptually depicted in Figure 2.3.

Even though decisions made in the project planning phase can have a great influence on project performance, the level of information available for the decision-making in this phase is often limited. For example, there may be a lack of clearly defined project objectives, scope and requirements. Making decisions under this circumstance is difficult and full of uncertainties.

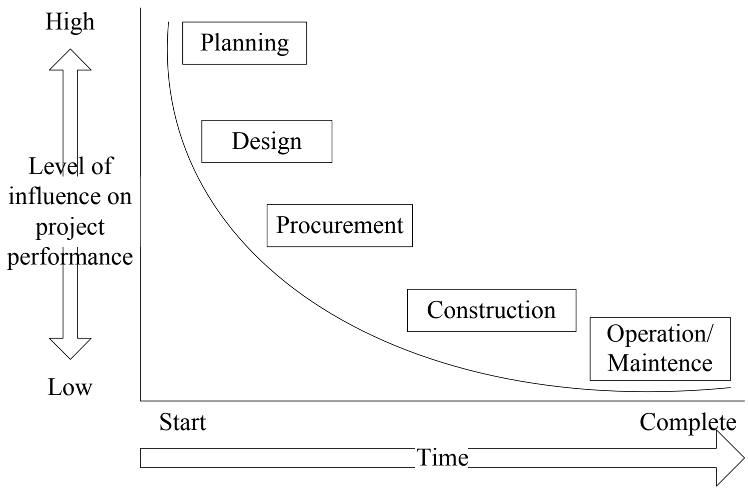


Figure 2.1 Levels of influence of project phases (source: adapted from Barrie and Paulson 1992)

2.2.2 Project planning in the public sector

Public project planning process. In the private sector, projects can be initiated top-down as well as bottom-up. In the public sector, however, projects are mostly developed in top-down process (Niekerk and Voogd 1999; Omar et al. 2009). Take the infrastructure project planning in Taiwan as an example (Council for Economic Planning and Development 2009). A central public authority first develops a master plan that sets out the long-term strategic objectives and lists the infrastructure projects that are needed to achieve these objectives. After this master plan is approved, a local public agency will develop an implementation plan for a specific infrastructure project that is within its authority. This implementation plan will address issues such as the project's designated PDS, budget and financial sources, timelines, potential implementation difficulties and strategies. If the infrastructure project requires the financial support from the central public authorities and/or involves using PDSs other than DBB, its implementation plan will need to be reviewed and approved by the central public authorities before it is put into practice.

Public decision-making. Decision-making has been highlighted as a major issue in project planning process (Goodman and Hastak 2006). Decision-makings in the public and private sectors are different in many aspects. Some of them are briefly described below. More detailed discussions can be found in Pollock et al. (1994).

In the private sector, the consequence of a decision can directly affect a decision-maker's career progression. A decision-maker may be promoted or fired for the results of his/her decisions. In the public sector, on the other hand, the impacts of a decision are often felt by those who are not directly involved in the decision-making process. For instance, a decision to build a highway may be made by a political official, yet this decision can significantly affect the people who live in the area. Because of this difference, a decision-maker in the public sector may be less motivated to put the necessary effort into making proper decisions.

The second difference is that political concerns in the public sector are more evident than they are in the private sector. A government official will often include a political criterion when making his/her decisions. This consideration can has more to do with the appearance of actions (or results) than with actual results of the decisions. For example, the government may decide to build a highway project for a political reason rather than for the area's long-term development need. The elected official's time horizon will also affect the decision-making in the public sector. Put in another way, the timing of elections creates a natural cycle of decision-making. Favorable decisions (e.g., increasing the police force) are often made in an election year, while unfavorable decisions (e.g., increasing taxes) are put off until after the election day. A decision-maker in the private sector does not have this built-in time cycle and he/her decisions can be geared more to the long-term.

The third difference is that, when making decisions, a decision-maker in the public sector places greater importance on social criteria such as the proper use of public resources, effectiveness (the attaining of goals and objectives) and equity (the fair distribution of the benefits) than about the project's profitability.

Organizations in the private sector are normally structured with clear lines of authority and can reduce bureaucratic inefficiencies by firing and reorganization if necessary. Organizational structures in the public sector are more complicated. It sometimes can be difficult to keep track of who is charge of certain situations. In the private sector, although a decision may involve a number of departments, the management makes the final decision. In the public sector, decisions can involve a variety of groups (both internal and external groups), and each of the groups has the potential to cause the project to fail. Bureaucracy in public agencies also makes their decision-making processes less efficient.

2.2.3 Project planning in a multi-project environment

In a multi-project environment, projects are interrelated directly or indirectly by their clients, business objectives, financing, resources, environment and/or implementation (Abdullah and Vickridge 1999). In other words, projects are not independent of each other and there may exist different types and degrees of interdependencies among them. Previous studies (e.g., Aaker and Tyebjee 1978; Gear and Cowie 1980; Fox et al. 1984) have identified four commonly-seen types of project interrelationships: (1) outcome (or technical) interrelationships, (2) resource-utilization interrelationships, (3) impact (or benefit) interrelationships, and (4) serial interrelationships. Outcome interrelationships among projects occur if a project's outcome (e.g. the probability of success of a given project) depends on other projects' outcomes. Resource-utilization interrelationships exist among projects if the total amount of resource utilization cannot be represented as the sum of individual projects' resource utilizations. Impact (or benefit) interrelationships among projects occur if the total impacts (or payoffs) of these projects do not equal to the sum of those of individual projects. Serial interrelationships occur when projects need to be implemented in sequence.

These project interrelationships can significantly influence a project's performance. Take the resource-utilization interrelationship as an example. Consider that Project A and Project B need to share the same resources. Due to the limitation on the amount of the resources, the two projects need to be implemented in sequence: first Project A and then Project B. In this case, if Project A is not completed on time, Project B will be delayed due to resource unavailability.

Resource-utilization interrelationships can however also result in time and/or cost savings. For example, consider that a machine is purchased for the implementation of Project A. If this machine can also be shared by other projects, the total cost of each project can be reduced. Another example is that if the information collected for a project (e.g., market research report) can be reused in other similar projects, the individual projects' costs can be decreased.

Project planning in such a multi-project environment represents significant challenges to project managers (Abdullah and Vickridge 1999). Among these challenges, project scheduling and resource allocation are the two biggest ones (De Maio et al. 1994; Payne 1995; Eskerod 1996; Levy and Globerson 1997; Platje and Seidel 1993). A proper consideration of project scheduling and resource allocation taking into account project interdependencies is therefore critical in planning a project in a multi-project environment.

2.2.4 Project estimating

Forecasting how long a project will take to complete and the cost to carry out the project is essential to effective project planning (Morris and Pinto 2004). There are a number of techniques that can be used to estimate project schedule and cost. Extensive review of these techniques is beyond the scope of this research. This section focuses only on techniques that are applied in this research.

2.2.4.1 Project scheduling: the Critical Path Method (CPM)

The Critical Path Method (CPM) is a project scheduling technique that has been widely employed in the construction industry (Meredith and Mantel 2003). Steps in CPM typically involve: (1) specify the individual activities; (2) determine the sequence of those activities; (3) draw a network diagram; (4) estimate the completion time for each activity; (5) identify the critical path which is the longest path through the network; (6) update the CPM diagram as the project progresses. Introduction to each of these steps can be found in a variety of project management-related literature.

CPM can be applied to multi-project scheduling (Meredith and Mantel 2003). It also shows the potential for managing project interdependencies. Consider that a project manager is developing the schedule of Project A. Consider further that the schedule of Project A is dependent on the progress of other two projects: Project B and Project C. Following the above described CPM steps, the project manager can first divide each of the projects into project phases and determines the sequence of those phases. He/she can then develop a single network diagram that connects these projects based on their interdependencies, as shown in Figure 2.2. Next, the project manager can estimate the duration of each of the project phases, and determine the impacts caused by the interdependencies on the estimated project schedule. In order to effectively manage project interdependencies, the project manager also needs to determine the types, the degree and precedence relationships of the project dependencies. Detailed descriptions of these three dimensions of project interdependencies and the structured procedure to evaluate project interdependencies can be found in Chapter 6.

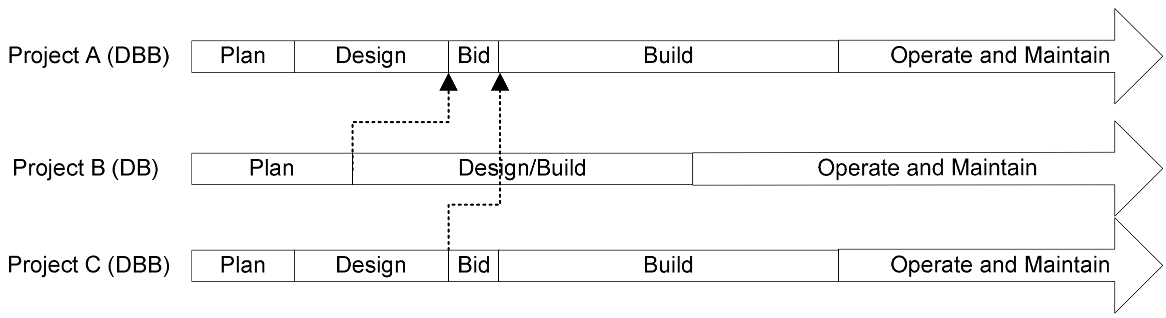


Figure 2.2 A sample project interdependency diagram

2.2.4.2 Cost estimating

Several types of methods are available for project cost estimating. These methods are varied in the information required for estimating and the accuracy of their estimates (Kerzner 2003). In the project planning phase, the project scope is often not clearly defined and the detailed project information (e.g., project design and construction plan) is not available. In this case, methods that require detailed project data are not suitable. Three types of estimating methods that can be applied in the project planning phase are: (1) expert opinion; (2) order-of-magnitude; and (3) analogy estimates. Brief descriptions, accuracy of estimates and advantages and disadvantages of these three types of methods are summarized in Table 2.1. In the project planning phase, cost estimates should consider total project life-cycle cost instead of the initial capital investment.

Table 2.1 Suitable cost estimating methods in project planning phase

Estimating methods	Description	Advantages	Disadvantages	Accuracy
Expert opinion	Estimates are made based on an expert's knowledge and experience.	• Available when there are insufficient data, parametric cost relationships, or past similar projects.	• Subject to bias • Increased project complexity can degrade estimates • Estimate substantiation is not quantifiable	Vary from expert to expert
Order-of-magnitude	Estimates are made based on past experience (not necessarily similar), scale factor， parametric curves or capacity estimates.	• Application is simple and low cost • Statistical database can provide expected values and prediction intervals • Can be used prior to detail design	• Requires parametric cost relationship to be established • Depends on quantity and quality of the data • Limited by data and number of independent variables	±35%
Analogy estimates	Estimates are made based on previous projects that are similar in scope and capacity.	• Relatively simple • Low cost • Emphasizes incremental project changes • Good accuracy for similar projects	• Requires analogous project information • Limited to commonly seen projects • May be limited to projects developed by the same company	±15%

Source: adapted from (Kerzner 2003)

2.2.4.3 Time/cost trade-off analysis

Time/cost trade-off analysis has long been a critical issue in project management. Many researchers have devoted considerable effort towards the development of systematic methods for solving time/cost trade-off problems. These methods can be categorized into three areas: (1) heuristic methods (e.g., Simens 1971; Moselhi 1993), (2) mathematical programming models (e.g., Kelly 1961; Burns et al. 1996; Elmagraby 1993), and (3) genetic algorithms (e.g., Feng et al. 1997; Li and Love 1997; Hegazy 1999). Despite the differences in their theoretical assumptions and methodological procedures, these methods share one assumption: project time and cost are conflicting with each other; and an increase in one of them corresponds to a decrease in the other. Howell et al. (2001) provided a new insight into this time/cost trade-off dilemma. They argued that by reducing variation in work flow, project performance can be improved which can result in a reduction in project duration and/or cost (to be discussed in more detail in the following section).

While these methods provide a decision-maker with more objective and systematic ways to solve time/cost trade-off problems, their applicability to time/cost trade-off analysis in the project planning phase is limited for two reasons. First, these methods require detailed project activity information to perform time/cost trade-off analysis; and such information is not available in the project planning phase. Additionally, the time/cost trade-off decisions in the project planning phase need to be considered from the project life-cycle perspective. The currently available time/cost trade-off analysis methods however focus mainly on the trade-offs in the construction phase. The differences between time/cost trade-off decisions in the project planning and construction phases are discussed in more detail in Section 5.2.

2.2.5 Project planning and system variation

Wait time and work flow variation. Howell et al. (2001) argued that variability in a system can negatively affect the project performance (e.g., increase the length of the project). Projects are a complex web of activities fed by supply chains. If there is variation in the release of work from one internal or external supplier to the next, increasing capacity utilization will increase the length of the project (wait time or cycle time) and increase work-in-process. The variability may be in processing times at each station, and/or in the arrival time of inputs from upstream. When the processing unit is running near its maximum capacity, the impact of increasing variability is more significant. This is so because the crew will have little slack time, and will be unable to respond to early deliveries.

Ideally, a crew in the system should get the job done on schedule and release work to the next crew with no delay. However, the variation in arrival times and/or work processing times is still possible. Figure 2.1 illustrates a situation where the start time of a task is related to the variable finish time of the prerequisite work. In this case there is a distribution of completion times of the prerequisite work around an average. If the following crew arrives at "Time A," there is a possibility that the prerequisite work is not completed. When this occurs, the crew's productivity will be diminished. In another scenario, the project manager could instruct the crew to arrive at "Time B," which is the most likely time for the advance work to be completed. Under this circumstance however, the length of the project becomes longer. By reducing the work flow variation, the project performance can be improved.

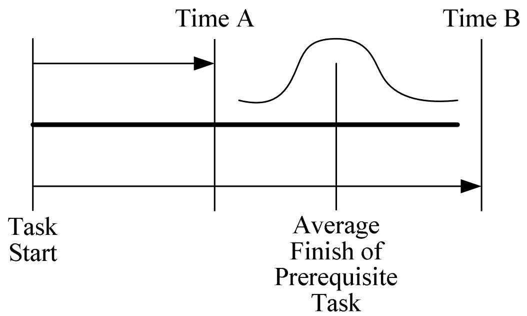


Figure 2.3 Arrival time for following crew (source: adopted from Howell et al. 2001)

This suggests that the method of managing the project is another critical variable that should be included in designing a project delivery system. Unfortunately, the industry assumes, for the most part, that there is only one way of managing a project, so misses opportunities such as variation reduction and the consequent improvement in project performance.

Implication to the management of project interdependencies. A multi-project environment can also be viewed as a system with a web of projects. Projects are linked, directly or indirectly, to each other by different types of interdependencies. In such an environment, a project's performance will be affected by its interrelated projects. For instance, if a project cannot obtain the required information from its interrelated projects, the project's schedule will be negatively affected. Project interdependencies are the major sources of variation in this system. Even though it is not possible (nor feasible) to accurately identify all project interdependencies and predict their impacts in the early project planning phase, a consideration of this issue can still improve the quality of the project planning.

2.3 The PDS Decision-making Problem

2.3.1 Alternative PDSs: DBB, DB, CMR and DBOM

Many PDSs are available to public agencies for infrastructure development. Each of them can have several variants. The aim of this section is not to review all available PDSs, but to discuss some commonly used ones and to highlight the point that PDSs are different in several aspects. As DBB, DB and CMR are three primary PDSs considered in this research, they are included in this review. Design-build-operate-maintain (DBOM) is also included because it has also been used to develop some infrastructure projects (e.g., Hudson-Bergen Light Rail project in the US).

2.3.1.1 An overview of alternative PDSs

This section reviews basic concepts and characteristics of four PDSs (contract structures). The results are summarized in Table 2.2.

Design-Bid-Build (DBB). DBB is usually referred to, within the industry and literature, as "the traditional method." In DBB, a project owner contracts separately with a designer and a contractor to design and build a facility. The finance, operation and maintenance of the project remain the owner's responsibilities. With a sequential process involving separate phases, this PDS is known for its lengthy delivery time and its potential to foster adversarial relationships between participants (Konchar and Sanvido 1998; Masterman 2002). However, DBB also has some benefits. It enables the project owner to have a well-defined project scope and an intense price competition during the tendering phase. DBB has been authorized in almost all countries for developing a variety of infrastructure projects.

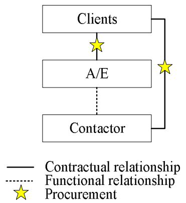
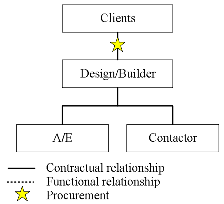
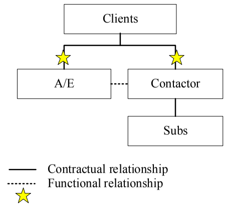
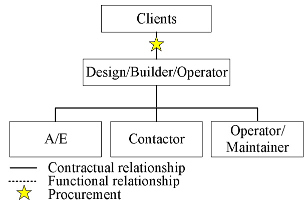
Construction Management at Risk (CMR). In CMR, a project owner contracts with a designer to provide design services. The project owner further contracts with a contractor for providing construction consulting service in the design phase. This contractor then takes on the roles and responsibilities of the traditional general contractor during the construction phase, holding all trade subcontracts and assuming risks associated with timely completion. CMR has several advantages to the project owner (Konchar and Sanvido 1998). First, the contractual alignment between owner and contractor can greatly reduce the probability of an adversarial relationship.

The early engagement of the contractor in the design phase can also increase the feasibility and constructability of the design. CMR is also expected to provide the project owner an early knowledge of project cost. The use of CMR is not fully authorized by all governments. For example, as of 12/2006, only a total of 14 states fully authorized their DOTs to use CMR in their transportation projects. In another 5 states, CMR can only be used after acquiring an extra approval or within the limitations in each fiscal year (Ghavamifar and Touran 2008).

Design-Build (DB). In DB, a project owner holds a contract with a single entity for both design and construction works. The owner still assumes the responsibilities of financing, operating and maintaining the project. Having a single entity responsible for project design and construction, DB can eliminate the potential for adversarial relationships such as those in DBB. DB can also reduce the overall project delivery time. For example, a DB project at least 33.5% faster than a DBB project (Konchar and Sanvido 1998). Projects with tight schedules, clearly-defined scopes, and standard and repetitive designs are all good candidates for this PDS (Mulvey 1997; Songer and Molenaar 1997; Konchar and Sanvido 1998). Unlike DBB, DB has not been fully authorized by some governments. However, its importance has been increasingly recognized and its acceptance is also increasing (Pietroforte and Miller 2002). For example, as of 12/2006, a total of 37 states in the US had either fully or partially (requiring an extra approval or on a pilot basis) authorized their Departments of Transportation (DOTs) to apply DB to their transportation projects (Ghavamifar and Touran 2008).

Design-Build-Operate-Maintain (DBOM). DBOM differs from DB in that it further integrates project operation and maintenance into a single contract. In other words, in addition to designing and building the project, a contractor is also granted the right to operate and maintain the constructed facilities for a time period. In DBOM, projects are still financed and owned by public agencies. Benefits of DBOM include that it enables public agencies to transfer a project's operation and maintenance risks to a private contractor and minimizes a project's life-cycle cost (Dahl et al. 2005). The use of DBOM for infrastructure development is not as common as DBB and DB. However, examples can still be found, such as the Hudson-Bergen Light Rail Transit System (HBLRTS) project in New Jersey, US.

Table 2.2 Characteristics of alternative PDSs: DBB, DB, CMR and DBOM

DBB	DB	CMR	DBOM
			
Pros: • Intensive price competition • Easy to tender • A higher degree of certainty • Distinctive roles Cons: • Lengthy process • Potential cost overruns • Potential adversarial relationships • Clients retain most risks	Pros: • Integration of design and build • Improved communication • Potential cost and time savings • Some risks transferred to the design-builder Cons: • Limited competition • Difficulty in tendering • Client's control over the project is lesser	Pros: • Reduced probability of an adversarial relationship between the owner and contractor • Increased feasibility and constructability of the design • An early knowledge of project cost Cons: • Legal issue in public contracting • CM is acting as the general contractor, not as the owner's representative • CM effort may add cost	Pros: • Integration of project life-cycle activities • Improved communication • Incentives for innovation • Potential cost and time savings • Most risks transferred to the private entity • Better project life-cycle costs Cons: • Limited competition • Difficulty in tendering • Client's control over the project is lesser.

2.3.1.2 A qualitative comparison

These four contract structures, commonly referred to as PDSs, are compared on how responsibilities and risks are allocated between a public agency and a contractor (as summarized in Tables 2.3 and 2.4), and on the characteristics of their tendering processes (as summarized in Table 2.5). A few things should be noted about Tables 2.2 and 2.3. First, although the term "contractor" is used, the contractor in DB and DBOM may be a consortium of multidisciplinary members. Second, Tables 2.3 and 2.4 are intended to present a general view about how responsibilities and risks are allocated between the public agency and the contractor in different PDSs. In real projects, the responsibility and risk allocations may be different from those in the tables depending on the provisions of the contract(s). Finally, in cases where both parties may share risks and responsibilities, the primary responsibility- and risk-taker are indicated.

Responsibility Allocation. The responsibility allocations between a public agency and a contractor in different PDSs are illustrated in Table 2.3. Unlike DBB and CMR, which is a segmented and sequential process, DB and DBOM integrate project phases into a single contract to varying degrees. In DB, design and construction responsibilities are integrated and assigned to a single contractor. In DBOM, two additional responsibilities, project operation and maintenance, are added to the contract. This integration of project phases offers the public agency several potential benefits (Garvin 2003, Dahl et al. 2005). First, it encourages innovation and reduces project delivery time and cost. It also allows some risks to be transferred from the public agency to the contractor. Furthermore, it may deliver more efficient and higher quality public services.

Table 2.3 Responsibility allocation in alternative PDSs

Responsibility	DBB		CMR		DB		DBOM	
	P	C	P	C	P	C	P	C
Finance	√		√		√		√	
Planning	√		√		√		√	
Design	√[1]		√[2]			√		√
Construction		√		√		√		√
Operation	√		√		√			√
Maintenance	√		√		√			√

P: Public Agency; C: Contractor

[1]It is the public agency's responsibility to provide design documents in DBB. This work can be done either by in-house or outside specialists.

[2]The design work can be performed wither by the public agency's in-house staff or outside specialists. The contractor is responsible for providing consulting on the feasibility and constructability of the design.

Risk Allocation. Risks involved in the entire project life-cycle can be grouped into five categories: (1) design, (2) construction, (3) operation, (4) market, (5) financial, and (6) political risks (Li et al. 2005). Table 2.4 illustrates how these risks are allocated between a public agency and a contractor. While this table is not sophisticated enough to represent all possible conditions in the real world, it gives a general idea about the degrees of risk assumed by the public agency and the contractor in different PDSs.

In DBB and CMR, the public agency assumes almost all the risks, except the construction risk. The degree of risk carried by the public agency decreases as the PDS moves from DBB to CMR, DB and DBOM, as shown in Figure 2.4. In DBOM, the public agency assumes the lowest degree of risk, while the contractor assumes the highest level of risk. Political risks, in all PDSs, are best born by the public agency as it is beyond the realm of the contractor.

Table 2.4 Risk allocation in alternative PDSs

Risk Category	Examples of Risk Factors	DBB		CMR		DB		DBOM	
		P	C	P	C	P	C	P	C
Design Risks	Design deficiency; delay in project approval and permits, etc.	√		√			√		√
Construction Risks	Construction cost overrun; delays in completion; material/labor availability, etc.		√		√		√		√
Operation Risks	Operational and maintenance cost overruns; low operating productivity, etc.	√		√		√			√
Political Risks	Change in legal and political administrative systems, etc.	√		√		√		√	
Financial Risks	Availability of finance; high finance costs; fluctuations in currency exchange rates and interest rates, etc.	√		√		√		√	
Market Risks	Demands lower than expected; prices are set too low, etc.	√		√		√			√

P: Public Agency; C: Contractor

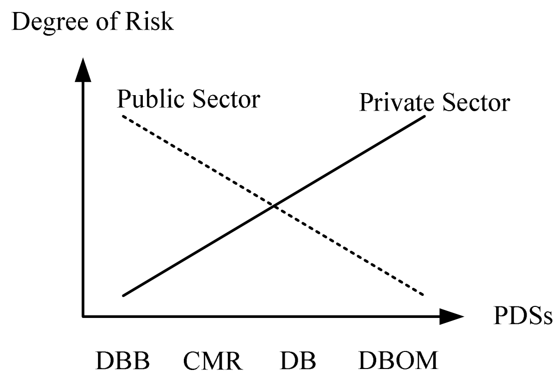


Figure 2.4 Conceptual degree of risk borne by the public and private sectors

Characteristics of Tendering Processes. The discussed PDSs also vary in the characteristics of their tendering processes. These differences are summarized in Table 2.5 and in the discussion below.

- *Contract period.* DBOM generally has a longer contract period than the other three PDSs. For example, the contract period for the HBLRTS project is 15 years (FHWA 2008).

- *Level of competition.* Because of the larger scale and the higher complexity of DB and DBOM projects, very often, only a limited number of contractors are qualified and available. In other words, the levels of competition in these two PDSs are lower than in DBB and CMR.

- *Contracting specifications.* Different specification methods, such as prescriptive specifications and performance-based specifications, are used to specify construction contracts in different PDSs. The prescriptive specifications, in which the public agency provides detailed guidance for the method and materials, are commonly used in DBB. In CMR, either prescriptive or performance-based specifications can be used depending on the owner's needs and the degrees of the design completed when the construction contract between the owner and the contractor is established. In DB and DBOM, the performance-based specifications are normally used to allow flexibility in selection of the best solutions for the project (Koppinen and Lahdenpera 2004). Under such specifications, the public agency specifies only the desired results rather than the specific methods to be used to accomplish these results. Definitions of these two types of specifications can be found in Transportation Research Board (1999).

- *Tender selection method.* In DBB, a contractor is often selected on the basis of a low bid. This price-only evaluation has been questioned for its tendency to cause poor project performance and encourage an underpriced bid. In CMR, the general contractor is generally selected based on its qualification. However, most public CMR laws require competitively bidding out the construction trade subcontract work packages. In this case, the project owner can get the advantage of price competition in the subcontract work packages combined with the qualifications-based selection of the general contractor (Touran et al. 2009). In DB, the tender selection can be based on price, on technical and quality assessment, or on a combination of price and quality (Molenaar et al. 1999). Value-based approaches are normally used in DBOM. In value-based approaches, tender proposals are evaluated against a pre-determined set of criteria.

- *Tender selection process.* Tendering costs in DB and DBOM projects are generally higher than in DBB and CMR. For example, Birnie (1997) found that, in the United Kingdom, tendering costs in DB projects (0.18-0.32%) are higher than in DBB projects (0.04-0.15%). To ensure that weaker tenders do not incur unnecessary tendering costs, a multistage tender selection process composed of the tender prequalification and proposal evaluation is often used in DB and DBOM.

Table 2.5 Characteristics in tendering processes of alternative PDSs

	DBB	CMR	DB	DBOM
Contract Period	Short-term	Short-term	Short-term	Long-term
Level of Competition	Higher	Higher	Limited	Limited
Contracting Specifications	Specification-based	Specification-based or performance-based	Performance-based	Performance-based
Tender Selection Method	Price-based (low bid)[1]	Price-based for subcontractors; Qualification-based for general contractor	Price-based, or Price/Quality-based, or Technical/Quality-based	Value-based
Tender Selection Process	Single-stage	Single stage	Single-stage or Multi-stage	Multi-stage

[1]In some cases, qualitative non-price factors, such as project completion time, and warranty period, may also be taken into account in the tender selection.

2.3.2 A PDS decision-making problem in a multi-project environment

The problem of designing and choosing a PDS has three general characteristics. First, it involves consideration of different PDS alternatives (e.g., DBB, DB and CMR in this research). These PDSs vary on several aspects. A PDS that can achieve certain project objectives better than others may also perform worse on some other objectives. This means that no single PDS is appropriate for all types of projects under all circumstances. Second, a PDS decision requires consideration of a variety of factors, which can be categorized into: (1) client's objectives (e.g., within-budget completion and on-time completion), (2) project characteristics (e.g., project type and size), and (3) external environment (e.g., market's competitiveness, and experienced contractor availability). A complete list of these factors and their descriptions can be found in Alhazmi and McCaffer (2000), Ambrose and Tucker (1999), and Luu et al. (2003a), etc. The variety of these factors and the interrelationships among some of the factors (e.g., a conflicting relationship between time and cost) further complicates the PDS decision-making problem. Third, a PDS decision often involves great uncertainty because it is made at the early stage of a project, a time when only limited information is available.

In addition to all the above characteristics, a PDS decision-making problem in a multi-project environment has one further characteristic: the existence of complex project dependencies. Projects are more or less interrelated with each other in the multi-project environment. These relationships can significantly affect project performance, and hence should be taken into account in the PDS decision-making process. Evaluating these project dependencies can be difficult considering that projects are different in their goals, scopes and physical conditions, and at different stages of completion. A procedure (see Chapter 6) is integrated into the proposed PDS decision-support framework to assist a decision-maker in considering project dependencies in their PDS selection processes.

2.3.3 Timing of the PDS decision-making

In practice, PDS decisions are mostly made in early project phases. For example, through a survey of 62 clients in 1994, Materman (2002) found that approximately 77% chose a PDS within the inception or feasibility stages (53% in the inception stage and 24% in the feasibility stage). 18% made their decisions during the outline design stage, and only 5% determined a PDS during the detailed design stage. As previously discussed, information available at these early project phases can be limited and imprecise. This makes a PDS decision-making difficult.

2.3.4 Factors affecting a PDS decision

Factors affecting PDS selection have been identified in various studies. Touran et al. (2009) identified a total of 24 factors and categorized them into: (1) project-level (e.g., schedule and cost); (2) agency-level (e.g., agency experience and agency goals and objectives); (3) public policy-regulatory (e.g., federal/state/local laws); (4) life-cycle (e.g., maintainability); and (5) others (e.g., construction claims). Luu et al. (2003a) identified three groups of factors including: (1) client's characteristics and objectives (e.g., client's requirements for within-budget completion, and for on-time completion); (2) project characteristics (e.g., project type and size); and (3) external environment (e.g., market's competitiveness, and experienced contractor availability). Detailed factors within each category are listed in Table 2.6. They also ranked the identified factors based on an empirical survey with clients and project managers in Australia.

The most important five factors are: (1) client's requirement for with-in budget completion; (2) client's requirement for on-time completion; (3) client's requirement for value for money; (4) project type; and (5) project size. Natural disasters, cultural differences, inclement weather, objection from local lobby groups and objection from neighbors are, on the other hand, the five least important factors.

Table 2.6 List of PDS selection parameters

PDS selection factors	Ranking
Client's characteristics and objectives	
Client's requirement for within-budget completion	1
Client's requirement for on-time completion	2
Client's requirement for value for money	3
Client's willingness to take risks	7
Client's trust toward other parties	9
Client's experience	12
Client's willingness to be involved	13
Client type	14
Client's in-house technical capability	16
Client's requirement for low operational cost	17
Client's requirement for low maintenance cost	18
Client's financial capability	18
Client's requirement for highly serviced or technically advanced building	20
Client's requirement for aesthetic building	24
Project characteristics	
Project type	4
Project size	5
Known site factors likely to cause problems	10
Building construction type	15
Unknown site risk factors	23
Usage of pioneering technology	27
Project site location	29
External environment	
Market's competitiveness	6
Experienced contractor availability	8
Technology feasibility	11
Regulatory feasibility	21
Materials availability	22
Political constraints	25
Industrial actions	26
Labor productivity	28
Objection from neighbor	30
Objection from local lobby groups	31
Inclement weather	32
Cultural differences	33
Natural disasters	34

Source: adapted from Luu et al. (2003a).

2.3.5 PDS selection process

In practice, a decision-maker tends to make a PDS decision intuitively or, in general terms, not in a structured way (Cheung et al. 2001; Luu et al. 2003b). Masterman (2002) concluded that a PDS selection process often starts with: a lack of understanding of the decision situation;

minimum knowledge of alternative PDSs; and very little idea of how to evaluate them and make the final choice. Such an unstructured decision-making process may increase the chance that an inappropriate PDS is selected. This can impede the realization of certain anticipated benefits associated with the chosen PDS and lead to project failure (Rwelamila and Meyer 1999).

Some researchers and institutions have recognized the importance of having a systematized decision-making process and have outlined formalized PDS decision-making procedures. For instance, the HM Treasury's Central Unit on Purchasing (1992) suggested a six-step process for determining a PDS. A guide prepared by a joint committee of Airports Council International-NA (ACI-NA), Airport Consultants Council (ACC) and the Associated General Contractors (AGC) of America divided the project delivery process into four steps including to: (1) examine the ability to use alternative PDSs; (2) establish a list of PDSs; (3) select an appropriate PDS; and (4) implement the selected PDS. Sanvido and Konchar (2005) developed a framework integrating a series of questions that a decision-maker needs to answer in order to choose an appropriate PDS and deliver a facility.

Though varying in details, the proposed procedures have four fundamental steps (as illustrated in Figure 2.5) including to: (1) identify clients' objectives; (2) search for alternative PDSs; (3) evaluate alternative PDSs; and (4) implement the selected PDS. The entire decision-making process requires inputs such as project characteristics, clients' experiences with particular PDSs and past project performance. It is constrained by market conditions, regulations and the agency's policies. The ultimate outputs will be efficient and high quality infrastructure services. In the next section, some PDS selection methods are reviewed.

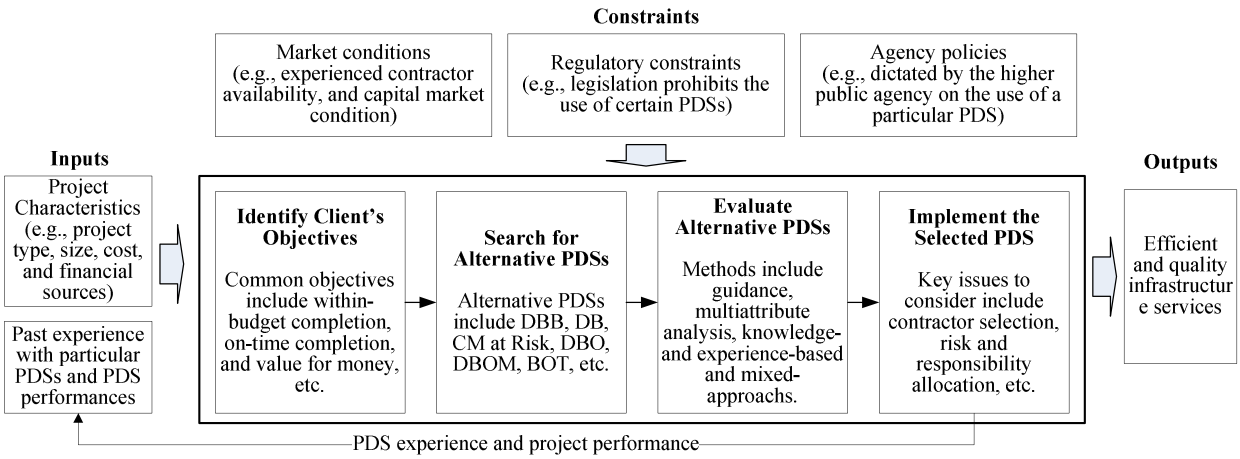


Figure 2.5 A PDS decision-making process

2.4 Available PDS Selection Methods

2.4.1 Overview of available PDS selection methods

There are many PDS selection methods. For better presentation, these methods are classified into four major groups on the basis of their underlying concepts. They are: (1) guidance, (2) multi-attribute analysis, (3) knowledge- and experience-based, and (4) the mix-method approaches. Table 2.7 shows the methods, within each group, that will be discussed in this section, along with their reference sources. Presentation of the specific methods will focus on their fundamental concepts, merits and limitations.

Table 2.7 Discussed PDS selection methods and their reference sources

Category	Methods	Selected References
Guidance	Individual PDSs	Songer and Molenaar (1996); Molenaar and Songer (1998); Beard et al. (2001); Chan et al. (2002); Gransberg et al. (2006).
	Comparison of alternative PDSs	Construction Industry Institute (1997); Konchar and Sanvido (1998); National Institute of Standards of Technology (2002); Ibbs et al. (2003).
	Formalized framework and guidelines	HM Treasury's Central Unit on Purchasing (1992); Sanvido and Konchar (2005); A joint committee of ACI-NA, ACC and AGC (2006).
	Decision charts	Construction Round Table (1995).
Multi-attribute Analysis	Weighted sum approach	Franks (1990); the HM Treasury's Central Unit on Purchasing (1992).
	Multi-attribute utility theory (MAUT)	Skitmore and Marsden (1988); Love et al. (1998); Cheung et al. (2001); Construction Industry Institute (2003); Oyetunji and Anderson (2006).
	Analytical hierarchical process (AHP)	Al Khalil (2002).
	Fuzzy logic approaches	Ng et al. (2002); Chan (2007).
Knowledge-/ experience-based methods	Case-based reasoning approach (CBR)	Luu et al. (2003b; 2005; 2006).
	Decision support system	Kumaraswamy and Dissanayaka (2000).
Mixed-method approaches	AHP/value engineering (VE)/multicriteria multiscreening	Alhazmi and McCaffer (2000).
	AHP/mean utility values	Cheung et al. (2001).
	MAUT/project database	Ng and Cheung (2007).
	A qualitative assessment/a weighted score approach	Touran et al. (2009).

2.4.1.1 Guidance

The word "guidance" is defined as "something that provides direction or advice as to a decision or course of action (WordNet, Princeton University)." Studies of individual and multiple PDSs, formalized PDS decision-making frameworks, guidelines and decision charts/matrix are methods of this kind as they provide general information about different PDSs and important rules for selecting an appropriate PDS. Studies focusing on individual PDSs, especially on design-build (DB), are many. For example, Beard et al. (2001) and Gransberg et al. (2006) examined different aspects of DB and discuss its suitability for particular types of projects. Other studies on DB can be found in Molenaar and Songer (1998), Chan et al. (2002) and Songer and Molenaar (1996), etc. Even though such studies provide deeper insights into a particular PDS, additional information is needed when choosing between a variety of PDSs. Many researchers/institutions therefore take a step further to compare performance of different PDSs. For instance, Konchar and Sanvido (1998) compared performance of design-bid-build (DBB), DB and construction manager-at-risk (CMR) with respect to a set of criteria (e.g., cost growth, construction speed and schedule growth). Ibbs et al. (2003) compared DBB with DB in terms of their performance on cost, schedule and productivity.

Similar comparison studies can also be found in various industry studies, such as Construction Industry Institute (1997) and National Institute of Standards of Technology (2002). These studies increase a decision-maker's understanding of performance differences between different PDSs. However, they are often limited to particular types of projects or performance measures. An example of a decision chart, which illustrates different PDSs' abilities to satisfy a set of project objectives, can be found in *Thinking About Building* (Construction Round Table, 1995). These charts and guidelines provide a decision-maker a brief and comprehensive profile of alternative PDSs. However, it itself is insufficiently sophisticated to allow a clear-cut decision to be made (Masterman 2002).

2.4.1.2 The multi-attribute analysis

The selection of a PDS is a multiple criteria decision-making problem. Many researchers have therefore based their methods on the multi-attribute analysis, which is an approach in which alternatives are evaluated with respect to multiple evaluation criteria. On the basis of how a decision-maker's preferences over different PDSs are elicited and measured, these methods can be classified into four groups: (1) the weighted sum, (2) the multi-attribute utility/value theory (MAUT/MAVT), (3) the analytical hierarchical process (AHP), and (4) the fuzzy logic approaches[1].

A weighted sum approach. A weighted sum approach typically consists of two steps. First, each PDS is scored on a numerical scale (e.g., 1-5 or 1-7) on the basis of its ability to satisfy evaluation criteria. A higher score normally represents a better performance, and a lower score indicates a worse performance. Next, weights are assigned to evaluation criteria to reflect their relative importance. The weighed scores of different criteria are then summed to obtain an overall score for the PDS. A PDS with the highest overall score is considered as the most appropriate one for the specific project. Detailed information about this type of approach can be found in Franks (1990) and the HM Treasury's Central Unit on Purchasing (1992).

Because its underlying concepts and calculation process are straightforward and easy to apply, the weighted sum approach can be a very useful screening tool to reduce the possible PDSs to a manageable number. However, the scores and weights are subjective and may vary widely from one decision-maker to another. Exclusive use of this approach is therefore not recommended.

Multi-attribute utility theory (MAUT). Several researchers (e.g., Skitmore and Marsden 1988; Love et al. 1998) apply MAUT to tackle the PDS decision-making problem. In MAUT, a decision-maker first defines utility functions for evaluation criteria, one for each criterion. He/she then uses these utility functions to derive a PDS's utility scores with respect to different criteria. Next, the decision-maker assigns weights to individual criteria to reflect their relative importance. Utility scores of different criteria are then weighted and summed to produce a global utility score for a PDS. A PDS with the highest utility score is considered the most appropriate one.

[1]Another method for multi-attribute analysis, Choosing by Advantages (Suhr 1999), is not included here for lack of references in the literature, but is becoming more frequently used in Integrated Project Delivery projects (Ballard 2008), and claims to be a superior method. Rigorous assessment of that claim has not yet been done.

Although MAUT allows a decision-maker to choose a PDS in a more objective manner, it has several limitations. First, MAUT uses utility functions to elicit a decision-maker's preferences. When a group of decision-makers is involved, the process to derive utility functions can become very cumbersome, time consuming and incorrect (Ibbs and Crandall 1982). The many types of utility functions (e.g., linear or non-linear) and ways to aggregate individual utility functions (e.g., additive or multiplicative aggregation) further compound the difficulty in determining suitable utility functions and obtaining an overall utility score.

To overcome this difficulty, several assistance tools and simplified methods are developed. For instance, Love et al. (1998) and Cheung et al. (2001) developed a set of mean utility values of criteria for alternative PDSs. This can provide a decision-maker a convenient way to calculate utility scores and to avoid his/her subjectiveness in determining the scores. Oyetunji and Anderson (2006) proposed a simple multi-attribute rating technique with swing weights (SMARTS), in which a linear value function, instead of a utility function, is used. SMARTS uses a numerical scale of 0-100 is used where 0 and 100 represent the worst and best performance respectively. These two points are joined by a straight line. All PDSs are then positioned on this straight line to reflect their performance relative to the two reference points. This same concept is also found in the PDS decision support tool developed by Construction Industry Institute (2003). The linearity assumption of a linear value function in such method however can be oversimplified, and hence may generate misleading answers (Belton and Stewart 2002).

Analytical hierarchical process (AHP). As with MAUT, the initial steps of AHP are to develop a hierarchy of criteria and to identify all possible alternatives. It differs from MAUT primarily in how a decision-maker's preferences are elicited, measured and presented (Guitouni and Martel 1998). AHP employs a pairwise comparison procedure, which requires a decision-maker to compare all alternatives with respect to evaluation criteria in turn. The decision-maker's preferences are presented in a ratio scale (e.g., 1/3 or 3) and are combined into an overall rating. An application of AHP to the PDS decision-making problem can be found in Al Khalil (2002).

AHP has two important advantages (Belton and Stewart 2002). First, it allows the problem to be broken down into hierarchical levels, which assists a decision-maker to develop detailed insights about the problem they intend to solve. In addition, the pairwise comparison procedure enables the decision-maker to make his/her judgment in a systematic manner. However, AHP has been criticized because of its inability to adequately deal with uncertainty and a lack of sound statistical theory (Belton and Stewart 2002). It is also limited in that, when the number of considered criteria and alternatives increases, the number of judgments that the decision-maker needs to make will significantly increase.

Fuzzy Logic Approach. Ng et al. (2002) argued that certain PDS evaluation criteria (e.g., flexibility, responsibility and quality level) are fuzzy (linguistic) in nature, which means that they are difficult to be defined by numeric values. Believing that previous PDS selection methods do not adequately address this fuzziness issue, they established the membership functions of those fuzzy criteria through an empirical study. A membership function is a function that maps a criterion to a degree of membership (0 to 1) in a fuzzy set, where 1 means that the criterion is a member of the set and 0 means that it is not. These functions can then be used to convert a decision-maker's preferences expressed in linguistic terms (e.g., high, medium, and low) to numeric values. The concepts and underlying assumptions of the fuzzy logic theory and its applications in construction industry can be found elsewhere (e.g., Paek et al. 1992; Carr and Tah 2001). Chan (2007) extended Ng et al.'s work to develop a fuzzy PDS selection model by incorporating fuzzy relation rules and weights of selection criteria.

The major advantage of the fuzzy logic approach is that it allows a decision-maker to convey his/her preferences in linguistic terms. However, the method has drawbacks. First, the extraction of fuzzy membership functions and fuzzy relation rules requires professional knowledge and skills. The process is also effort and time consuming, especially when it involves a group of decision-makers. If more than one decision-maker is involved in the process, different perceptions about the same linguistic term may cause confusion. Weighting the influence of the different decision-makers is also a problem.

2.4.1.3 Knowledge- and experience-based methods

Given that a decision-maker's past experience is one important influential factor in selecting a PDS (Masterman 2002), some researchers have developed their methods on the basis of knowledge- and experience-sharing concepts. Luu et al. (2003b; 2005; 2006) used a case-based reasoning approach (CBR) to formulate PDS selection criteria and to develop a case-based procurement advisory system. The system utilizes experiences from previous projects and knowledge of experts to provide a decision-maker an early indication of the likely future outcomes of a new project. A similar concept can also be found in the decision support system for building project procurement developed by Kumaraswamy and Dissanayaka (2000).

Although this method can assist a decision-maker with his/her PDS choices, several challenges remain. First, for such a method to be effectively implemented, a case database that stores a number of well-documented real word projects is required. Unfortunately, in the construction industry, such a database rarely exists. Even if such a database were available, experiences and solutions to problems retrieved from previous projects may not be applicable to the current projects because each construction project is unique, and, in many cases, differences exist between previous and current projects.

2.4.1.4 Mixed-method approaches.

Instead of focusing on a single approach, some researchers combine multiple methods to solve the PDS decision-making problem. For example, Alhazmi and McCaffer (2000) proposed a Project Procurement System Selection Model (PPSSM), which integrates AHP and Value Engineering (VE) into a multi-criteria multi-screening system. Cheung et al. (2001) established mean utility values of PDS selection criteria for different PDSs and used AHP to determine the relative importance of different criteria. Ng and Cheung (2007) integrated MAUT and a database of previous projects to develop a Web-based Virtual Project Delivery System Adviser for Infrastructure Facilities (VPDSA-IF). Touran et al. (2009) integrated a qualitative assessment and a weighted score approach to develop a decision support system for PDS selection for transit projects. Although a mixed-method approach may be able to combine the advantages of different methods, it may also possess the inherent problems of those methods. Sometimes, the complexity of the mixed-method approach may be further increased.

2.4.2 Characterization of the discussed PDS selection methods

As observed in the previous section, the purpose of developing a new method is often to overcome certain limitations of the available ones. For instance, the weighted sum approach improves the imprecision nature of the guidance-type methods. MAUT uses utility functions to reduce the subjectivity involved in the weighted sum method. SMARTS and mean utility scores of evaluation criteria are developed to improve the practicability of MAUT. AHP allows a decision-maker to compare different criteria in a systematic manner. Fuzzy logic approach is introduced to address the fuzziness of certain evaluation criteria. Finally, knowledge- and case-based approaches are proposed to integrate the experts' knowledge and the lessons learned from the previous projects into the PDS selection process. Despite the fact that these new approaches have overcome some limitations of the old approaches, they still possess limitations. Of course, none of these methods is perfect and each has advantages and drawbacks.

Besides the differences in their knowledge bases, the discussed methods vary in terms of their complexities and levels of required information for implementation. Figure 2.6 conceptually outlines these two major differences. Some methods (e.g., guidance-type and weighted sum approaches) are relatively easy to use, while others (e.g., the MAUT, AHP and the fuzzy logic approaches) require more sophisticated skills and theoretical knowledge. In terms of level of information required, guidance-type approaches only require rough information about project characteristics and objectives. However, other methods will need higher levels of information. For example, MAUT needs information such as utility functions. Fuzzy logic approach requires information such as criteria membership functions and fuzzy relation rules. A database of previous projects is needed for knowledge- and experience-based approaches.

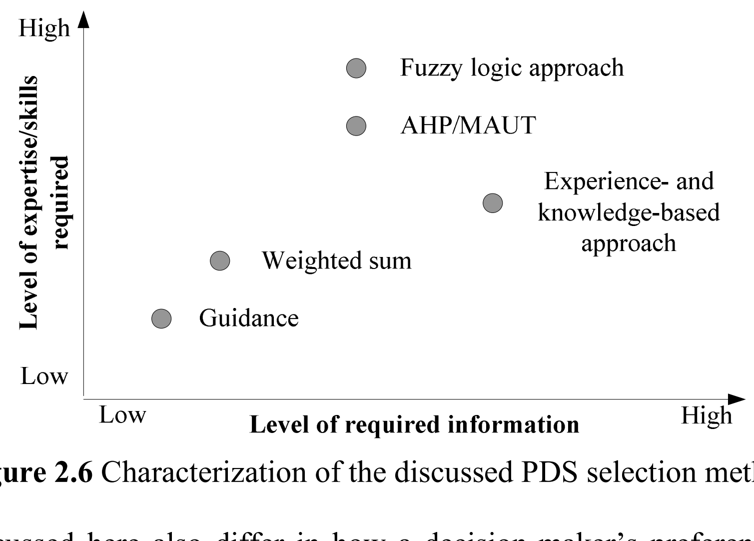


Figure 2.6 Characterization of the discussed PDS selection methods

The methods discussed here also differ in how a decision-maker's preferences are elucidated. For example, in AHP, a decision-maker's preferences are elucidated through a pairwise comparison process, while in the other methods this is done through a direct rating process. The ways that a decision-maker's preferences are expressed and measured in the discussed methods are also different. In fuzzy logic approach a decision-maker's preferences can be expressed in linguistic terms. However, in other approaches, a decision-maker conveys his/her preferences in numeric values. All these differences need to be considered when choosing a suitable PDS selection method.

Despite the above mentioned differences, the discussed PDS selection methods share two limitations. First, they fail to, or at least not adequately, consider project dependencies in evaluating alternative PDSs. Furthermore, they also do not allow a decision-maker to explicitly consider possible time/cost trade-offs in making their PDS decisions. More detailed descriptions of these two limitations can be found in Section 1.2.

2.5 Multiple Criteria Decision Analysis (MCDA)

2.5.1 Basics of MCDA

A Multiple Criteria Decision-making (MCDM) problem is a decision-making problem that involves consideration of multiple criteria (Belton and Stewart 2002). These criteria can be conflicting with each other. Solving a MCDM problem is thus to seek a balance among the considered criteria. MCDM problems can be as simple as personal choices (e.g., selecting a new apartment) or as sophisticated as management decisions at an agency level (e.g., choosing a location for a power station). A decision-maker in the later case, especially when multiple decision-makers are involved, will need to consider complex and changing information reflecting different viewpoints. To organize and synthesize such complex information and to ensure that all criteria are probably taken into account requires the assistance of structured approaches (Miller 1956). Multiple Criteria Decision Analysis (MCDA) is a collection of approaches that can fulfill this purpose. They help individuals (or groups) make decisions taking explicit account of multiple criteria.

Some decision-makers expect that MCDA approaches will give them "right" answers for their decision-making problems and provide them an "objective" analysis that can relieve them of the responsibility of making difficult judgment. These two expectations are, however, myths. Belton and Stewart (2002) argued that there is no such thing as the "right answer" even when MCDA approaches are used. A MCDA approach helps a decision-maker structure a problem, express/communicate his/her preferences and aggregate information from different sources. Different MCDA approaches may lead to different answers depending on how the problem is structured, what information is used and how a decision-maker's preferences are elucidated and aggregated. Belton and Stewart (2002) also emphasized that subjectivity is inherent in all decision-making situations (e.g., a decision-maker's choices of criteria and relative "weights" given to those criteria). MCDA approaches may be able to make the subjective judgment explicit and the judgment-making process transparent; they cannot eliminate the subjectivity. A structured analysis is meant to serve as an aid to a decision-maker, not as a substitute for him/her (Keeney and Raiffa 1972).

The analysis results of MCDA approaches are not used to replace a decision-maker's intuitive judgments or experience. Rather, they serve to complement and to challenge these intuition and judgments. They also provide a basis for discussions. The use of MCDA approaches can lead to better considered, justifiable and explainable decisions. In sum, MCDA approaches help a decision-maker:

- Structure a decision-making problem and learn about a decision-making situation;
- Express his/her own and others' values and judgments;
- Take explicit account of multiple (and often conflicting) criteria; and
- Organize, synthesize and properly present information, and identify (often through extensive discussion) a preferred course of action.

2.5.2 The MCDA process

Decision-making is a rational and intentional action based on four elements (March 1991):

- A knowledge of alternatives. A decision-maker has a set of alternatives.
- A knowledge of consequences. The decision-maker knows the consequences of alternative actions.
- A consistent preference ordering. The decision-maker has consistent values by which consequences of alternative actions can be compared in terms of his/her subjective values.
- A decision rule. The decision-maker has rules by which he/she selects a single alternative action on the basis of its consequences for the preferences.

The MCDA process systematically addresses the above four elements. Belton and Stewart (2002) divided the MCDA process into four distinct stages including to: (1) structure the decision-making problem, (2) build a MCDA model, (3) apply the MCDA model to the decision-making problem, and (4) develop an action plan. This process is illustrated in Figure 2.7 and described below.

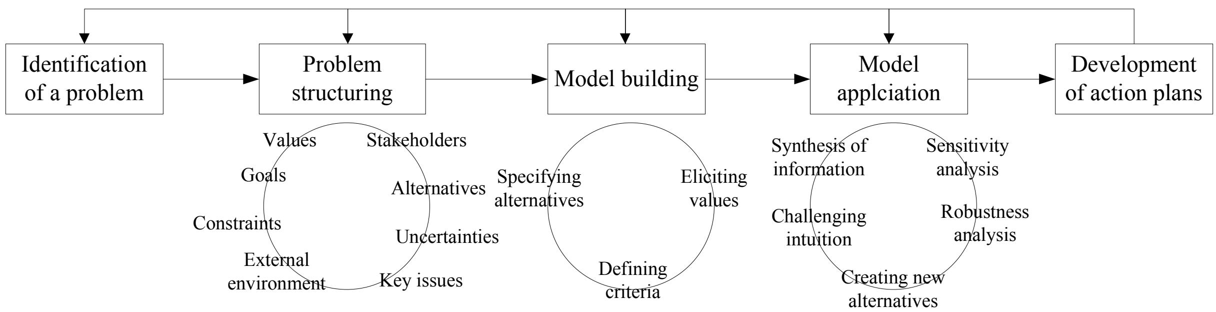


Figure 2.7 The MCDA process

Problem structuring. "*A problem well structured is a problem half solved" (*Belton and Stewart 2002). "*The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill*" (Einstein and Infeld 1938). These statements indicate the critical role of a MCDA problem structuring in a successful decision-making. Main tasks in this stage including to identify involved stakeholders, develop different alternatives, determine goals and constraints of the decision-making, examine uncertainties associated with the decision-making and consider other key issues.

Model building. This stage aims at structuring models to represent a decision-maker's preferences and value judgments. Some MCDA approaches are described in Section 2.5.3. Even though MCDA approaches vary in their theoretical assumptions and methodological procedures, they have in common the steps: specify the considered alternatives, define the criteria and determine measures which can differentiate the relative significance of the criteria.

Model application. Model application processes can be different from model to model. The aims of model application, however, are similar. They are to help a decision-maker synthesize information, conduct a sensitivity analysis and ensure a robustness analysis. The model application results can be used to challenge the decision-maker's intuitive judgments. In this model application process, the decision-maker may also need to create new alternatives that can best satisfy his/her objectives if necessary.

Action plan development. The final stage of the MCDA process is to develop an action plan. The implementation results of the action plan can be valuable sources of information for future similar decision-making situations.

2.5.3 MCDA methods

MCDA methods are many and different. Most of them however can be presented as a combination of two steps: construction and exploitation (Bouyssou 1996). In the construction step, information/data required for a decision-making problem are collected and a MCDA method is structured. In the exploitation step, the collected information/data are processed by the structured MCDA method and recommendations for course of actions are generated. Figure 2.8 illustrates such a schematization (Guitouni and Martel 1998).

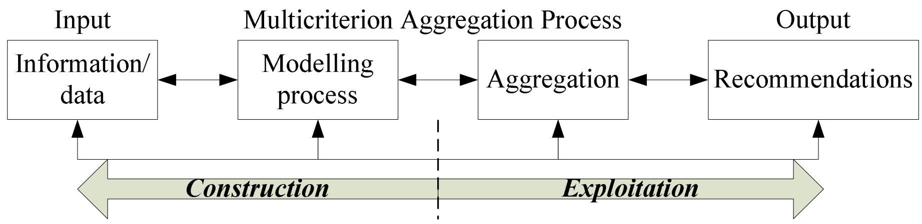


Figure 2.8 Schematization of MCDA methods (Source: adapted from Guitouni and Martel (1998))

Despite the similarity in their method-structuring processes, MCDA methods vary in their theoretical assumptions and methodological procedures. Guitouni and Martel (1998) classified MCDA methods into four groups including: (1) elementary methods; (2) single synthesizing criterion approaches; (3) outranking methods; and (4) mixed methods. A list of example MCDA methods in each of the categories along with their brief descriptions can be found in Table 2.8.

Elementary methods. MCDA methods in this group are straightforward and often involve only a minimum level of mathematical calculation. Such methods may provide a decision-maker an ordering of the considered alternatives or serve as a filter that eliminates undesired alternatives. Examples of elementary methods include the weighted sum, lexicographic method, conjunctive method, disjunctive method and max-min method. A weighted sum approach has been applied to solve the PDS decision-making problem.

Single synthesizing criterion approaches. MAUT and MAVT are two commonly seen single synthesizing criterion approaches. This type of method assumes that there exist utility (or value) functions that can represent a decision-maker's preferences on evaluation attributes. A single overall utility/value score can be obtained through an additive, multiplicative or distributional approach. The considered alternatives can be ranked based on their total utility/value scores. Some other methods that belong to this category include AHP, SMART, utility theory additive (UTA), and fuzzy maximum. Many PDS selection methods are developed based on methods within this category.

Outranking methods. ELECTRE is the first method using an outranking synthesizing approach. This type of method seeks to eliminate alternatives dominated according to a set of given weights. The result will be a partial order. This type of method is useful for a decision-maker to sort large lists of alternatives down to a short list. Other examples of outranking methods include ELECTRE I, ELECTRE II, ELECTRE III, ELECTRE IV, PROMETHEE, PROMETHEE I and PROMETHEE II. These methods are normally based on the same (or similar) principles as ELECTRE, but with some differences in their practical steps.

Mixed methods. Mixed methods refer to those MCDA methods that use a combination of any of the above discussed methods.

Despite the large number of available MCDA methods, no one is perfect and appropriate for all decision-making problems and situations. Bouyssou et al. (1993) even argued that this great diversity of MCDA methods can be a weakness. It is so because there is still no way to decide whether one method makes more sense than another in a specific decision-making situation and a decision-maker can face difficulty in choosing among them.

Guitouni and Martel (1998) proposed a set of guidelines to assist a decision-maker in choosing an MCDA method that best meets his/her decision-making needs. The decision-maker first needs to determine the stakeholders in the decision-making process. He/she then has to consider his/her preferred preference elucidation modes and desired results (e.g., an alternative ranking). The decision-maker also needs to consider the availability of information and choose an MCDA method that can properly handle the available information. Finally, the decision-maker needs to consider whether the fundamental hypothesis of a MCDA method can be met and whether a decision-support system for the method is available.

Table 2.8 A list of MCDA methods

MCDA	Description
Elementary methods	
Weighted sum	The performance of an alternative is computed as the weighted sum of its evaluations along each criterion. The global performance is used to make a choice among all the alternatives.
Lexicographic method	Based on the logic that in some decision-making situations a single criterion seems to predominate. The procedure consists of comparing all the alternatives with respect to the important criterion, and proceeds with the next one until only one alternative is left.
Conjunctive method	An alternative which does not meet the minimal acceptable level for all criteria is rejected. The minimal acceptable levels for each criterion are used to screen out unacceptable alternatives.
Disjunctive method	An alternative is selected on the basis of its extreme score on any one criterion. Desired levels for each attribute are used to select alternatives which equal or exceed those levels on any criterion.
Maximin	The overall performance of an alternative is determined by its weakest or poorest evaluation.
Single synthesizing criterion approaches	
Multi-attribute utility theory (MAUT)	Aggregation of the values obtained by assessing partial utility functions on each criterion to establish a global utility function U. Under some conditions, U can be obtained in an additive, multiplicative or distributional manner.
Multi-attribute value theory (MAVT)	Aggregation of the values obtained by assessing partial value functions on each criterion to establish a global value function V. Under some conditions, such V can be obtained in an additive, multiplicative or mixed manner.
Analytic hierarchy process (AHP)	Converting subjective assessments of relative importance into a set of weights. This technique applies the decomposition, the comparative judgments on comparative elements and measures of relative importance through pairwise comparison matrices which are recombined into an overall rating of alternatives.
Simple multi-attribute rating technique (SMART)	Simple way to implement the multi-attribute utility theory by using the weighted linear averages, which give an extremely close approximation to utility functions.
Utility theory additive (UTA)	Estimate the value functions on each criterion using ordinal regression. The global value function is obtained in an additive manner.
Fuzzy max-min	This procedure is based on the same principle as the standard max-min procedure. The evaluations of the alternatives are fuzzy numbers
Outranking methods	
ELECTRE I	The concept of outranking relationship is used. The procedure seeks to reduce the size of nondominated set of alternatives (kernel). The idea is that an alternative can be eliminated if it is dominated by other alternatives to a specific degree. The procedure is the first one to seek to aggregate the preferences instead of the performance.
ELECTRE II	ELECTRE II uses two outranking relations (strong and weak)
ELECTRE III	The outranking is expressed through a credibility index
ELECTRE IV	This procedure is like ELECTRE III but does not use weights
PROMETHEE I	PROMETHEE I is based on the same principles as ELECTRE and introduces six functions to describe the decision-makers' preferences along each criterion. This procedure provides a partial order of the alternatives using entering and leaving flows.
PROMETHEE II	PROMETHEE II is based on the same principles as PROMETHEE I. This procedure provides a total preorder of the alternatives using an aggregation of the entering and leaving flows.
Mixed methods	
Fuzzy conjunctive/ disjunctive method	When data are fuzzy, the match between values and standard levels provided by the DM and the evaluations becomes vague and a matter of degree. The degree of matching is computed using the possibility measure and the necessity measure. The alternatives with the highest degree of matching are considered the best.
Martel and Zaras method	This procedure uses the stochastic dominance to make pairwise comparison. These comparisons are used as partial preferences and an outranking relationship is built based on a concordance index and discordance index.

Source: adapted from Guitouni and Martel (1998).

2.5.4 Uncertainty in MCDA

Uncertainties are inevitable in MCDA. They may take different forms and arise from various sources. Friend (1989) classified uncertainties based on areas they are related to, such as uncertainties about values, decision areas, and the environment. French (1995) identified uncertainties specifically associated with decision-aid model building, and classified them into: (1) uncertainties in structuring the model (or the problem), (2) uncertainties in the USing the model, and (3) uncertainties in interpreting results. Another commonly seen way is to categorize uncertainties into internal uncertainty and external uncertainty (Belton and Stwart 2002).

Internal uncertainty. Internal uncertainties are those in relation to MCDA model structuring, model application processes and judgmental inputs required by the models. This type of uncertainty can be resolvable or unresolvable. Unresolvable uncertainties are often arisen from ambiguity or imprecision associated with the model developing process. For instance, if it is not clear about what level of detail should be incorporated into a model and/or what criteria sets should be included in the model, it will not be possible to develop an appropriate model. These unresolvable uncertainties can be addressed by integrating an iteration procedure into the model structuring process. This iteration procedure provides a decision-maker the opportunities to go back, restructure and consider the decision-making problem from different angles, and hence enable him/her to develop a more comprehensive MCDA model. Resolvable uncertainties on the other hand are those arose from imprecision (or ambiguity) of meaning (e.g., what does the "quality of life" mean?) and estimates of inputs. This type of uncertainty can be handled by conducting a sensitivity analysis.

In a sensitivity analysis, input parameters are changed, one at a time, by a certain percentage and the impacts of these changes on model outputs are evaluated. This analysis can provide a decision-maker the opportunities to investigate the significance of certain parameters (or missing information), and to explore the impacts of uncertainties associated with his/her judgments. The analysis results can help the decision-maker determine the robustness of his/her decisions. They can also serve as a basis for group discussions in a group decision-making situation.

External uncertainty. External uncertainties are uncertainties about the external environment. There are two kinds of external uncertainties. The first one is the uncertainty about how a decision under consideration is related to other decisions. For example, when choosing a location for a power plant project, a public agency would prefer a site in an area with sufficient supporting infrastructure projects (e.g., road systems). In this case, decisions made regarding the area's infrastructure projects will affect the attractiveness of a particular site. The best way to address uncertainties of this kind is to collaborate or negotiate with other infrastructure projects' decision-makers and to consider possible impacts of their decisions in the decision-making process. The second kind of external uncertainty is about issues outside the control of a decision-maker. For example, when making a decision about the size of a highway system (e.g., two lanes or three lanes), future population increase in the areas is an important factor to consider. This factor however will be affected by a number of other factors such as the economic and social environments. All these factors should be taken into account.

There is a number of ways that can be used to handle external uncertainties in MCDA. Among them, scenario planning and decision theory are two commonly used ones. In scenario planning, alternatives under consideration are evaluated for a number of, usually three, scenarios relevant to the decision context (Van der Heijden 1996). In this analysis there is no attempt to describe all possible scenarios or to determine the likelihood of the different scenarios. Rather, the aim is to define good strategies that are robust over a range of possible futures. Decision theory, on the other hand, uses probability distributions to describe the likelihood of uncertain events.

2.6 Summary of Literature Review

This chapter reviews literature on subjects that are related to this research. Issues in the public project planning are discussed. Four selected PDSs are reviewed and compared; and the PDS decision-making problem is defined. Different methods that have been developed for evaluating and choosing a proper PDS are also discussed, and their rationales, advantages and limitations are analyzed. This review does not only provide fundamental knowledge for conducting this research, but also help identify the limitations in the literature on the project planning and the PDS decision-making.

In the project planning and management domain, it is found that project planning and management research to date is heavily biased in favor of the management of a single project (Eskerod 1996; Evaristo and van Fenema 1999; Levy and Globerson 1997; Tsai and Chiu 1996; Van der Merwe 1998). Interdependencies among projects are often ignored or under-addressed, despite that they may significantly affect a project's performance. The similar "single-project dominant" situation is also observed from the review of the literature on the PDS decision-making. In recommending an appropriate PDS, almost all available PDS selection methods evaluate a project in isolation. They fail to, or at least inadequately, address project dependencies and possible time/cost trade-offs in their PDS decision-making processes. This may result in a PDS being selected based on unrealistic expectations of its benefits.

Chapter 3
Research Methodology

3.1 Introduction

This chapter describes the research methodology. A framework that provides an overview of how this research is conducted is presented in Section 3.2. Section 3.3 provides descriptions of data sources and data collection techniques. Measures taken to ensure data reliability and quality are described in Section 3.4. Finally, how the developed framework is verified and validated is discussed in Section 3.5.

3.2 Research Framework

This research aims at developing a decision-support framework to help decision-makers in public agencies design and choose a PDS among the regulation-authorized alternatives in a multi-project environment. A four-phase cyclic approach is applied to develop the framework, as illustrated in Figure 3.1.

Phase 1. The research problem, scopes and objectives are defined. This is achieved mainly through an extensive literature review on research-relevant subjects including project planning, alternative PDSs, PDS selection methods and multiple attribute decision analysis. Knowledge obtained from this literature review also forms the foundation for the development of the decision-support framework.

Phase 2. The decision-support framework is developed through three major steps. First, commonly used PDS selection criteria synthesized from the literature are categorized into two groups: performance (PERF) and general PDS criteria. Methods to deal with these two groups of criteria are then developed individually, and integrated together to form the overall decision-support framework. The developed framework is then verified by the researcher with a focus on its functions, logic and consistency.

Phase 3. The developed framework is verified and validated internally and externally. A more detailed discussion on how these verifications and validations are performed can be found in Section 3.4. In brief, internal verification is performed by the researcher to ensure that the proposed framework addresses unique characteristics of the PDS decision-making. External validation is performed together by the researcher and the industry practitioners. The aim is to test the applicability of the proposed framework.

Phase 4. The research findings, lessons learned and suggestions for future framework implementation are documented. Limitations of this research and future research directions are also presented.

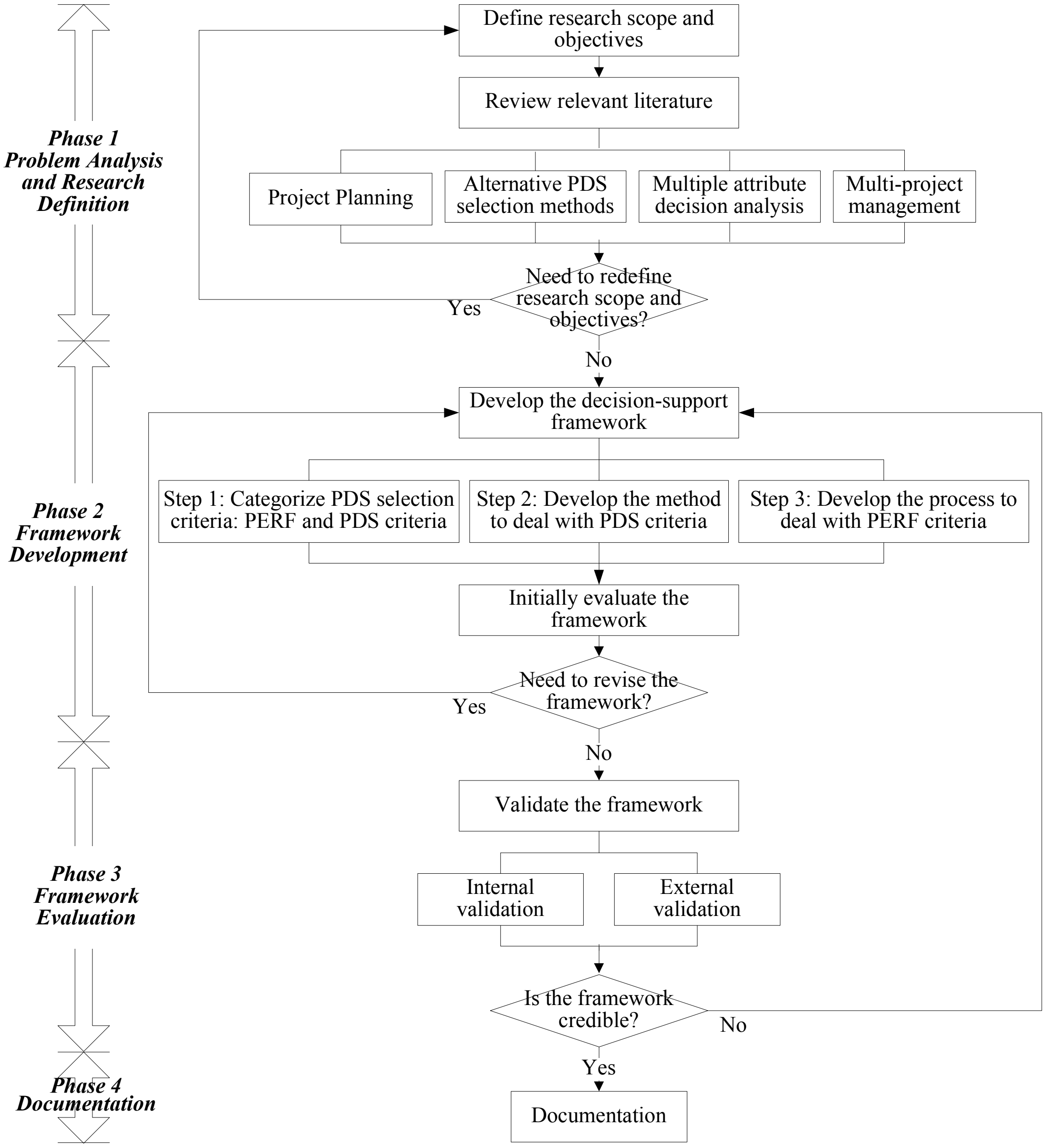


Figure 3.1 Research framework

3.3 Data Collection Techniques

This research uses both primary and secondary data. The secondary data are collected from multiple sources, such as books, journal articles, conference proceedings, and technical reports/documents. These data are first used to identify and understand the research problem, and to define the research scope and objectives. They are then combined with the primary data to develop, evaluate and validate the PDS decision-support framework. The primary data are collected mainly by interviews with participating practitioners and observations. Three data collection techniques used in this research are described below. How these techniques are applied to collect case study data is described in Chapter 7.

3.3.1 Literature and document analysis

Literature review is first performed to understand the research problem, define the research scope and objectives. The literature review results are presented in Chapter 2. The knowledge gained from this literature review is subsequently used to develop the PDS decision-support framework.

Document analysis is performed in the later framework application phase. It focuses on analyzing formal and informal documents of case study projects. The document analysis results are expected to enrich and verify data collected through interviews and observations.

3.3.2 Interviews

Interviews are used to understand how a PDS decision is made in practice and to collect case study data. Two types of interviews, namely semi-structured and structured interviews, are performed. Semi-structured interviews are mainly conducted in the initial data collection phase. In such an interview, the researcher prepares a set of general questions. How these questions are sequenced and whether other questions are asked, however, is dependent on the interviewee's responses (Bryman 2004). These semi-structured interviews aim at gathering comprehensive knowledge on a specific issue. Semi-structured interviews are conducted mainly by telephone, but e-mail is also used to clarify confusion and/or collect further information.

Structured interviews are conducted to get a deeper insight into research problems and collect detailed data on case study projects. General interview questions focus on how PDS decisions are currently made in the public agency. Case study project specific interview questions include, but not limited to, project objectives/constraints, the regulation-authorized PDSs, the estimated project timelines and cost distributions in different PDSs, the interrelated projects and the project dependencies. Detailed descriptions of these different groups of data can be found in Chapter 7. These structured interviews are conducted on a face-to-face basis, and are complemented by telephonic communications and email correspondence. Information collected through these interviews, both semi-structured and structured, is documented on interview templates.

3.3.3 Observation

Observation is used in conjunction with interviews to strengthen data collection. Through observations, the researcher is able to check for the interviewee's nonverbal expression of feelings, to observe events that the interviewees may be unable or unwilling to share, and to discover problems of which interviewees are unaware (Marshall and Rossman 1995; Schmuck 1997).

3.4 Data Reliability and Quality Control

The results of qualitative studies can be very difficult to measure (Leedy 1993; Meyers 2004). For this reason, the reliability and quality of data collection is important. In this research, three measures, namely triangulation, using standard data collection procedures and forms and performing a sensitivity analysis, are taken to enhance the quality and credibility of the data collection. More detailed discussions on how these three measures contribute to the quality and credibility of qualitative data can be found in Patton (1999), Abowitz and Toole (2010) and Lucko and Rojas (2010).

3.4.1 Triangulation

Triangulation is a useful technique for strengthening the reliability and credibility of data collection (Patton 1999; Jick 1983). In this research, two types of triangulation are used: triangulation of methods and triangulation of data sources. Methods triangulation is used to check consistency of findings generated by different data collection methods. For example, results derived from interviews are cross-checked with those obtained from observations and/or literature and document analysis. The triangulation of methods can avoid the problems linked with a specific data collection method (e.g., biased or untrue responses in an interview) (Patton 1999). Triangulation of data sources is used to examine of the consistency of different data sources in the same collection method (Patton 1999). For instance, an interviewee's responses to the same question at different times are compared. When different data collection methods and sources yield consistent results, the data credibility is ensured. If inconsistencies are found, the collected data are further examined and the interviewees are contacted for clarification.

3.4.2 Use of standard data collection procedures and forms

A standard data collection procedure is followed to ensure that data are collected in a systematic and consistent manner. First, to allow interviewees time to familiarize themselves with the questions and to gather necessary information, a list of interview questions is sent to them in advance. The interviewees are then contacted, via phone and/or email, to clarify any ambiguities and confusion. After all ambiguities are resolved, a time is scheduled for a formal face-to-face interview. These formal interviews are conducted at the interviewees' offices and lasts for about 30-60 minutes. At the end of each interview, the interview results are summarized and sent to the interviewees for verification. If necessary, the interviewees are contacted again for answer clarification. This standard procedure is followed in all structured interviews. Standard data collection forms are also used to simplify data recording and reduce the likelihood of errors or missing information.

3.4.3 Sensitivity analysis

Even though the above two measures can enhance the reliability and quality of the collected data, some uncertainties embedded in the interviewee's responses are still inevitable. A powerful tool to address this type of uncertainty is sensitivity analysis (Lucko and Rojas 2010). Through sensitivity analysis, the impacts of the variability in the values of inputs on outputs can be quantified (Elmaghraby 2000). In this research, a sensitivity analysis is also performed to investigate how uncertainties associated with certain data may affect the PDS decision-making.

3.5 Framework Verification and Validation

The proposed decision-support framework is carefully verified and validated to ensure its quality and applicability. The objectives of the verification and validation are summarized in Table 3.1.

Table 3.1 Framework verification and validation

Types	Objectives
Verification	The proposed framework is logically coherent and meets the predefined framework requirements.
Validation	The proposed framework addresses unique characteristics of the PDS decision-making.
	The proposed framework can help decision-makers evaluate and choose a PDS in a structured manner.

3.5.1 Framework verification

Before the framework is developed, a list of framework requirements is established. This list contains both functional and general requirements. Functional requirements are those that describe what the framework must do in order to fulfill its intended purposes. These requirements are developed based mainly on the characteristics of the PDS decision-making, and the limitations of currently available PDS selection methods. General requirements are those necessary to assure the applicability and usability of the framework in the industry. The purpose of verification is to examine whether the developed framework satisfy these predefined requirements. This verification is performed mainly by the researcher at any time during the framework development process.

Verification is also performed for the data collected in the framework application phase. This verification is conducted both internally by the researcher and externally by interviewees. Internally, the researcher cross-checks data collected from different sources (triangulation of data sources) and through different methods (triangulation of methods). Externally, the collected data is verified by interviewees prior to analysis.

3.5.2 Framework validation

Different PDS selection methods may produce different results. However, it is very difficult, if not impossible, to validate whether one method produces more accurate results than another. The use of an appropriate PDS is just one among the many factors that may affect project efficiency and success. If a project fails, it is not necessarily because the wrong PDS was used.

Furthermore, there is no way to compare the performance of different PDSs on the same project because each project is unique and its implementation is irreversible. This means that it is also not possible to tell for sure whether a PDS is superior to others for a specific project.

For these reasons, the aim of validation in this research is not to determine whether the proposed decision-support framework gives more "accurate" answers than others. Rather, it is to examine: (1) whether the proposed framework fulfills its intended purposes; and (2) whether the framework is applicable in the industry. This is accomplished through case applications.

The developed decision-support framework is applied to a wastewater treatment plant project in Taiwan. This application provides the researcher the opportunities to: (1) identify the missing contents of the framework; (2) observe the framework implementation difficulties; and (3) solicit industry practitioners' feedbacks on the framework.

Chapter 4
The PDS Decision-Support Framework: Overview

4.1 Introduction

As previously discussed, designing and choosing a PDS is a difficult task and requires the assistance of structured decision-making methods. Even though the currently available PDS selection methods fulfill their purposes of rationalizing PDS decision-making, they suffer from the following limitations: (1) they do not sufficiently, if at all, take into account project interdependencies and possible time/cost trade-offs; (2) they do not provide decision-makers the opportunity to "design" a PDS for their needs; and (3) their applications in industry are limited due to the common perception by practitioners that the methods are difficult to understand and use. This chapter presents a PDS decision-support framework that can cope with the characteristics of the PDS decision-making and overcome the inherent limitations of the currently available methods.

This chapter is structured as follows: First, the assumptions and a list of requirements for the PDS decision-support framework are presented respectively in Sections 4.2 and 4.3. The overall framework is described, step-by-step, in Section 4.4. A discussion of how the framework meets the pre-defined requirements, and how it is different from other currently available PDS selection methods, are given in Section 4.5. Section 4.6 is the summary of the chapter.

4.2 Framework Assumptions

The PDS decision-support framework was developed based on three major assumptions:

- A PDS is defined as a framework that defines how project phases are integrated and by whom the project phases are implemented (Miller 1998). Three fundamental forms of PDSs are DBB, DB and CMR (Construction Industry Institute 2003). Another form of contract structure has emerged in the last few years under the name "integrated project delivery." This contract structure is fundamentally a 3-way agreement between owner, architect, and CM/GC, with joining agreements signed by design and construction specialists as they join the team (Matthews and Howell 2005). This contract structure, however, is beyond the scope of this research and presents an interesting direction for future work.

- The decision-support framework aims at helping a decision-maker design and choose a PDS that best meets project objectives. It is assumed that the decisions on project management strategies, such as methods of contractor selection (e.g., price-based, value-based), compensation (e.g., cost plus and fixed fee, or cost plus a percentage) and project government methods, are made after the basic form of PDS is determined. This assumption is consistent with the process employed by the public agency with whom the case study was performed. However, it may not yield the best PDS selection. Subsequent specification (e.g., methods of compensation, methods of selection, methods of project governance, organizational structure and integration) of a PDS not selected at the first stage of analysis could perform better than any subsequent specifications of the PDS that was selected at the first stage of analysis. The multitude of possible combinations and sequences reveals that PDS 'selection' might better be called PDS 'design', and that is something for future research to explore.

- It is assumed that public agencies can only use a PDS that is authorized by regulations. They have limited flexibility to adapt PDSs to the specific circumstances of individual projects. In this regard, the "design" of PDS alternatives is accomplished through modifying the regulation-authorized PDSs.

4.3 Framework Requirements

The decision-support framework is not a tool that will give a decision-maker an ultimate answer. Rather, it is a framework that helps the decision-maker collect, analyze and synthesize the required information. Based on studies on the characteristics of PDS decision-making and the limitations of available PDS selection methods, a list of functional and general requirements that an improved PDS decision-support framework should satisfy is developed. Functional requirements are functions that need to be included in the framework in order to fulfill its intended purposes; general requirements are those that can enhance the applicability and usability of the framework in the industry.

4.3.1 Functional requirements

- The framework can allow consideration of multiple PDS alternatives and multiple objectives (F1).
- The framework can integrate consideration of project dependencies and possible time/cost trade-offs (F2).
- The framework can allow a decision-maker to verify estimates, adjust certain information and review the consequences of such adjustments (F3).
- The framework can facilitate communication among decision-makers (F4).
- The framework can provide a decision-maker the opportunities to "design" a PDS to maximize its capability to meet project objectives (F5).

4.3.2 General requirements

- The framework is easy to understand and use by industrial practitioners (G1).
- The framework is flexible enough so that certain steps can be modified to better meet a decision-maker's specific situation (G2).

4.4 Overall Framework

The proposed framework has five distinct stages and gates, as shown in Figure 4.1. The stages are where project objectives/constraints are defined (Stage 1), regulation-authorized PDSs are identified (Stage 2), evaluation criteria are determined (Stage 3), PDS alternatives are designed and evaluated (Stage 4) and an appropriate PDS is selected (Stage 5). Each of these stages can be further organized into a set of steps. Gates are checkpoints where outputs of each stage are discussed and verified by decision-makers. These stages and gates are described in detail in the following sections.

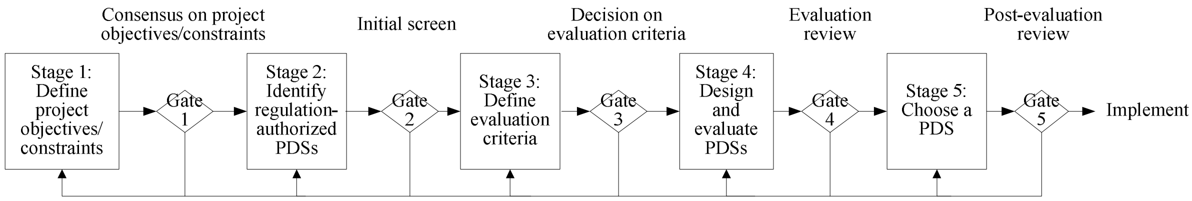


Figure 4.1 Overall PDS decision-support framework

4.4.1 Stage 1: Define project objectives/constraints

The first stage toward a PDS choice is to define project objectives/constraints. Even though project objectives/constraints can vary from one project to another, they are closely linked to three project performance measures: time, cost and quality. Objectives/constraints that cannot be categorized into these three categories are grouped together under the "others" category. Table 4.1 lists some examples of generic objectives in these four categories.

Table 4.1 Examples of generic project objectives/constraints

Categories	Examples of generic objectives/constraints
Time	• Minimize total project duration • Complete the project on schedule
Cost	• Minimize project cost • Complete the project on budget
Quality	• Meet or exceed project requirements
Others	• Seek innovation opportunities throughout the lifecycle • Minimize impact on the environment • Minimize inconvenience to the community and public

In this stage, a decision-maker also needs to determine the mandatory constraints for project schedule and cost. For project schedule constraints, the decision-maker must determine the project's maximum acceptable and minimum desired durations, such as "the total project duration is preferred to be within 15 months and cannot exceed 30 months," or a specific completion date. The decision-maker also needs to identify the project's mandatory completion date and major schedule milestones. Similarly, the decision-maker also has to determine the maximum acceptable as well as the minimum desired project costs. For example, the total project cost is preferred to be below \$5 million and cannot exceed \$10 million. Financial sources and potential difficulties in securing financial resources should also be examined. The decision-maker also has to determine the scale (e.g., 10-110) that will be used to measure project quality. The defined project constraints are indicated in a performance profile. A sample performance profile with constraints is shown in Figure 4.2.

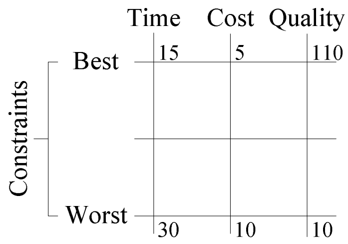


Figure 4.2 A sample performance profile with constraints

The benefits of defining project constraints in terms of a range of values instead of a fixed number are two-fold. First, a decision-maker is generally more comfortable about providing a range of values. In addition, the range between the highest and the lowest criteria requirements leaves the decision-maker flexibility to consider possible trade-offs in the decision-making process.

4.4.2 Stage 2: Identify regulation-authorized PDSs

A variety of PDSs are currently available for infrastructure project development. This research focuses primarily on the three fundamental forms of PDSs: DBB, DB and CMR. Among these three PDSs, DBB is generally fully authorized by almost all governments for infrastructure development. However, the use of DB and CMR may be prohibited by regulations or subject to certain conditions (e.g., authorized but needs extra approvals; authorized for a pilot program and/or with some limitations). When the former situation occurs, the regulation-prohibited PDSs should be eliminated from further consideration. In the latter situation, conditions accompanied by the use of the PDSs should be documented, and their impacts on project objectives (e.g., estimated time to acquire the extra approvals) should be taken into account later in the PDS decision-making process.

4.4.3 Stage 3: Define PDS selection criteria

In this stage, a decision-maker defines a set of selection criteria that best reflect his/her pre-defined time, cost, quality and other objectives. Since time, cost and quality are three prime project performance measures that ultimately determine a project's success, they are grouped and defined as performance (PERF) criteria. With rare exception, PERF criteria are the decision-maker's primary concerns in choosing a PDS because they must meet certain mandatory constraints. For example, a project has to be completed within a certain budget and by a specified deadline. The project also needs to meet a list of specifications to fulfill its planned purposes. How a project performs on PERF criteria is affected not only by the characteristics of the PDS it uses (e.g., how project phases are integrated), but also by several other factors (e.g., project dependencies, time/cost trade-offs and external factors). To effectively integrate these factors into a PDS decision-making process, PERF criteria (except quality) are measured on a quantitative basis. Time is measured in days, months or years; cost is measured in dollars.

Criteria other than time, cost and quality are grouped and defined as general PDS criteria. The choice of general PDS criteria can vary from project to project. Previous studies (e.g., Skitmore and Marsden 1988; Love et al. 1998; Cheung et al. 2001; Luu et al. 2005; Chan 2007; Kumaraswamy and Dissanayaka 2001; Oyetunji and Anderson 2006; Ng and Cheung 2007) have highlighted seven commonly-used general PDS criteria, including: (1) time certainty (TC), (2) cost certainty (CC), (3) flexibility (FL), (4) complexity (CO), (5) risk transfer (RT), (6) price competition (PC), and (7) point of responsibility (PR). A project's performance on general PDS criteria is largely determined by the characteristics of the PDS used. For example, a project's performance on PR is mainly determined by how project phases are integrated in a particular PDS. DB is perceived to have better performance than DBB on PR because it integrates design and construction services into a single contract. These general PDS criteria are often qualitative in nature and are better measured on a relative scale.

The above two groups of criteria are summarized in Table 4.2. These criteria are by no means definite. A decision-maker may choose different criteria to reflect particular PDS selection circumstances based on experience and knowledge.

Table 4.2 Descriptions of PERF and general PDS criteria

Group	Criterion	Description
PERF	Time (T)	The time taken to complete the project, including project planning, procurement, design and construction durations.
	Cost (C)	The cost required to complete the project, including project planning, procurement, design and construction costs.
	Quality level(QL)	The quality required of the completed project.
General PDS	Time certainty (TC)	The certainty over the time for completion of the project.
	Cost certainty (CC)	The certainty over the cost for completion of the project.
	Flexibility (FL)	The ability and authority for the client to effect changes.
	Complexity (CO)	The suitability of the PDS to tackle complex projects.
	Risk transfer (RT)	The transfer of risk to the contactor.
	Price competition (PC)	The degree of price competition pertaining to the PDS.
	Point of responsibility (PR)	The clarity of allocation of responsibility.

Note: some definitions are adopted from Cheung et al. (2001).

4.4.4 Stage 4: Design and evaluate PDSs

As previously discussed, PERF criteria and general PDS criteria are different in how they are affected by various factors and how they are measured. In this regard, these two groups of criteria are handled separately in the proposed framework. Figure 4.3 illustrates factors affecting a project's performance on these two groups of criteria, how these two groups of criteria are measured and their relationships with the PDS decision.

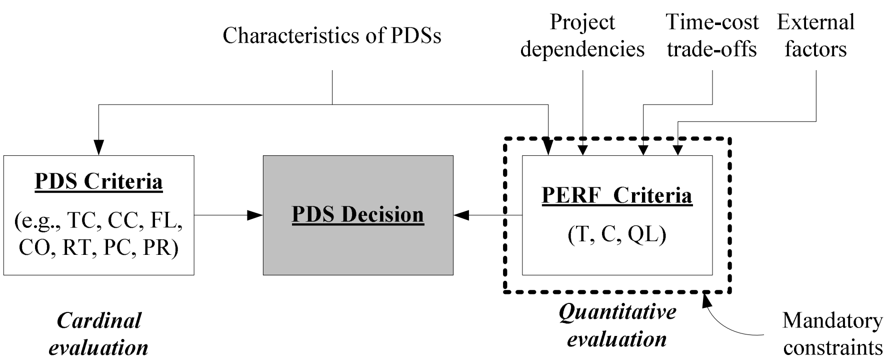


Figure 4.3 Two groups of PDS selection criteria

4.4.4.1 Deal with PERF criteria

In currently available PDS selection methods, PERF criteria are mostly evaluated on a decision-maker's perceived values (e.g., utility scores or scores) of different PDSs' abilities to satisfy the criteria. For example, in the MAUT method, DB usually receives a higher utility score than DBB on time criterion because DB is expected to deliver a project in a timelier manner. This method has three limitations. First, the perceived values are subjective and vary from one decision-maker to another. Second, the perceived values cannot indicate whether the mandatory time- and cost-constraints are met in a PDS, and these values have little, if any, use for future project management and control. Third, a PDS's ability to satisfy certain objectives does not guarantee its success. Whether a PDS can achieve its expected performance on PERF criteria is highly dependent on the project's dependencies with other projects and on external factors. If these factors are not taken into account, a higher perceived value can be misleading.

Making realistic estimates on time and cost during the early planning stage, and understanding possible implementation difficulties, thereby making appropriate decisions, can also significantly contribute to project success (CIRC 2001; Chan and Kumaraswamy 2002; Iyer and Jha 2005; Iyer and Jha 2006). With this in mind, and to overcome the limitations of using perceived values in dealing with PERF criteria, a decision-maker is urged to estimate project schedules and costs in different PDSs, taking into consideration project interdependencies, possible time/cost trade-offs and external factors. These schedule and cost estimates are useful not only for PDS decision-making but also for further project planning and control. Quality levels of the project under different PDSs are evaluated on a relative scale (e.g., 10-110).

Figure 4.4 illustrates steps to deal with PERF criteria. The first step is to estimate project time and cost, given a PDS. These estimates can be based on information from past similar projects and a decision-maker's experience. These estimates are used to determine time/cost trade-off rules in that particular PDS. The derived trade-off rules are then applied to adjust the initial estimated project schedule and cost for project dependencies. A NPV-based method for deriving these time/cost trade-off rules is presented in Chapter 5; a procedure to evaluate project dependencies is described in Chapter 6. The project's quality levels under different PDSs are also evaluated on a relative basis. This process is repeated for each of the PDSs under consideration.

The final outputs of this process are the new project's estimated durations, costs and quality levels under different PDSs. These results are presented in the form of a performance profile. An example of a performance profile on PERF criteria is shown in Figure 4.5. This performance profile presentation format has two advantages. First, it gives a decision-maker a more holistic view of the considered PDSs' performance. In addition, it highlights cases where a PDS may score highly overall but score poorly on certain criteria. This information provides the decision-maker the opportunities to develop proactive management strategies.

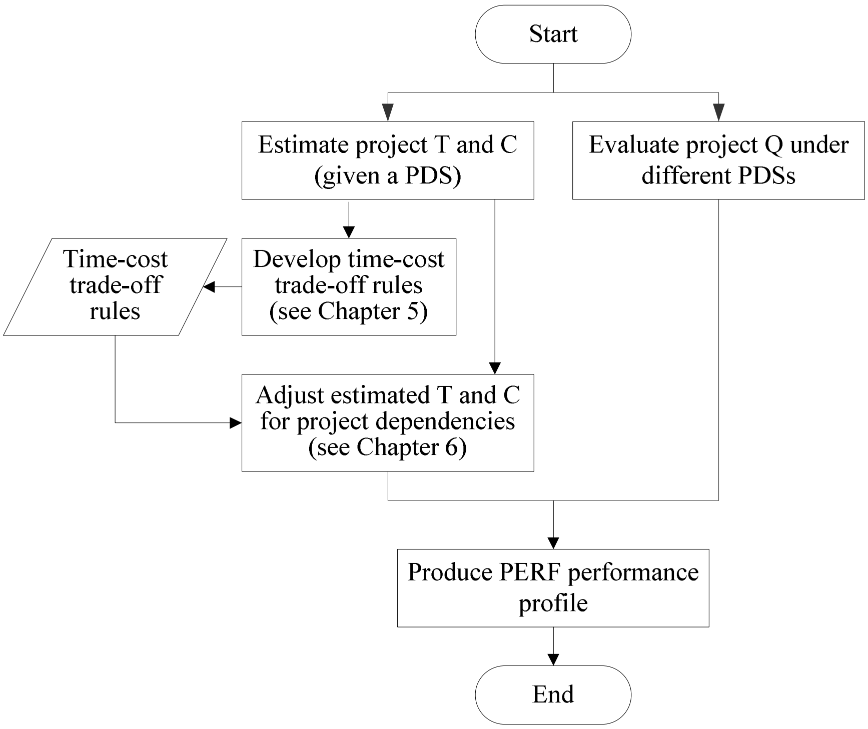


Figure 4.4 Steps to deal with PERF criteria

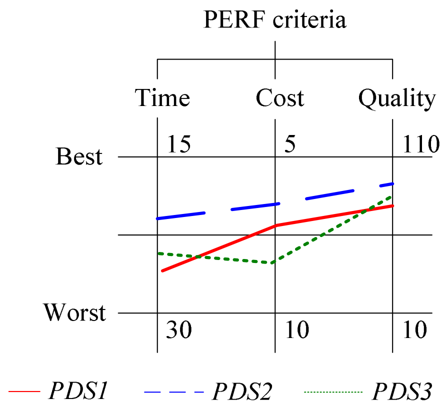


Figure 4.5 An example of performance profile on PERF criteria

4.4.4.2 Deal with general PDS criteria

A weighted score approach is used to evaluate PDSs on general PDS criteria. The weighted score approach has three steps: (1) weigh general PDS criteria; (2) score PDSs; (3) calculate weighted scores and ranked PDSs.

Weigh general PDS criteria. To weigh general PDS criteria, a decision-maker first ranks the criteria in order of importance (from the most to the least important)[2]. Then, each of the criteria

[2]It should be noted that this weighting of criteria is a key point of difference between currently accepted multi-attribute decision making methods and the previously mentioned Choosing by Advantages (Suhr 1999).

is assigned weights from 10-110 (where 110 represents the most important and 10 represents the least important). Equal weightings of criteria should be avoided as it fails to distinguish the levels of importance of the criteria and will make decision-making more difficult. Finally, the assigned weights are normalized to make them sum to one. An example of the ranking, non-normalized and normalized weights of the general PDS criteria is shown in Table 4.3.

Table 4.3 An example of ranking and weights of general PDS criteria

Criterion	Rank	Non-normalized weights	Normalized weights
TC	1	110	0.24
CC	2	90	0.20
RT	3	85	0.19
PC	4	70	0.15
FL	5	50	0.11
PR	6	40	0.09
CO	7	10	0.02
Total		455	1

Score PDSs. A numerical scale (e.g., 10-110) is used to score PDSs. A PDS with the best performance on a criterion is assigned the highest score; the PDS with the worst performance on the same criterion is assigned the lowest score. These two points are joined by a straight line. All other considered PDSs are positioned on this straight line to reflect their performance relative to the two reference points.

Rank PDSs. For each PDS, scores on the general PDS criteria are multiplied by the criteria's corresponding weights to achieve weighted scores. These weighted scores are summed to arrive a total weighted score. Table 4.4 is an example that shows the scorings (on a scale of 10-110) and ranking of three PDSs with respect to general PDS criteria. The shown values in the table are for demonstration purposes only; they do not represent real data.

Table 4.4 Example of scorings of PDSs

General PDS criteria	Wi	PDS1		PDS2		PDS3	
		Score	Weighted score	Score	Weighted score	Score	Weighted score
TC	0.24	110	26.6	10	2.4	20	4.8
CC	0.20	110	21.8	50	9.9	10	2.0
RT	0.19	10	1.9	100	18.7	110	20.5
PC	0.15	110	16.9	10	1.5	90	13.8
FL	0.11	10	1.1	60	6.6	110	12.1
PR	0.09	10	0.9	80	7.0	110	9.7
CO	0.02	10	0.2	80	1.8	110	2.4
Total	1		69.3		47.9		65.4
Rank			1		3		2

The evaluation results of general PDS criteria are also presented in the form of a performance profile. A performance profile on general PDS criteria, based on the values in Table 4.4, is shown in Figure 4.6. PDSs that have similar overall scores on general PDS criteria (e.g., PDS1 and PDS3 in the table) can have different performance profiles. A decision-maker is therefore suggested to look into the breakdown performance profile on individual general PDS criteria (as shown in Figure 4.7) when making PDS choices.

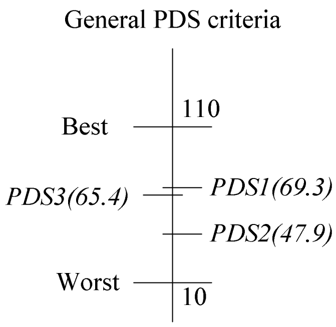


Figure 4.6 An example of performance profile on general PDS criteria

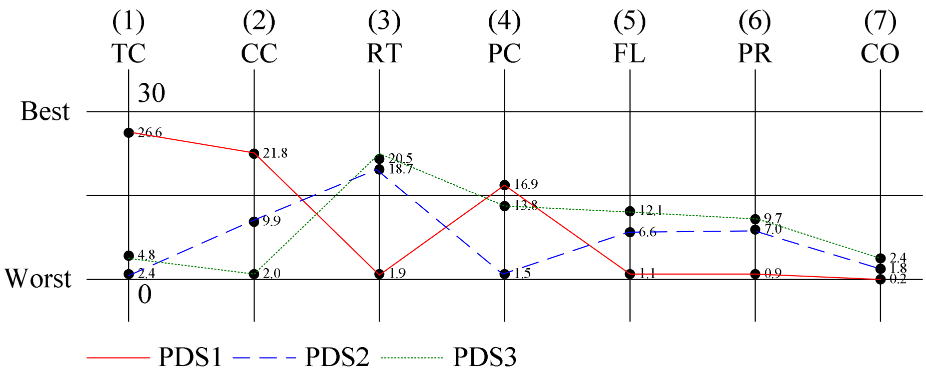


Figure 4.7 Breakdown performance profile on individual general PDS criteria

4.4.4.3 Sensitivity analysis

As discussed in Chapter 1, a PDS decision is made at a time when only limited and imprecise information is available. For this reason, some degrees of uncertainty in the estimates of project schedule and cost are inevitable. Subjective biases associated with the determination of criteria weights may also affect the PDS evaluation results. In order to address these uncertainties and subjective biases, a sensitivity analysis should be performed. Some variables that are expected to affect the PDS evaluation results include the discount rate, the estimated project durations and costs (particularly the durations and costs of design and construction phases), and the weights for general PDS criteria. A sensitivity analysis on these parameters is recommended. Such sensitivity analysis results can provide a decision-maker a better understanding of the inherent uncertainties in the estimates, and the impacts of these uncertainties on PDS decisions.

4.4.5 Stage 5: Choose a PDS

Performance profiles on PERF criteria (as shown in Figure 4.5) and general PDS criteria (as shown in Figure 4.6) are combined to form an overall performance profile, as shown in Figure 4.8. Figure 4.8 can be broken down to show the performance profiles of individual criteria if necessary.

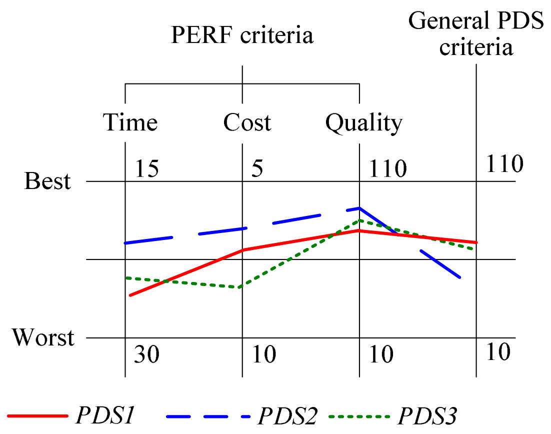


Figure 4.8 An example of overall PDS performance profile

The overall and break-down performance profiles are used as a basis to facilitate discussions among involved PDS decision-makers. As previously discussed, project schedule and cost usually need to meet mandatory constraints. If a PDS cannot deliver the project within mandatory time or cost (or both) constraints, it should be eliminated from the choice set, unless these constraints can be met through further time/cost trade-off adjustments. For PDSs that can meet the mandatory time and cost constraints, their performance on individual evaluation criteria are considered. In principle, if there is a PDS that dominates all other PDSs on all criteria, the dominant PDS is considered to be the most appropriate one. In this case, a decision-maker still needs to determine whether the dominant PDS performs poorly on certain important criteria. If so, the decision-maker can develop proactive management strategies to improve the PDS's performance on those criteria. When no single dominant PDS exists, a decision-maker should consider the PDSs' performance on individual criteria in the order of their importance. A PDS that performs better on important criteria is considered to be more appropriate. The above decision-making rules are by no means absolute. They can be further adjusted to reflect different decision-makers' preferences and circumstances.

In currently available PDS selection methods, a decision-maker usually chooses a PDS based on the total scores of the considered PDSs. This decision-making principle cannot help distinguish among PDSs with similar overall scores but different performance profiles. Consider an example where two criteria, A and B, are used to evaluate two PDSs, PDS1 and PDS2. The weights of criteria A and B are assumed to be, respectively, 70% and 30%. Assume further that PDS1 is scored 30 and 100, respectively, on criterion A and B; and PDS2 is scored 70 and 10, respectively, on criterion A and B. This makes the total weighted scores of PDS1 and PDS2 both 51. If only the total weighted scores are considered, the decision-maker is indifferent between the two PDSs. This may change if the performance profiles of the two PDSs are taken into consideration. The performance profile shows that PDS1 performs well on criterion B but poorly on criterion A; PDS2 is the opposite. As criterion A is more important to the decision-maker, PDS2 may be preferred. The performance profile also shows that PDS2 performs poorly on criterion B. The decision-maker can thus develop proactive management strategies to improve PDS2's performance on criterion B.

4.5 Discussion

4.5.1 The proposed framework vs. the framework requirements

This section presents a discussion of how the proposed framework addresses the functional and general requirements outlined in Section 4.3. Table 4.5 provides a summary of the discussion. Throughout the discussion, "F" or "G," followed by a number, is used to denote specific functional and general requirements. For instance, F1 represents the first functional requirement; G1 represents the first general requirement.

Table 4.5 Requirements and features of the framework

No	Framework requirements	Framework features
F1	Consideration of multiple PDSs and criteria	The framework allows decision-makers to evaluate alternative PDSs with respect to two groups of criteria.
F2	Consideration of project dependencies and possible time/cost trade-offs	The framework integrates a NPV-based method and a structured procedure to help decision-makers derive time/cost trade-off rules and consider project dependencies in the PDS decision-making process.
F3	Opportunities for information verification and adjustments	Stage-gate framework structure provides decision-makers the opportunities to review, discuss and verify the information and make necessary adjustments.
F4	Facilitating communication	Stage-gate framework structure and performance profile presentation format both facilitate communication among decision-makers.
F5	Opportunities for PDS modification	The consideration of time/cost trade-off rules and project dependencies provides decision-makers the basis for PDS modifications.
G1	Easy to use and understand	The framework integrates concepts and techniques that are currently in use in the industry or are straightforward.
G2	Flexibility for application	Stage-gate structure provides decision-makers opportunities to add and modify involving stages and gates; and to choose techniques they are familiar with.

F: functional requirements; G: general requirements.

The proposed framework allows a decision-maker to evaluate alternative PDSs with respect to two groups of criteria (PERF and general PDS criteria) (F1). It also helps the decision-maker to consider project dependencies and possible time/cost trade-offs in the PDS decision-making process (F2). These functions are organized into a number of stages and gates. With each stage and gate being clearly outlined, the decision-maker can move easily and logically from one stage and gate to the next (G1). Such a stage-gate structure offers two additional benefits (Cooper 1990). First, the gate after each stage provides the decision-maker opportunities to review information and his/her estimates. These gates are also the times at which a group of decision-makers discusses the results and achieves a consensus (F3, F4). The stage outputs that do not pass these gates are adjusted and re-reviewed. This iterative and interactive process can enhance the validity of information generated by the proposed framework. A stage-gate structure also allows the decision-maker to add, remove or modify certain stages and gates of the framework to tailor it to his/her needs (G2). The decision-maker can also choose to use familiar techniques.

To be easily understood and used by industry practitioners, the framework is developed based on concepts that are intuitively clear and easy to explain; it integrates techniques that have been applied in industry (G1). For instance, information is displayed to decision-makers in an understandable manner (e.g., performance profiles). This can also facilitate communication among them (F4). Another example is to use a NPV method, with some revisions and extensions, to help a decision-maker derive time/cost trade-off rules. There are three reasons to use a NPV method: First, the NPV method has been commonly used in industry to evaluate and/or compare project investments. Its concepts and calculation procedure should be familiar to most practitioners. Even if this is not the case, the concepts of a NPV method are straightforward and easy to learn. The second advantage of using a NPV method is that it requires only macro-level project information that is available in the early project planning phase. Lastly, the NPV method does not require complex mathematical calculations. All its calculations can be performed by Excel. Using concepts and techniques that are straightforward and familiar to practitioners is expected to enhance the applicability and usability of the proposed framework.

Belton and Stewart (2002) suggested that MCDA should equally emphasize evaluating given alternatives and creating good alternatives. Following this principle, the fifth feature of the framework is to provide a decision-maker the opportunities to "design" a PDS to accommodate the impacts of project dependencies and to proactively avoid possible implementation difficulties (F5). The reason for modifying a PDS, instead of creating a new one, is that the choices of PDSs for public projects are limited by regulations. Public agencies cannot create a PDS that is not authorized by the legislature. They can only make modifications to the regulation-authorized PDSs. One example of such modifications is to begin the procurement process during the design phase in DBB. This changes "traditional DBB" into "DBB with early procurement". Another example is to hire a project manager to assist and supervise the project implementation process in DBB. In this case, "traditional DBB" is changed to "DBB with project manager".

4.5.2 The proposed framework vs. the available PDS selection methods

Different PDS selection methods may produce different results; it is very difficult, if not impossible, to determine whether one method produces more accurate results than another (a discussion on this argument can be found in Section 3.5.2). For this reason, the comparison of the proposed PDS decision-support framework with other currently available PDS selection methods focuses on their functions, instead of their results.

As discussed in Section 2.4, currently available PDS selection methods are limited in that they do not take into account project interdependencies and possible time/cost trade-offs in evaluating alternative PDSs. The proposed framework fills this gap by integrating a NPV-based method for deriving time/cost trade-off rules and a structured procedure for evaluating impacts of project interdependencies into the PDS decision-making process. Furthermore, in addition to helping a decision-maker choose a PDS among a set of given PDSs, the proposed framework takes a step further by providing the decision-maker the opportunities to modify regulation-authorized PDSs to better meet expectations and needs. It also allows the decision-maker to develop proactive management strategies to overcome potential bottlenecks associated with the selected PDS. The proposed framework is structured in a way that can facilitate communication among involved decision-makers. Table 4.5 summarizes the above differences in functions of the proposed decision-support framework and other currently available PDS selection methods.

Table 4.6 The proposed framework vs. available PDS selection methods

	Guidance	Multi-attribute analysis	Knowledge- and experience-based methods	The proposed framework
Consider multiple criteria	Yes	Yes	Yes	Yes
Consider multiple PDSs	Yes	Yes	Yes	Yes
Explicitly consider time/cost trade-offs	No	No	No	Yes
Consider impacts of project interdependencies	No	No	No	Yes
"Design" a PDS to better meet the decision-making needs	No	No	No	Yes

4.6 Summary

This chapter presents a decision-support framework for designing and choosing a PDS among regulation-authorized PDSs in a multi-project environment. The proposed framework can help a decision-maker "design" alternative PDSs and evaluate them with respect to a set of PERF and general PDS criteria, while also taking into account project dependencies and possible time/cost trade-offs. The overall framework has five stages: (1) define project objectives/constraints; (2) identify regulation-authorized PDSs; (3) define evaluation criteria; (4) design and evaluate PDSs; (5) choose a PDS. After each stage is a gate that provides decision-makers the opportunity to review, discuss and verify the stage outputs. Such a stage-gate structure has the potential to facilitate communication among decision-makers and is easy to understand and implement. In addition, information is displayed to decision-makers in the form of performance profiles, which can help them identify the criteria by which a PDS may perform poorly. This allows decision-makers to develop proactive management strategies. The framework is developed based on concepts that are easy to understand and integrates techniques that have been used by industry practitioners. This is expected to increase the framework's applicability.

In the next chapter, a NPV-based method for deriving time/cost trade-off rules is presented. A procedure to evaluate project dependencies is described in Chapter 6. A case study that illustrates the application of the overall framework is presented in Chapter 7.

Chapter 5
NPV-based Method for Deriving Time/cost Trade-off Rules

5.1 Introduction

This chapter proposes a NPV-based method for deriving time/cost trade-off rules in the early project planning phase. In Section 5.2, some applications of the NPV method to project scheduling and time/cost trade-off analysis and their limitations are discussed. In Section 5.3, characteristics of the time/cost trade-off decision-making in the project planning phase are described. The proposed NPV-based method is explained in Section 5.4. Section 5.5 provides two illustrative examples using data collected from a wastewater treatment plant project in Taiwan. Limitations of the NPV-based method are discussed in Section 5.6, and a chapter summary is given in Section 5.7.

5.2 Previous Research

NPV is defined as the discounted sum of all expected future revenues minus the initial cost and the discounted sum of all expected future costs (Hirst 2001; Newan et al. 2004). The concept of NPV has been employed by a number of researchers to solve project scheduling and time/cost trade-off problems.

Russell (1970) was the first to consider the NPV of cash flows in a network and suggested that the maximization of NPV should be the ultimate objective. Other researchers further expand and/or enhance Russell's concept. For example, Elmaghraby and Herroelen (1990) and Yang et al. (1992) developed, respectively, a procedure and an integer-programming approach for scheduling a project to maximize its NPV. Smith-Daniels and Aquilano (1987) and Smith-Daniels and Smith-Daniels (1987) proposed an approach for project scheduling where the NPV of a project is maximized subject to capital and material constraints. Talbot (1982) proposed a computationally tractable integer-programming approach for solving a large class of non-preemptive resource-constrained project scheduling problems. Padman and Smith-Dainels (1993) proposed an optimization-guided heuristic approach to deal with resource-constrained project scheduling problems with an aim at maximizing a project's NPV. Finally, but not the least, Sunde and Lichtenberg (1995) presented a heuristic NPV cost/time tradeoff (CTTO) approach to help decision-makers balance cost, time and resources.

Even though the above mentioned approaches may help a decision-maker develop an optimal project schedule that maximizes the project's NPV, their applications to the time/cost trade-off analysis in the early project planning phase are limited for several reasons. First, almost all of these approaches are developed for a project with a complex network of activities. Their applications require the decision-maker to possess knowledge of detailed activity information (e.g., the detailed work breakdown structure and the estimated schedule and resource utilization of each activity). Such detailed activity-level information is generally not available in the early project planning phase. Even if such information is available, the employment of these methods often requires professional mathematical knowledge and computational/programming skills. Industrial practitioners may not possess these required knowledge and skills and/or prefer to have more straightforward methods (Solberg 1992). In addition, the special computational algorithms required by these methods may take weeks (or longer) to build; the decision-maker may only have limited time to make time/cost trade-off decisions in the project planning phase.

For the above reasons, there is a need for a method that can allow a decision-maker to rapidly perform time/cost trade-off analysis to support his/her trade-off decisions in the project planning phase. This method should also be able to be applied with macro-level project information and be easy to understand. The NPV-based method presented in this chapter can fill this gap.

5.3 Time/cost Trade-off Decisions in the Project Planning Phase

Time/cost trade-off decisions are made in almost all project phases. However, time/cost trade-off decision-makings at different project phases vary based on several factors: (1) the trade-off decision-makers; (2) the purposes of the trade-offs; (3) the levels and scopes of the trade-off decisions; (4) the information available for the trade-off decision-making.

In the project planning phase, a project owner establishes time and cost objectives and explores the availability of means to accomplish these two objectives. In project scheduling, the project owner estimates total project duration, develops project timelines, and determines major milestones. In terms of the project cost, the project owner estimates the total project cost, plans the cost distribution over different project phases, and considers financial sources. In this objective-establishment process, time/cost trade-offs are inevitable (or desirable). For example, a project's cost distribution is directly linked to the project's timeline. If it is estimated that the adequate financial resource will not be available at a certain time, the project owner may need to adjust the project timeline. Such adjustments may involve time/cost trade-off decisions.

Time/cost trade-off decisions in this planning phase focus on strategic-level considerations. This means that these decisions are made considering the entire project life cycle instead of a specific project phase. Assume that a project owner decides to allocate more money to the design phase to shorten the design duration. This decision will decrease the financial resources that can be allocated to other project phases (e.g., construction phase). In this case, certain adjustments to project timelines and cost distributions of other project phases are needed. Such adjustments may involve trade-offs between time and cost, not only within the same project phase, but also across different project phases.

Consider a project that is composed of two project phases. Each of the phases has its duration and associated cost. This creates six possible trade-off relationships between time and cost, as illustrated in Figure 5.1. These trade-off relationships are either within the same phase (as presented with solid lines) or across the two phases (as presented with dotted lines). Trade-off decisions made in the project planning may involve consideration of all, or any of, these six possible trade-off relationships.

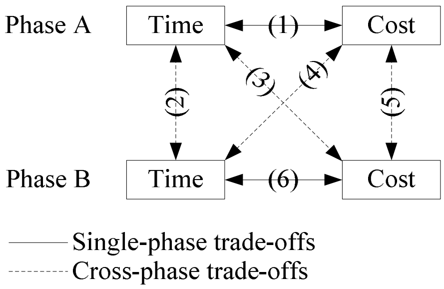


Figure 5.1 Possible time/cost trade-offs in a two-phase project

Another characteristic of the time/cost trade-off decisions in the project planning phase is that they have only limited and imprecise information available. For this reason, the trade-off decisions made in this phase generally rely heavily on the information from past similar projects.

5.4 The NPV-based Method

As discussed in the previous section, a method that can help a decision-maker make time/cost trade-off decisions in the project planning phase must: (1) be applied with limited information; (2) derive trade-off rules between time and cost within single phase and across different phases. This method also needs to be easily understood and applied.

The NPV-based method presented in this section meets all these requirements. First, a NPV method allows linkages to be made between duration and cost associated with the same project phase and across different phases. This would allow a decision-maker to determine time/cost trade-offs within single phase and across multiple phases. Second, a NPV calculation only requires macro-level project information (e.g., estimated phase durations and phase costs) that is available in the early project phase. Third, the NPV calculation has been widely performed in the project planning phase to assess a project's economic feasibility and/or to compare multiple investment opportunities (e.g., Ye and Tiong 2000). Certain information hence should be readily available. This can significantly reduce decision-makers' effort in performing a time/cost trade-off analysis. In addition, concepts and procedures of NPV calculation should be familiar to most practitioners. Even if this is not the case, the NPV concepts should be straightforward and easy to learn.

5.4.1 Basic concepts and assumptions

Project time and cost are highly interrelated. A variation in project duration will generally, if not always, result in a corresponding change in cost. A decision-maker needs to determine the value of a change in time (e.g., how much a 2-month decrease in duration is worth to them) so that he/she can make proper time/cost trade-off decisions. To determine this value of a change in time requires the knowledge of a "unit time value" (UTV). UTV is the value of a *time unit* to a decision-maker. A time unit can be hours, days, months or years, depending on the project owner's choices. After UTV is determined, the total time value (TTV) can be calculated by using the following equation, where TTV is total time value, UTV is the unit time value, and T is time. An application of UTV and TTV to the determination of value of time in innovative contracting methods (e.g., bidding on cost/time (A+B)) for highway projects can be found in Herbsman et al. (1995).

$$TTV=UTV\times T$$

For example, if a one-month reduction in time is valued at $30,000/m (UTV), and if the project duration can be reduced by 2 months (T), the total time value (TTV) of this reduction in project duration is $60,000 ($30,000/m×2m=$60,000). In other words, a decision-maker would be willing to pay an extra $60,000 to reduce the project duration by two months. The present NPV-based method can help a decision-maker determine this UTV.

The NPV-based method is developed based on two assumptions:

- A project does not have a single set of durations and costs but has several alternative sets of durations and costs that can achieve the same overall outcome. The outcome here refers to the baseline NPV.
- The estimated costs and benefits associated with a project phase are assumed to be uniformly distributed over the duration of that phase.

5.4.2 Process of the NPV-based method

The proposed framework is developed based on the basic concepts of an NPV calculation and a sensitivity analysis. It takes a few additional steps to convert the NPV calculation and sensitivity analysis results into trade-off rules. This is composed of three main stages: (1) create a baseline NPV; (2) calculate impacts of variable variations on the baseline NPV; (3) convert impact results to time/cost trade-off rules. Each of the stages can be further broken down into steps, as illustrated in Figure 5.2. In Figure 5.2, dotted lines represent the information flows (e.g., exchanges of information) and solid ones represent the process flows (e.g., sequence of steps). This process is repeated for all considered PDSs to determine time/cost trade-off rules in individual PDSs.

The following sections provide a step-by-step description of the NPV-based method. It should be noted that cash streams and timelines shown in the figures are used for demonstration purposes only; values in the tables are also hypothetical numbers.

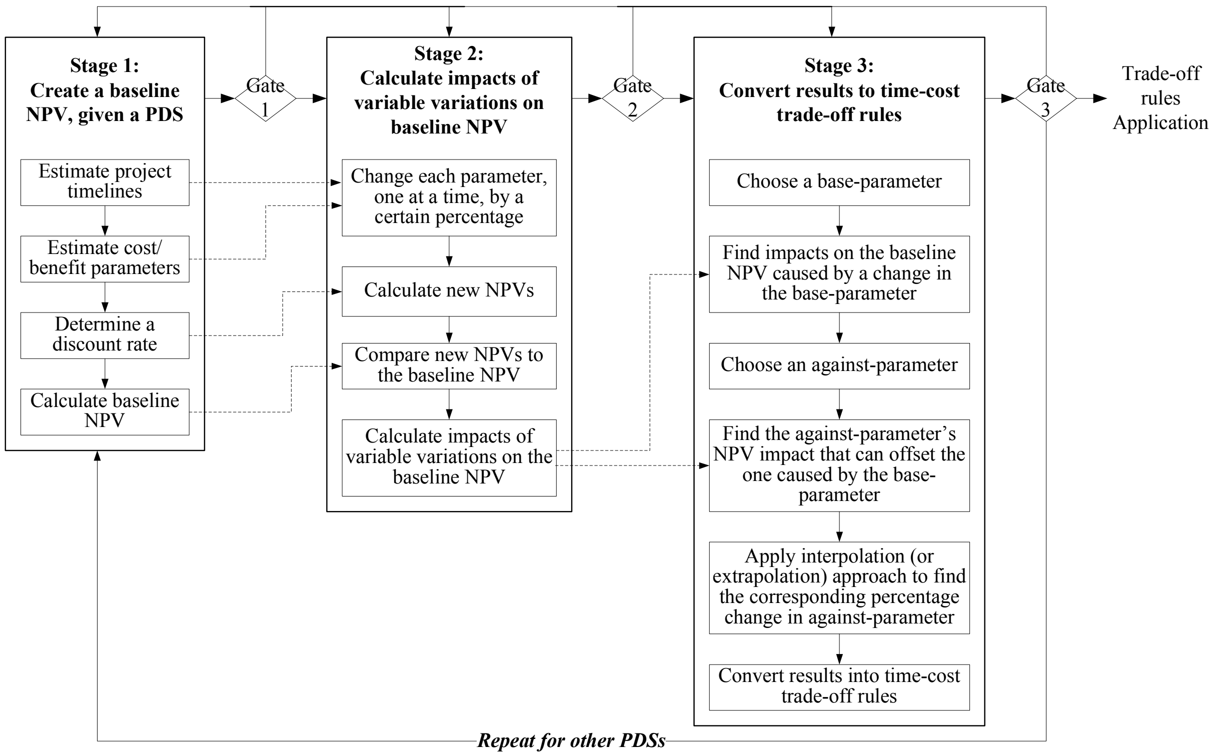


Figure 5.2 Process of the NPV-based method

5.4.2.1 Stage 1: Create a baseline NPV, given a PDS

The first stage of the NPV-based method is to create a baseline NPV, given a PDS. This is achieved through four steps: (1) estimate project timeline; (2) estimate cost/benefit parameters; (3) determine a discount rate; (4) calculate the baseline NPV.

Step 1: Estimate project timeline. To estimate the project timeline, a decision-maker first needs to deconstruct the project life cycle into individual phases. For instance, in DBB, a project life cycle is divided into planning (Plan), procurement (for design) (Pro(D)), design (D), procurement (for construction) (Pro(C)), construction (C), and operation/maintenance (O/M) phases. After these project phases are properly laid out, the decision-maker then estimates the duration of each project phase. These estimates can be made based on information from one (or several) previous similar projects with the same PDS, or on the decision-maker's experience. A 30-year life-span is used for the NPV calculation.

For PDSs that have not been fully authorized by regulations (e.g., DB and CMR), there may be no previous similar projects using the same PDSs. In this case, the decision-maker can first estimate the project timeline in DBB, and then use this information as a basis to develop the project timeline in the innovative PDS. Consider that a decision-maker is estimating the project timeline in DB and finding that there are no previous similar projects being implemented through DB. In this case, the decision-maker can first estimate the project timeline in DBB. Assume that the construction duration in DBB is estimated to be 10 months. Given that the construction speed of DB is about 12% faster than that of DBB (Konchar and Sanvido 1998), the construction duration in DB is thus estimated to be 9 months (10/1.12=9). Durations of other project phases in DB can also be estimated following the same process. More performance differences between DBB, DB and CMR can be found in Konchar and Sanvido (1998).

Step 2: Estimate cost/benefit parameters. Each project phase has costs and/or benefits. Examples of the costs and/or benefits associated with project phases in DBB are provided in Table 5.1.

Table 5.1 Examples of costs and benefits in DBB

Project phase	Cost/benefits
Planning	Project planning cost (e.g., preliminary feasibility study cost)
Procurement (design)	Procurement cost (e.g., designer selection process cost)
Design	Design cost (e.g., design fees, administrative cost)
Procurement (construction)	Procurement cost (e.g., contractor selection process cost)
Construction	Construction cost (e.g., direct and indirect construction cost, administrative cost, external advice fees)
Operation and maintenance	Operation/maintenance cost (e.g., cleaning and repair costs)
	Benefits (e.g., revenues)

Precise estimates of these parameters are neither possible nor feasible (both financially and technically) in the project planning phase due to the lack of detailed project information. However, a decision-maker can still make reasonable estimates based on historical data from previous similar projects and his/her experience. Costs associated with each of the project phases can be estimated individually, or on the basis of their relative percentages of the total project cost (e.g., 85% of the total project cost). The percentages of the costs of different project phases in different PDSs can be found in a paper by Kopplinen and Kahdenperä (2007). If no similar previous project is available for a specific PDS, the decision-maker can still begin with the cost estimating in DBB and use the estimates as a basis for the cost estimating in other PDSs.

Benefits occur when the operation/maintenance phase begins. Unlike cost estimating, benefit estimating is not so straightforward. Project benefits can be tangible and intangible. Tangible benefits are those that can be measured and expressed in monetary terms (e.g., revenue); intangible benefits are those that cannot be easily quantified (Dué 1989). Measurements and estimation methods for intangible benefits are different from case to case, and they are beyond the scope of this research. The present NPV-based method considers only the tangible benefits. Tangible benefits can be estimated based on the data from other similar projects and the forecast of future conditions.

The estimated costs and benefits of project phases are assumed to be uniformly distributed along their durations. An example of cost and benefit estimates in DBB is presented in Figure 5.3.

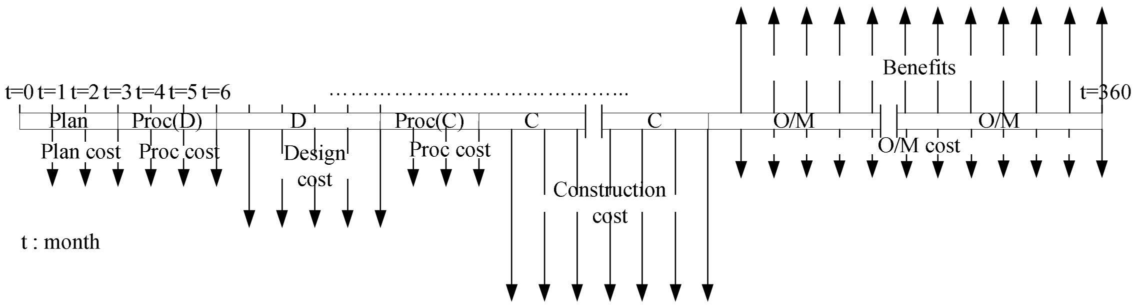


Figure 5.3 Example cost and benefit parameters in DBB

Step 3: Determine a discount rate. The selection of a discount rate can affect the NPV results. However, there are still are no strict rules for the selection of an appropriate discount rate. In this research, a discount rate of 4%, as recommended by the United States Office of Management and Budget (OMB), is adopted (OMB 2005). It is recognized that, in the past two decades, the OMB's recommendation for discount rates has varied greatly. For this reason, a sensitivity analysis is performed on different discount rates to investigate their impacts on the trade-off rules.

In some studies, different discount rates are applied to different time phases (e.g., 4% for year 1-5 and 3% for year 6-25) to reflect the uncertainty associated with the future. In this research, the discount rate is assumed to remain constant throughout the project life.

Step 4: Calculate project NPV. The discount rate determined in the previous step is used to discount the project's cash flow back to the present value using the following equation, where NPV is the net present value; t represents time; n is the analytic horizon; and r is the discount rate. This calculation can be performed using a spreadsheet program. The calculated NPV is defined as the baseline NPV.

$$NPV=\sum_{t=0}^{n}\frac{(\text{Revenues-Costs})_t}{(1+r)_t}$$

5.4.2.2 Stage 2: Calculate impacts of variable variations on the baseline NPV

This stage calculates impacts of variable variations on the baseline NPV. This is done through three distinctive steps. First, values of time and cost parameters are increased or decreased, one at a time, by a certain percentage (e.g., 5%, 10%, and 15%). Next, the new NPVs under each of these changes are calculated. These new NPVs are then compared to the baseline NPV to determine the impacts caused by the changes. These results are organized in a NPV variation table. An example NPV variation table that shows impacts of changes in construction duration and cost on the baseline NPV is shown in Table 5.2.

Table 5.2 Example NPV variation table: construction duration and construction cost

Phase	Parameter	Changes in parameters	Changes in the baseline NPV
Construction	Construction duration	+10%	-7.85%
		+5%	-3.94%
		0	0.00%
		-5%	3.94%
		-10%	7.85%
	Construction cost	+10%	-32.20%
		+5%	-16.10%
		0	0.00%
		-5%	16.10%
		-10%	32.20%

5.4.2.3 Stage 3: Derive time/cost trade-off rules

This stage is to derive time/cost trade-off rules from the NPV variant tables developed in the previous stage. This is done by answering the question: how can the impact caused by a change in one parameter on the baseline NPV be offset by a change in another parameter? Five steps can answer this question.

Step 1. A decision-maker chooses a parameter intended for trade-off (referred to as the base-parameter herein). For example, a decision-maker might want to shorten the construction duration by trading it off with another parameter. The construction duration here is defined as the base-parameter.

Step 2. The decision-maker identifies the impacts caused by the changes in the base-parameter on the baseline NPV in a NPV variation table. Consider the example from the previous step where the base-parameter is the construction duration. Referring back to Table 5.2, it is found that a 5% increase in the construction duration decreases the baseline NPV by 3.97%.

Step 3. The decision-maker chooses a parameter intended for trade-off against the base-parameter. This parameter is defined as the against-parameter. Consider the previous example again, if the decision-maker plans to trade off the construction duration (base-parameter) against the construction cost. Construction cost is defined as the against-parameter.

Step 4. The decision-maker identifies the impact on baseline NPV caused by a change in the against-parameter that can offset that caused by the base-parameter in a NPV variation table. Consider again the examples from the previous steps. It is known that a 5% increase in the construction duration causes the baseline NPV to decrease by 3.97%. The against-parameter is the construction cost. In this case, the decision-maker needs to find a percentage change in the construction cost that can increase the baseline NPV by 3.97% to offset the impact caused by the change in the construction duration. Referring back to Table 5.2, it is found that when the construction cost decreases by 5% and 10%, the baseline NPVs increases, respectively, by 16.1% and 32.2%. This tells the decision-maker that if the baseline NPV needs to be increased by 3.97%, the construction cost will need to be decreased by a percentage between 0% and 5%.

Step 5. From the previous step, it is known that the construction cost needs to be decreased by a percentage between 0% and 5%. In this step, the decision-maker uses interpolation (or extrapolation) to find the exact percentage change. The concept of a linear interpolation (or extrapolation) is visualized in Figure 5.4. The relationship between X_1, X_2, X_3, Y_1, Y_2, and Y_3 is presented in the equation after the figure.

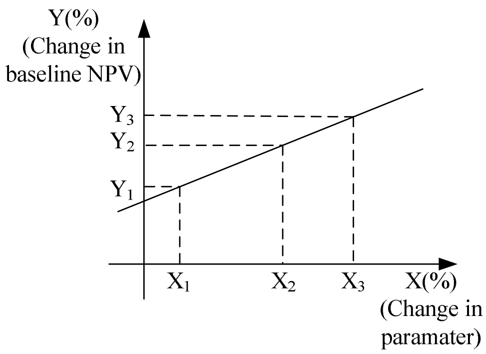


Figure 5.4 Concept of a linear interpolation (or extrapolation) approach.

$$\frac{(Y_2-Y_1)}{(Y_3-Y_1)} = \frac{(X_2-X_1)}{(X_3-X_1)}$$

Following the same example in Step 4, it is known that when construction cost is decreased by 5% (X_2) and 10% (X_3), the baseline NPVs will increase, respectively, by 16.1% (Y_2) and 32.2% (Y_3). The decision-maker is looking for the percentage change in construction cost (X_1) that can increase the baseline NPV by 3.97% (Y_1). By performing the extrapolation, X_1 is found to be 1.23%. This means that if the decision-maker plans to decrease the construction duration by 5% without affecting the baseline NPV, the maximum percentage of the increase in the construction cost that he/she would be willing to accept is 1.23%.

Step 6. The decision-maker converts the results of Step 5 into time/cost trade-off rules by using the following equation:

$$\text{UTV} = \frac{\text{Change in cost parameter (\$)}}{\text{Change in time parameter (months)}}$$

From the previous example, it is known that a 1.23% increase in the construction cost is the maximum amount of money that the decision-maker would be willing to pay to reduce the construction duration by 5%. In this same example, assume that the estimated construction duration and cost are 40 months and \$6,000,000. In this case, the decision-maker is willing to pay \$73,800 (\$6,000,000×1.23%=\$73,800) to shorten the construction duration by 2 months (40m×5%=2m). This gives us a UTV of \$36,900/m (\$73,800/2m=\$36,900/m). This UTV is the trade-off rule between the construction duration and construction cost. With this UTV, if the decision-maker plans to shorten the construction duration by 3 months, he/she would be willing to pay an extra \$110,700 (\$36,900/m×3=\$110,700) in the construction cost. On the contrary, if the decision-maker plans to save \$110,700 in the construction cost, the maximum acceptable extension in the construction duration would be 3 months.

By calculating the impacts of the individual parameters on the baseline NPV, a decision-maker can determine trade-off rules between any selected pair of time/cost parameters within a single phase (e.g., design duration vs. design cost) and across different phases (e.g., design duration vs. construction cost).

5.4.3 Sensitivity analysis

Due to the lack of detailed and precise information, estimates of the durations and costs of project phases inevitably have some degree of uncertainty. These uncertainties can affect the results of the time/cost trade-off rules. Among these estimates, durations and costs of design and construction phases are expected to have greater impacts on the trade-off rules than others. The use of different discount rates will also have significant impacts of the trade-off rules. A sensitivity analysis on these parameters is therefore recommended.

5.5 Illustrative Examples

Data used in illustrative examples are obtained from a wastewater treatment plant project in Taiwan (referred to as the Case Project). Detailed descriptions of the Case Project and the data collection process and methodology can be found in Chapter 7. This section presents the application of the NPV-based method to the Case Project for deriving time/cost trade-off rules in DBB (Section 5.5.1) and DB (Section 5.5.2).

5.5.1 Deriving time/cost trade-off rules in DBB

5.5.1.1 Stage 1: Create a baseline NPV

Step 1: Estimate project timelines in DBB. In DBB, the Case Project is divided into planning, procurement (for design), design, procurement (for construction), construction, test operation/maintenance, and official operation/maintenance phases. Estimated durations of each of the project phases are shown in Table 5.3. These estimates are made by the Case Project's project manager based on data from previous similar projects and experience. A 30-year life-span is used for the NPV calculation.

Table 5.3 Estimated phase durations in DBB

Project phase	Duration (month)
Planning	6
Procurement (for design)	2[1]
Design	20
Procurement (for construction)	4[2]
Construction	29
Operation/Maintenance (test)	6
Operation/Maintenance (official)	293
Total[3]	360

[1]One month is for document preparation; the other one month is for public advertising and designer selection.
[2]Three months are for document preparation; the other month is for public advertising and contractor selection.
[3]A 30-year life-span is used.

Step 2: Estimate cost/benefit parameters. The estimated cost/revenue distribution in DBB is presented in Table 5.4. The cost/benefit associated with a phase is assumed to be equally distributed in the duration of that particular phase. To estimate the costs of different project phases, the project manager first used a unit cost method to estimate the Case Project's construction cost. The designated capacity of the Case Project is 40,000 CMD. According to the construction cost data from past similar projects, the unit cost is about $1,250/CMD. The construction cost is thus estimated to be $50,000,000 (40,000CMD×$1,250/CMD=$50,000,000). The design cost is estimated to be 5.4% of the construction cost (Public Construction Commission Executive Yuan 2002), which is $2,700,000 (5.4%×$50,000,000=$2,700,000). The planning and procurement costs are estimated to be, respectively, 0.5% and 0.1% of the sum of the design and construction costs based on the project manager's experience and judgments. The sum of design and construction cost is $52,700,000. Thus, the planning cost is estimated to be $263,500 ($52,700,000×0.5%=$26,350); the procurement cost is estimated to be $52,700 ($52,700,000×0.1%=$52,700). The operation/maintenance cost and revenue are estimated based on data from past similar wastewater treatment plant projects.

Table 5.4 Estimated cost/revenue distribution in DBB

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917[1]	$52,700,000×0.5%=$263,500; $263,500/6=$43,917/m
	Procurement	8,783[2]	$52,700,000×0.1%=$52,700;$ 52,700/6=$8,783/m
	Design	135,000[3]	5.4%[1]×$50,000,000=$2,700,000; $2,700,000/20=$135,000/m.
	Construction	1,724,138	40,000CMD×$1,250/CMD=$50,000,000; $50,000,000/29=$1,724,138/m
	Operation/ Maintenance	271,849[4]	7.15 (NTD/m^3)×1,460 (10,000m^3/year)=10,439 million NTD/year=$271,849/m
Operation Revenue		778,395[5]	830,288 (NTD/day)×30days/m=24,908,640 NTD/m=$778,395/m.

[1]Estimated to be 0.5% of the sum of design and construction cost; the estimated duration of planning phase is 6 month.
[2]Estimated to be 0.1% of the sum of design and construction cost. The cost includes the procurement costs of two procurement phases (for design and for construction). Thus, the total duration is 6 months (two for design procurement and four for construction procurement).
[3]The % is specified in "Regulations for Selection and Fee Calculation of Technical Services Providers Entrusted by Entities," Public Construction Commission Executive Yuan, 2002, Taiwan. The design duration is 20 months.
[4]The operation/maintenance cost and revenue are estimated based on data from past wastewater treatment plant project; $1=32 NTD.
[5]There is no revenue during the test operation/maintenance phase.

Step 3: Determine a discount rate. The discount rate used for the NPV calculation is 4% (OMB 2005), and it is assumed to remain constant throughout the project life.

Step 4: Calculate the project NPV. The Case Project's cash flow diagram in DBB is shown in Figure 5.5. Given a 4% discount rate, the baseline NPV is approximately $28.79 million. Such an NPV calculation can be performed by an EXCEL spreadsheet.

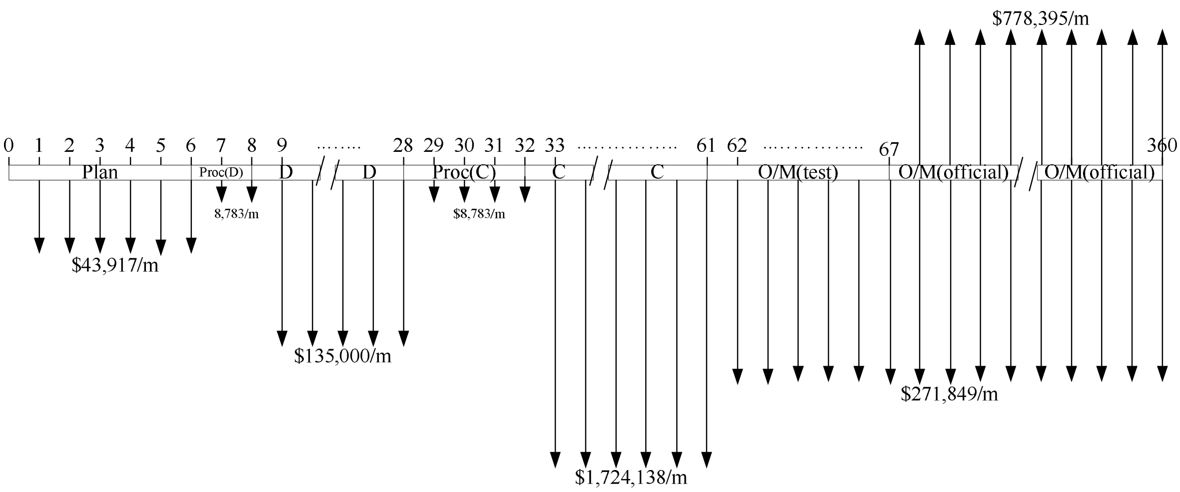


Figure 5.5 Case Project's cash flow diagram in DBB

5.4.1.2 Stage 2: Create NPV variants

This stage is to calculate variant NPVs. Among all project phases prior to the operation/maintenance phase, the design and construction are two phases that have the longest durations and consume the greatest cost. Their durations and costs have significant impacts on the project's NPV. For this reason, the calculation below focuses on the trade-off rules within and across these two phases. Figure 5.6 illustrates the six trade-off relationships. Variant NPVs under changes of each of the four parameters, namely, design duration (D_D), design cost (D_C), construction duration (C_D) and construction cost (C_C), are summarized in Table 5.5.

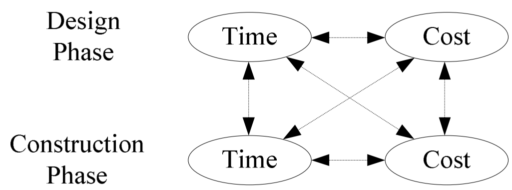


Figure 5.6 Trade-offs between design and construction phases

Table 5.5 Variant NPVs in DBB

Phase	Parameter	Changes in parameters	NPVs	Changes in the baseline NPV
Design	Time	10%	28,283,747	-1.76%
		5%	28,536,097	-0.88%
		0	28,789,292	0.00%
		-5%	29,043,337	0.88%
		-10%	29,298,233	1.77%
	Cost	10%	28,535,367	-0.88%
		5.0%	28,662,330	-0.44%
		0	28,789,292	0.00%
		-5%	28,916,255	0.44%
		-10.0%	29,043,218	0.88%
Construction	Time	10%	27,836,577	-3.31%
		5%	28,311,703	-1.66%
		0	28,789,292	0.00%
		-5%	29,269,359	1.67%
		-10%	29,751,914	3.34%
	Cost	4%	26,976,635	-6.30%
		2%	27,882,964	-3.15%
		0	28,789,292	0.00%
		-2%	29,695,621	3.15%
		-4%	30,601,949	6.30%

Note: columns marked in grey show the baseline NPV

5.5.1.3 Stage 3: Derive time/cost trade-off rules

Table 5.6 summarizes the trade-off rules between the duration and cost of the design and construction phases. Detailed explanations are provided after the table.

Table 5.6 Time/cost trade-off rules between design and construction phases in DBB

		Design		Construction	
		Duration (D_D)	Cost (D_C)	Duration (C_D)	Cost (C_C)
Design	Duration (D_D)	NA	- \$270,000/m	-1.32	-\$280,000/m
	Cost (D_C)	NA	NA	-\$355,263/m	-0.96
Construction	Duration (C_D)	NA	NA	NA	-\$362,069/m
	Cost (C_C)	NA	NA	NA	NA

Design Duration (D_D) vs. Design Cost (D_C). It is found in Table 5.5 that a 5% increase in the design duration will result in a 0.88% decrease in the Case Project's baseline NPV. This is because the starting date of the operation/maintenance phase is delayed, meaning a delay in revenue generation. To offset the impact caused by this change in the design duration, the NPV needs to be increased by 0.88%. Referring to Table 5.5, to increase NPV by 0.88%, the design cost needs to be reduced by 10%. In sum, if the design duration is increased by 5%, a decision-maker will need to reduce the design cost by 10% to prevent the baseline NPV from falling.

The Case Project's design duration and design cost are 20 months and \$2,700,000 (\$135,000/m×20m=\$2,700,000). A 5% increase in the design duration means one extra month (20m×5%=1m); a 10% decrease in the design cost means an extra \$270,000 (\$2,700,000×10%=\$270,000). This makes the trade-off rule between the design duration and design cost \$270,000/m (\$270,000/1m=\$270,000/m). The relationship between design duration and design cost is negative. This means that an increase in the design duration will require a decrease in the design cost.

Design Duration (D_D) vs. Construction Duration (C_D). As indicated in Table 5.5, a 5% increase in the design duration will result in a 0.88% decrease in the Case Project's baseline NPV. If the project manager wishes to trade off the design duration against the construction duration, he needs to find a percentage change of the construction duration that can increase the baseline NPV by 0.88%. Referring back to Table 5.5, a 5% and 10% decrease in the construction duration can result in, respectively, a 1.67% and 3.34% increase in the baseline NPV. Thus, in order to increase the baseline NPV by 0.88%, the construction duration needs to be reduced by a percentage between 0% and 5%. By performing an extrapolation, this percentage is found to be 2.63%. In brief, if the project manager plans to increase the design duration by 5%, the construction duration must be shortened by 2.63% to prevent the baseline NPV from falling.

The Case Project's design duration and construction duration are, respectively, 20 and 29 months. A 5% increase in the design duration means one extra month (20m×5%m=1); a 2.63% decrease in the construction duration equals a reduction of 0.76 month (29m×2.63%=0.76m). This makes the trade-off rule between the design duration and construction duration a negative 1.32 (1m/0.76m=1.32). This trade-off rule indicates that if the project manager plans to increase the design duration by 1.32 months, the construction duration should be shortened by one month.

Design Duration (D_D) vs. Construction Cost (C_C). The same process is applied to determine the trade-off rule between the design duration and construction cost. It is known that a 5% increase in the design duration will result in a 0.88% decrease in the Case Project's baseline NPV. From Table 5.5, it is found that the construction cost needs to be reduced by a percentage between 0% and 2% to increase the baseline NPV by 0.88%. An extrapolation calculation is performed, and this percentage is found to be 0.56%. This means that if the design duration is increased by 5%, the project manager will need to reduce the construction cost by 0.56% to prevent the baseline NPV from falling.

The Case Project's design duration and construction cost are 20 months and $50,000,000. A 5% increase in the design duration means one extra month (20m×5%=1m); a 0.56% decrease in the construction cost means an extra of $280,000 ($50,000,000×0.55%=$280,000). This makes the trade-off rule between the design duration and construction cost $280,000/m ($280,000/1m=$280,000/m), with a negative relationship. In other words, if the project manager plans to increase the design duration by one month, the construction cost should be reduced by $280,000.

Design Cost (D_C) vs. Construction Duration (C_D). From Table 5.5, it is found that a 5% increase in the design cost will result in a 0.44% decrease in the Case Project's baseline NPV. Table 5.5 also shows that, to offset this 0.44% decrease in the baseline NPV, the construction duration needs to be reduced by a percentage between 0% and 5%. This percentage is found to be 1.32% by performing an extrapolation. This means that if the project manager wishes to increase the design cost by 5% without affecting the baseline NPV, the construction duration should be reduced by 1.32%.

The Case Project's design cost and construction duration are $2,700,000 and 29 months. A 5% increase in the design cost means an extra $135,000 ($2,700,000×5%=$135,000); a 1.32% decrease in the construction duration equals a reduction of 0.38 month (29m×1.32%=0.38m). This makes the trade-off rule between the design cost and construction duration a negative $355,263/m ($135,000/0.38m=$355,263/m). This trade-off rule indicates that if the project manager plans to increase the construction duration by one month, the design cost should be reduced by $355,263 to prevent the baseline NPV from falling.

Design Cost (D_C) vs. Construction Cost (C_C). Table 5.5 shows that a 5% increase in the design cost will result in a 0.44% decrease in the Case Project's baseline NPV. To offset this impact, the baseline NPV needs to be increased by 0.44% by changing the construction cost by a certain percentage. Referring back to Table 5.5, it is found that this percentage is between 0% and 2%. By performing an extrapolation, this percentage is found to be 0.28%. In sum, if the project manager plans to increase the design cost by 5%, the construction cost should be reduced by 0.28% to avoid the baseline NPV falling situation.

The design cost and construction cost are, respectively, $2,700,000 and $50,000,000. A 5% increase in the design cost equals an extra $135,000 ($2,700,000×5%=$135,000); a 0.28% decrease in construction cost equals a reduction of $150,000 ($50,000,000×0.28%=$140,000). This makes the trade-off rule between the design cost and construction cost negative 0.96 ($135,000/$140,000=0.96). This trade-off rule means that if the project manager plans to increase the design cost by $0.96, the construction cost should be reduced by $1.

Construction Duration (C_D) vs. Construction Cost (C_C). As shown in Table 5.5, a 5% increase in the construction duration will result in a 1.66% decrease in the Case Project's baseline NPV. Table 5.5 also shows that the construction cost needs to be reduced by a percentage between 0% and 2% to offset this impact. An extrapolation calculation is performed and this percentage is found to be 1.05%. If the project manager plans to increase the construction duration by 5%, the construction cost should be decreased by 1.05% to prevent the baseline NPV from falling.

The Case Project's construction duration and construction cost are 29 months and $50,000,000. A 5% increase in the construction duration represents an extra 1.45 months (29m×5%=1.45m); a 1.05% decrease in the construction cost equals a reduction of $525,000 ($50,000,000×1.05%=$525,000). This makes the trade-off rule between the construction duration and construction cost negative $362,069/m ($525,000/1.45m=$362,069/m). This trade-off rule indicates that if the project manager plans to increase the construction duration by one month without affecting the baseline NPV, the construction cost should be reduced by $362,069.

5.5.2 Deriving time/cost trade-off rules in DB

5.5.2.1 Stage 1: Create a baseline NPV

Step 1: Estimate project timelines in DB. In DB, the Case Project is divided into planning, procurement (for design/build), design/build, and test and official operation/maintenance phases. The planning phase in DB is estimated to be 3 months longer than it is in DBB because of the complexity associated with the DB project planning. The DB procurement phase is also extended to 6 months, in which four months are for procurement document preparation and two month are for public advertising and design/builder selection (as required by Taiwan's procurement regulations). Because there were no other similar wastewater treatment plant projects implemented through DB in the past, the project manager estimated the duration of the design/build (D/B) phase based on his experience with other types of public projects.

The project manager compared the project durations of two similar public projects he had previously supervised: one in DBB and the other one in DB. He found that the project's delivery speed (including design and construction durations) in DB is about 30% faster than in DBB. This number is considered acceptable after being cross-checked with the data from Konchar and Sanvido (1998), which suggested that the delivery speed of DB is about 33% faster than that of DBB. The Case Project's project manager then used 30% as a basis to adjust the phase durations in DBB to obtain the estimated D/B duration in DB. In DBB, the estimated design and construction durations are, respectively, 20 and 29 months. Thus, the D/B duration in DB was estimated to be 34 months (49m×70%=34m). The duration of each of the project phases in DB is summarized in Table 5.7. A 30-years life-span is used for the NPV calculation.

Table 5.7 Estimated phase durations in DB

Project phase	Duration (month)
Planning	9
Procurement (for design/build)	6[1]
Design/Build	34
Operation/Maintenance (test)	6
Operation/Maintenance (official)	305
Total	360

[1]Four months are for document preparation; the other two months are for public advertising and design/builder selection.

Step 2: Estimate cost/benefit parameters. The estimated cost/revenue distribution in DB is presented in Table 5.8. The monthly planning, procurement, and operation/maintenance costs, and the monthly operation/maintenance revenue, are the same as those in DBB. According to Konchar and Sanvido (1998) the unit cost in DB is about 6% less than in DBB. The unit cost in DBB is estimated to be $1,250/CMD. This makes the unit cost in DB approximately $1,175/CMD ($1,250×0.94=$1,175). The Case Project's construction cost in DB is thus estimated to be $47,000,000 (40,000CMD×$1,175 /CMD=$47,000,000). The design cost is 5.4% of the construction cost (Public Construction Commission Executive Yuan, 2002), which is $2,538,000 (5.4%×$47,000,000=$2,538,000). Thus, the total D/B cost is estimated to be $49,538,000.

Step 3: Determine a discount rate. The discount rate used for NPV calculation is 4% (OMB 2005), and it is assumed to remain constant throughout the project life.

Step 4: Calculate the project's NPV. The Case Project's cash flow diagram in DB is shown in Figure 5.7. Given a 4% discount rate, the NPV is approximately $34.3 million.

Table 5.8 Estimated cost/revenue distribution in DB

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB
	Procurement	8,783	Same as in DBB
	Design/Build	1,457,000	40,000CMD×$1,175/CMD[1]=$47,000,000; 5.4%×$47,000,000=$2,538,000; $47,000,000+$2,538,000 =$49,538,000; $49,538,000/34m= $1,457,000/m
	Operation/ Maintenance	271,849	Same as in DBB
Operation Revenue		778,395	Same as in DBB

[1] It is estimated that the unit cost in DB is 6% less than it is in DBB (Konchar and Sanvido 1998).

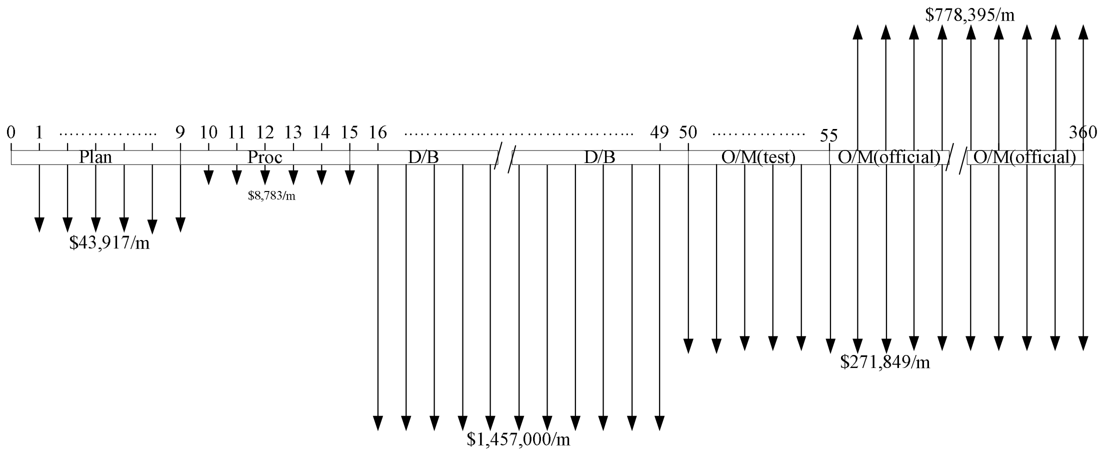


Figure 5.7 Case Project's cash flow diagram in DB

5.5.2.2 Stage 2: Create NPV variants

This stage is to change time and cost parameters, one parameter per time, to see how a particular change affects the baseline NPV. As the design and construction are integrated into a single phase in DB, only the trade-off rule between D/B duration and D/B cost is calculated, as illustrated in Figure 5.8. Variant NPVs under changes of each of the two parameters, namely, D/B duration (D/B_D) and D/B cost (D/B_C), are summarized in Table 5.9.

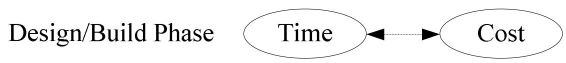


Figure 5.8 Trade-offs between D/B duration and D/B cost

Table 5.9 Variant NPVs in DB

Phase	Parameter	Changes in parameters	NPVs	Changes in the baseline NPV
Design/Build	Time	10%	33,118,047	-3.42%
		5%	33,701,898	-1.71%
		0	34,289,332	0.00%
		-5%	34,880,370	1.72%
		-10%	35,475,033	3.43%
	Cost	4%	32,510,860	-5.19%
		2.0%	33,400,096	-2.59%
		0	34,289,332	0.00%
		-2%	35,178,567	2.59%
		-4.0%	36,067,803	5.19%

Note: Columns marked in grey show the baseline NPV

5.4.2.3 Stage 3: Derive time/cost trade-off rules

From Table 5.9, it is found that a 5% increase in the D/B duration will result in a 1.71% decrease in the Case Project's baseline NPV. To offset the impact caused by this change in the D/B duration, the NPV needs to be increased by 1.71%. Referring to Table 5.9 again, to increase NPV by 1.77%, the D/B cost needs to be reduced by a percentage between 0% and 2%. By performing an extrapolation, this percentage is found to be 1.32%. This means that if the project manager plans to increase the D/B duration by 5%, the D/B cost should be reduced by 1.32% to prevent the baseline from falling.

The Case Project's D/B duration and D/B cost are estimated to be 34 months and \$49,538,000. A 5% increase in the D/B duration means an extra 1.7 months (34m×5%=1.7m); a 1.32% decrease in the D/B cost equals a reduction of \$653,901 (\$49,538,000×1.32%=\$653,901). This makes the trade-off rule between the D/B duration and D/B cost \$384,647/m (\$653,901/1.7m=\$384,647/m), with a negative relationship. This trade-off rule indicates that if the project manager plans to increase the D/B duration by one month without affecting the baseline NPV, the D/B cost should be reduced by \$384,647, as presented in Table 5.10.

Table 5.10 Time/cost trade-off rules between D/B duration and D/B cost in DB

		Design/Build	
		Duration (D/B_D)	Cost (D/B_C)
Design/Build	Duration (D/B_D)	NA	- \$384,647/m
	Cost (D/B_C)	NA	NA

5.4.3 Sensitivity analysis

As discussed in Section 5.4.3, the use of different discount rates can significantly affect the Case Project's NPVs, and hence the time/cost trade-off rules. For this reason, a sensitivity analysis using two additional discount rates, namely, 2% and 6%, is performed to illustrate how trade-off rules vary. The results are summarized in Table 5.11. This table provides the project manager with a quick and easy reference to make time/cost trade-off decisions under different economic conditions.

Table 5.11 Time/cost trade-off rules in DBB and DB under different discount rates

		Discount Rates		
		2%	4%	6%
DBB	D_D vs. D_C	- $382,590/m	- $270,000/m	- $167,400/m
	D_D vs. C_D	-1.11	-1.32	-1.69
	D_D vs. C_C	-$380,000/m	-$280,000/m	-$180,000/m
	D_C vs. C_D	-$411,962/m	-$355,263/m	-$280,432/m
	D_C vs. C_C	-1.0	-0.96	-0.93
	C_D vs. C_C	-$420,690/m	-$362,069/m	-$306,896/m
DB	D/B_D vs. D/B_C	- $445,842/m	- $384,647/m	- $323,454/m

5.6 Limitations of the NPV-based Method

The proposed NPV-based method is limited because it only considers project benefits that can be measured in monetary terms (tangible benefits) in the NPV calculation process. Intangible benefits are not considered, although they may also play a role in the trade-off decision-making process. For example, the early completion of the Case Project can contribute to improvement in the quality of water treatment, which significantly reduces the impact to the environment. If this intangible benefit is taken into consideration, the project manager may be willing to pay more for earlier project completion.

Additionally, the proposed NPV-based method needs to be combined with a decision-maker's careful judgments as to what are reasonable project durations and costs. Take the Case Project's construction duration as an example. When the reality is not considered, the proposed method can permit a reduction in the construction duration from 29 months to one month (or even less). According to the trade-off rules shown in Table 5.6, in DBB, this reduction in the construction duration will increase the project cost by $10,500,000. Even if the Case Project does not have a budget limit, in reality it is still not practical (or feasible) to complete the construction of a 40,000 CMD-capacity wastewater treatment plant within one month. For this reason, when using the proposed method to derive time/cost trade-off rules, a decision-maker should have an idea about reasonable phase durations and costs. In the above example, if 20 months is considered to be the reasonable minimum construction duration for the Case Project (on the premise of not affecting construction quality), the project manager should not attempt to shorten the construction duration to less than 20 months by simply trading it off against cost.

5.7 Summary

Time/cost trade-off decisions can be inevitable during the project planning phase in establishing project time and cost objectives. In this phase, time/cost trade-off decisions are considered on the strategic-level. This means that, when making a time/cost trade-off decision, a decision-maker needs to consider all project life cycle phases instead of individual project phases. To do this, the decision-maker will need the trade-off rules between time and cost across different project phases, in addition to those within a single project phase. The NPV-based method presented in this chapter can help the decision-maker derive such trade-off rules with only macro-level project information.

The present method is developed based on the concepts of a NPV method with a sensitivity analysis, but the method takes a step further to convert the sensitivity analysis results to trade-off rules. The method consists of three stages: (1) create baseline NPV; (2) calculate impacts of variable variations on the baseline NPV; (3) convert impact results to time/cost trade-off rules. When applied to a case study project in Taiwan, the method is proven to help the project manager make more explicit and objective time/cost trade-off decisions in the project planning phase. The derived trade-off rules can help the project manager understand what to give up on one objective (e.g., time) for a performance increase on the other objective (e.g., cost). It also provides the project manager the opportunity to conduct a scenario analysis for different sets of project durations and costs. All these can contribute to effective project planning and informed PDS decision-making.

The proposed method, however, needs to be used with a decision-maker's careful judgment as to what are reasonable project phase durations and costs. The proposed method is also limited in that it considers only the tangible project benefits in its analysis process.

Chapter 6
Procedure to Evaluate Project Dependencies

6.1 Introduction

As previously discussed, currently available PDS selection methods fail or are insufficient at taking into account project dependencies in their PDS evaluation processes. Consequently, a PDS may be selected based on an unrealistic expectation of what it can achieve. In this chapter, a procedure that can help a decision-maker systematically evaluate impacts of project dependencies on the new project's estimated time and cost in different PDSs is proposed. The proposed procedure not only helps a decision-maker make more realistic time and cost estimates, but the procedure also allows the decision-maker to identify possible project implementation bottlenecks in the project planning phase.

This chapter is structured as follows. Section 6.2 discusses the basic concepts and assumptions of the proposed procedure. A discussion on the three dimensions -namely, types, degrees and precedence relationships - of project dependencies is provided in Section 6.3. The procedure to evaluate impacts of project dependencies on a project's estimated time and cost given a PDS is described in Section 6.4. Section 6.5 provides an illustrative example. Section 6.6 gives the chapter summary.

6.2 Basic Concepts and Assumptions

Dependencies exist *"when actions taken by one referent system affect the actions or outcomes of another referent system"* (McCann and Ferry 1979). Giachetti (2006) expanded this definition to include "the degrees" of the dependencies by stating that *"dependency is the degree to which the actions or outcomes of one task affect the actions or outcomes of a second task."* These definitions capture the two important dimensions of dependencies. First, dependencies occur between tasks; second, dependencies can have different degrees of impacts on the referent task. Section 6.3 provides a more detailed discussion of these two dimensions.

The procedure proposed in this chapter attempts to help a decision-maker systematically evaluate impacts of project dependencies on a project's estimated time and cost given a PDS. Its development is based on the following three assumptions:

- Given the same PDS, a project can be implemented with different sets of durations and costs. This means that trade-offs between time and cost are possible and allowed.

- It is also assumed that project phases can be separated and/or split. For instance, in DBB, after the design phase is completed, a project manager can temporarily hold the project and delay the starting date of the construction phase; or, a project manager can divide the project's construction phase into multiple sub-phases.

- When dependencies occur between two projects, either one of them can be modified to accommodate the impacts caused by these dependencies. However, the proposed procedure assumes that the modifications are made primarily to the new project. This is based on the assumption that when a project is contracted out with a private contractor, its implementation is restricted by the contract provisions. Making modifications to such projects can be difficult and costly.

6.3 Three Dimensions of Project Dependencies

6.3.1 Types of project dependencies

There are many types of project dependencies. Several different classification schemes are found. For example, Giachetti (2006) divided dependencies into two groups: direct and indirect. Dependency is considered to be direct when Project A requires an action by Project B (e.g., delivery of materials); it is indirect when Project A requires an action of Project B contingent on the Project A's own action (e.g., delivery of materials according to a production schedule generated by Project A).

Kiggundu (1981) identified two groups of task dependencies: initiated and received. Initiated task dependency is the degree to which work flows from a particular task to one or more other tasks; received task dependency is the extent to which a task is affected by workflow from one or more other tasks. In this research, project dependencies are grouped according to their sources. Figure 6.1 shows the two groups of project dependencies that are treated in this research.

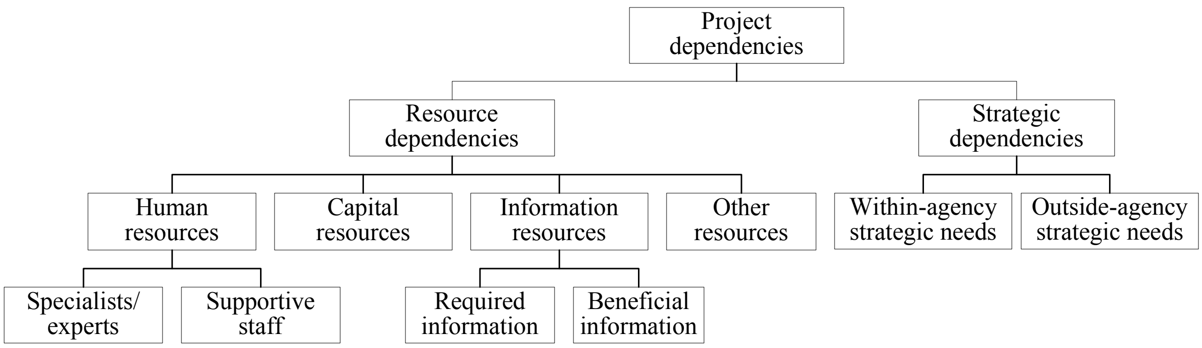


Figure 6.1 Two groups of project dependencies

6.3.1.1 Resource dependencies

Resource dependencies usually result from a decision-maker's resource allocation decisions. An organization has only limited resources with which to implement its projects. A decision to allocate certain resources to one project takes away resources from another project. When projects need to share and compete for resources (e.g., labor, funding and facilities), resource dependencies arise. A consideration of resource dependencies and a proper resource allocation are critical to multi-project management (Ferns 1991; Pellegrinelli 1997; Gray 1997). In this research, four types of resources are considered: human, capital, information and others.

Human resources. Human resource dependencies arise when multiple projects share/compete for the same pool of human resources. Human resources here are grouped into specialists and supportive staff. The availability of human resources, especially the specialists, can have a direct impact on project performance.

Assume that a new project is to be implemented using DB. The preparation of DB procurement documents and the management of the DB procurement process will require a DB-experienced project manager. Assume further that all DB-experienced project managers in the agency are currently occupied by other projects. Under this circumstance, the schedule of the new project will depend on the progress of other projects. If one of the ongoing projects is completed ahead of schedule, its project manager will be freed up for the new project earlier than planned. This means that the new project's procurement phase may be started earlier than planned. On the contrary, if other ongoing projects are delayed, the new project's procurement phase will also be delayed.

Capital resources. Capital resource dependencies exist between projects that compete for the same source of capital. When considering capital resource dependencies, a decision-maker needs to consider both the amount of the required capital and the time when the capital is needed. The unavailability of capital can also significantly affect project performance.

Information resources. Information resource dependencies exist among projects that share the same pieces of information. Information can be categorized based on its necessity to an activity/phase: required and beneficial. Required information is the information that is necessary for a project activity/phase to proceed. The availability of such information will have a direct impact on project schedule, and possibly an indirect impact on project cost. Consider that the design of Project A cannot proceed without certain information from Project B. If Project B fails to deliver such information on time, Project A will be delayed. On the other hand, if Project B is ahead of schedule, meaning that such information can be available earlier, the design of Project A may proceed earlier than planned. Either way, the Project A's planned schedule is directly affected.

Beneficial information, on the other hand, is not necessary for the implementation of an activity/phase. But its availability may improve project performance (e.g., save project cost and/or time). For example, procurement documents prepared for a project can be reused, with some modifications, in other similar projects. This can save a project manager time, effort and money.

Other resources. There are also other types of resources. For example, if two projects need to share the same construction space, space dependencies arise. The specialized contractor is also a type of resource. Assume that the new project requires a contractor with specific technological knowhow or capabilities, and it is found that such qualified contractors are occupied by other projects. In this case, the new project's schedule may need to be adjusted to this situation.

6.3.1.2 Strategic dependencies

Strategic dependencies are primarily the results of a decision-maker's strategic consideration (e.g., political consideration). Such types of dependencies are very common among public projects. In this research, strategic dependencies are divided into two groups: within-agency and outside-agency. Both can have direct impacts on the project schedule.

Within-agency strategic dependencies. Within-agency strategic dependencies are determined more or less arbitrarily by the agency's senior managers based on the agency's strategic needs or the managers' subjective project priority-setting. Strategic needs can be the results of a resource availability consideration. For example, a decision-maker may require a project to be completed by a certain date to free up human resources for other projects. Strategic needs can also be the results of political consideration, such as when a project is required to be completed by a certain date to fulfill a political promise.

Outside-agency strategic dependencies. Outside-agency strategic dependencies exist among the new project and outside projects. Such dependencies can result from some upper-level plans. For instance, assume that a public agency is developing a new highway project, and this project is a part of a regional development plan. In the same regional development plan, there is another railway project which is developed and supervised by another public agency. Assume further that the regional development plan aims to improve the local economy and the area's livability within 5 years. To achieve this goal requires the completion of the above two transportation projects. In this case, there exists an outside-agency strategic dependency between these two projects. The public agencies in charge of these projects may need to coordinate with each other to set up the project completion dates.

6.3.2 Degrees of project dependencies

Giachetti (2006) and Kiggundu (1981) suggested that criticality is one important dimension of dependency. Not all dependencies have the same degree of impact on project performance. In this research, the dependency criticality is measured by three degrees: (1) slightly dependent; (2) somewhat dependent; (3) highly dependent.

Consider an example where the implementation of Project A depends to a certain degree on Project B. If Project A can still be successfully implemented even without Project B's deliverables, this project dependency is assessed to be slightly dependent. When the delays in Project B deliverables are likely to cause similar delays in Project A, this project dependency is determined to be somewhat dependent. Finally, if Project A cannot proceed without Project B's deliverables, this project dependency is considered to be highly dependent. In this case, if things of Project B are out of control, Project A's outcomes will be adversely affected.

To determine the degrees of project dependencies is a critical step in the choice of proper dependency management strategies (McCann and Ferry 1979). A decision-maker may choose different management strategies for the project dependencies with different degrees. For slightly dependent project dependencies that have no (or minimum) impact on project performance, a close monitoring program and progress reporting are considered sufficient. For somewhat dependent project dependencies that may affect project performance, some additional management strategies may be necessary. For instance, the decision-maker may integrate some flexibility in the project planning to account for possible impacts caused by these dependencies. For strongly dependent project dependencies that can have direct impacts on project performance, more aggressive management strategies are required. For example, the decision-maker may need to adjust the project schedule and develop proactive management strategies to accommodate potential impacts caused by these project dependencies. Table 6.1 provides descriptions of these three degrees of project dependencies and their possible management strategies.

Table 6.1 Degrees of project dependencies and management strategies

Degrees	Description	Management strategies
Slightly dependent	The project can still be successful without deliverables from its linkage project.	• Closely monitor the progress of the linkage project
Somewhat dependent	The project may be delayed without deliverables from its linkage project.	• Allow some flexibility in project planning to account for possible delays. • Closely monitor the progress of the linkage project
Highly dependent	The project cannot proceed without deliverables from its linkage project.	• Re-adjust project schedule to accommodate effects of project dependencies. • Create proactive project management strategies to minimize possible impacts of project dependencies. • Closely monitor the progress of the linkage project.

6.3.3 Precedence relationships of project dependencies

The precedence relationships resulting from project dependencies can be different. Take the project dependency between Project A and its linkage Project B as an example. This project dependency may constrain Project A to proceed only after Project B is completed. Or, it may require Project A and Project B to be completed at the same time. Or, Project A needs to be completed by a certain percentage at the time when Project B's deliverables are available. Table 6.2 describes how the precedence relationships of project dependencies are defined in this research.

Table 6.2 Definitions of precedence relationships

<table>
<tr><td colspan="2">Precedence relationships</td><td>Definition</td></tr>
<tr><td rowspan="4">Basic</td><td>Start-to-Start (SS)</td><td>A phase of one project can only be started when (or after) a phase of another project is started.</td></tr>
<tr><td>Start-to-Finish (SF)</td><td>A phase of one project needs to be finished at the time when a phase of another project begins.</td></tr>
<tr><td>Finish-to-Start (FS)</td><td>The start of a phase of one project is dependent on the finish of a phase of another project.</td></tr>
<tr><td>Finish-to-Finish (FF)</td><td>A phase of one project can be finished only after a phase of another project is finished.</td></tr>
<tr><td colspan="2">Precedence relationships with "percent complete"</td><td>A "percent complete" is added to the precedence relationships to indicate the relative position of the connecting points in the project phases.</td></tr>
</table>

6.3.3.1 Basic types of precedence relationships

In this research, four types of precedence relationships are used to define project dependencies. They are: (1) Start-to-Start (SS), (2) Start-to-Finish (SF), (3) Finish-to-Start (FS), (4) Finish-to-Finish (FF). These four types of precedence relationships are widely used in the construction industry for project scheduling, such as in CPM (Meredith and Mantel 2003). Industry practitioners should thus have little, if any, difficulty understanding these concepts. Their descriptions for the purposes of this research are described below.

Start-to-Start (SS). SS is a relationship in which the start of a project phase is dependent on the start of a phase of another project. An example is shown in Figure 6.2. As Figure 6.2 shows, a SS relationship exists between Phase X of Project A and Phase Y of Project B (denoted as S_XS_Y). This means that Phase Y of Project B can only start at (or after) the time when Phase X of Project A starts.

Start-to-Finish (SF). A SF relationship means that a project phase needs to be finished at the time when a phase of another project begins. Figure 6.3 shows an example where a SF relationship exists between Phase X of Project A and Phase Y of Project B (denoted as S_XF_Y). This means that at the time when Phase X of Project A begins, Phase Y of Project B needs to be completed.

Finish-to-Start (FS). FS is a relationship in which the start of a project phase is dependent on the finish of a phase of another project. Figure 6.4 shows such a relationship between Phase X of Project A and Phase Y of Project B (denoted as F_XS_Y). Under this relationship, Phase Y of Project B can only be started when (or after) Phase X of Project A is completed.

Finish-to-Finish (FF). A FF relationship requires a project phase to be finished only after a phase of another project is finished. As shown in Figure 6.5, a FF relationship exists between Phase X of Project A and Phase Y of Project B (denoted as F_XF_Y). This means that Phase X of Project A and Phase Y of Project B need to be finished at the same time.

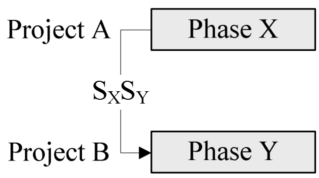


Figure 6.2 Start-to-Start (SS)

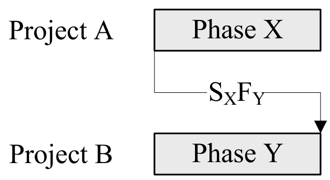


Figure 6.3 Start-to-Finish (SF)

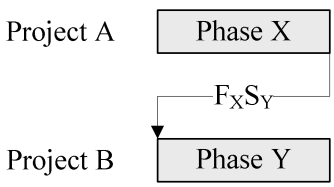


Figure 6.4 Finish-to-Start (FS)

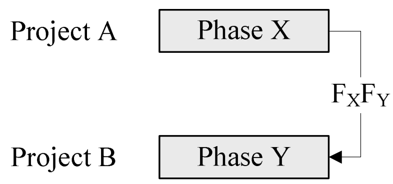


Figure 6.5 Finish-to-Finish (FF)

6.3.3.2 Precedence relationships with "percent complete"

In the above four basic precedence relationships, the connecting points of the two different projects' phases are assumed to be either their starting points or their ending points. In practice, however, there are also some cases where the project dependency constrains a certain time point in a project phase. In this case, "a percent complete" is added to the above precedence relationships to indicate the relative position of the connecting point in that particular phase. Figures 6.6 and 6.7 show two examples. Figure 6.6 shows a FS relationship between Phase X of Project A and Phase Y of Project B; Phase Y of Project B can only start when (or after) Phase X of Project A is 60% completed (denoted as $F_X(60\%)S_Y$). Figure 6.7 indicates a FF relationship between Phase X of Project A and Phase Y of Project B; when Phase X of Project A is 10% completed, Phase Y of Project B needs to be 90% completed (denoted as $F_X(10\%)F_Y(90\%)$).

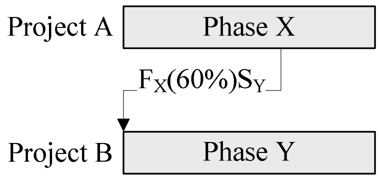


Figure 6.6 FS with percent complete

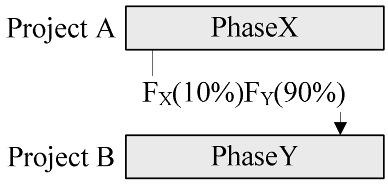


Figure 6.7 FF with percent complete

6.4 Procedure to evaluate project dependencies

The procedure to evaluate the impacts caused by project dependencies on the new project's estimated schedule and cost has five distinct stages: (1) identify interrelated projects; (2) define project dependencies; (3) evaluate impacts caused by project dependencies on the new project estimated schedule given a PDS; (4) choose project dependency management strategies; (5) adjust the new project's estimated schedule and cost by applying the predefined time/cost trade-off rules. The last three steps are repeated for all PDSs that are under evaluation. This procedure is illustrated in Figure 6.8 and explained stage-by-stage in the rest of this section.

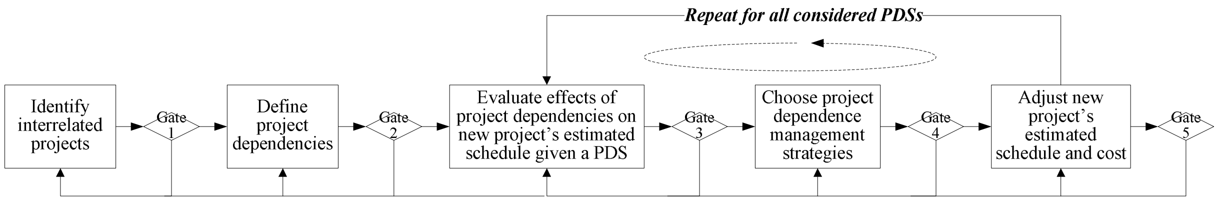


Figure 6.8 Procedure to evaluate project dependencies: overview

6.4.1 Stage 1: Identify interrelated projects

In this first stage, a decision-maker identifies projects that are interrelated with the new project. These interrelated projects can be physical and non-physical projects (e.g., approval of budget) that are inside and outside the agency. The decision-maker also needs to collect information about the identified interrelated projects. Such information includes, but is not limited to, the projects' PDSs (for physical projects), current status, anticipated future timelines (major milestones for non-physical projects) and required resources.

6.4.2 Stage 2: Define project dependencies

In this stage, the decision-maker defines the types (e.g., resource dependencies or strategic dependencies), the degrees (e.g., slightly dependent, somewhat dependent or highly dependent) and the precedence relationships (e.g., SS, FS or FF) of each of the project dependencies.

6.4.3 Stage 3: Evaluate impacts caused by project dependencies on the new project's estimated schedule, given a PDS

Making dependencies visible to a decision-maker is critical to their successful management (Thiry 2004). For this reason, a project dependency diagram for each of the considered PDSs is created to assist the decision-maker in evaluating project dependencies. A project dependency diagram can show the estimated timeline of the new project given a PDS. It also shows the current status and anticipated timelines of the interrelated physical projects and the milestones of non-physical projects. In addition, the precedence relationships of the dependencies between the new project and its interrelated projects are indicated. Figure 6.9 is an example of such a project dependency diagram.

Figure 6.9 shows the new project's timeline in DB. The new project is interrelated with three physical projects (Project A, B and C) and two non-physical projects (special budget approval and related regulation approval). Anticipated timelines (milestones) of these interrelated projects are also presented in the figure. Additionally, the precedence relationships of the project dependencies between the new project and its interrelated projects are indicated. These include: (1) the new project's procurement phase cannot begin until the budget is approved (FS_{Pro}); (2) at the time when the design of the new project is 20% completed, the regulation should have been approved ($FS_{D/B}(20\%)$); (3) the new project needs to be completed at the same time when Project C is completed ($F_C F_{D/B}$); (4) the design/build phase of the new project can only be started when (or after) the design/build phase of Project B is completed ($F_{D/B} S_{D/B}$); (5) the design/build phase of the new project can only be started when (or after) the build phase of Project A is completed ($F_C S_{D/B}$). Such visualization can help the decision-maker effectively evaluate and manage project dependencies.

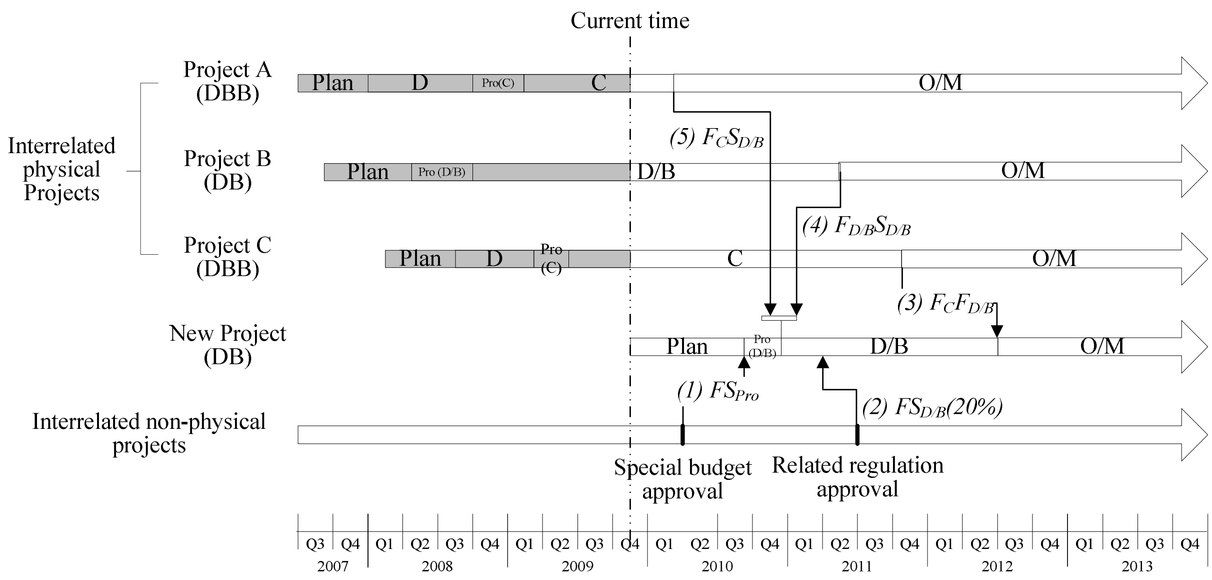


Figure 6.9 An example of project dependency diagram

Project dependencies can directly affect the new project's estimated schedule. They can cause a certain project phase (or a certain point in a project phase) to begin either *earlier* or *later* than planned. Assume that A is a certain point in the project. This point can be the start or end of a project phase, as shown in Figure 6.10(a). It can also be a time point in a project phase, such as in Figure 6.10(b). Project dependencies can cause A to be moved to an earlier time (presented as A') or a later time (presented as A").

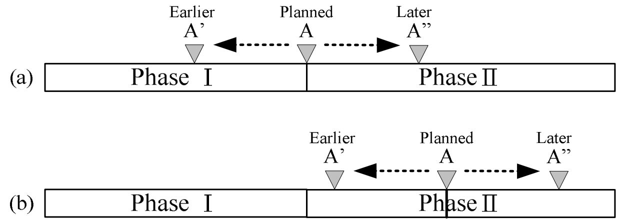


Figure 6.10 Two types of impacts of project dependencies on schedule

Referring back to the example in Figure 6.9, the dependency between the new project and Project B (numbered as (4) in the figure) requires the new project's design/build phase to be started when (or after) Project B's design/build phase is completed. From Figure 6.9, it can be seen that the initial estimated starting date of the new project's design/build phase is in 01/2011. It can also be seen that Project B's design/build phase is estimated to be completed in 04/2011. In this case, the decision-maker may choose to delay the starting date of the new project's design/build phase for three months to accommodate the impacts caused by the project dependency.

6.4.4 Stage 4: Choose response strategies and adjust the estimated schedule and cost

As discussed in the previous section, project dependencies may cause a project phase (or a certain point in that phase) to be implemented either earlier or later than planned. The decision-maker needs to choose proper management strategies to accommodate these impacts. One possible management strategy is to change the duration of a project phase (e.g., extend or shorten the duration). This type of strategy will generally involve a change in the project cost; in addition, time/cost trade-off rules derived in Chapter 5 are needed for making the corresponding cost adjustments. The second possible strategy is to split a project phase to two (or more) sub-phases or to separate sequential phases with a time interval. This type of strategy may have less impact on the project cost as compared to changing phase duration(s). The decision-maker can also modify a PDS. Lastly, the decision-maker can take a combination of any of the above three strategies. These strategies are by no means exhaustive; they are representative of the types of approaches that can be used.

Different strategies will have different impacts on the new project's estimated schedule and cost. In the rest of this section, a hypothetical project that has two sequential phases, Phase A and Phase B (as shown in Figure 6.11), is used to illustrate impacts of different strategies on project schedule and cost when Phase B needs to be started: (1) earlier than planned, or (2) later than planned.

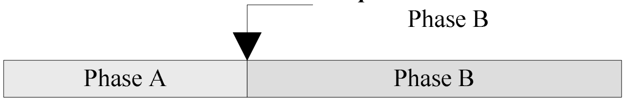


Figure 6.11 A two-phase hypothetical project: as-planned timeline

6.4.4.1 Earlier than planned

Assume that, due to project dependencies, Phase B needs to be started earlier than planned (as shown in Figure 6.12). In this case, a decision-maker can choose to: (1) change phase duration(s); (2) modify the PDS; or (3) both.

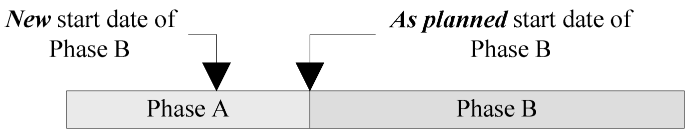


Figure 6.12 Earlier than planned

Change phase duration(s). The decision-maker can change the duration of one project phase, or several, to meet Phase B's new starting date. As shown in Figure 6.13, the decision-maker can either: (a) shorten the duration of Phase A and continue Phase B as is to save time; or (b) shorten the duration of Phase A and extend the duration of Phase B (in trading off with cost) to meet the original estimated project completion date. Either of these two strategies will involve changes in the project cost. Time/cost trade-offs rules are required to make these time and cost adjustments.

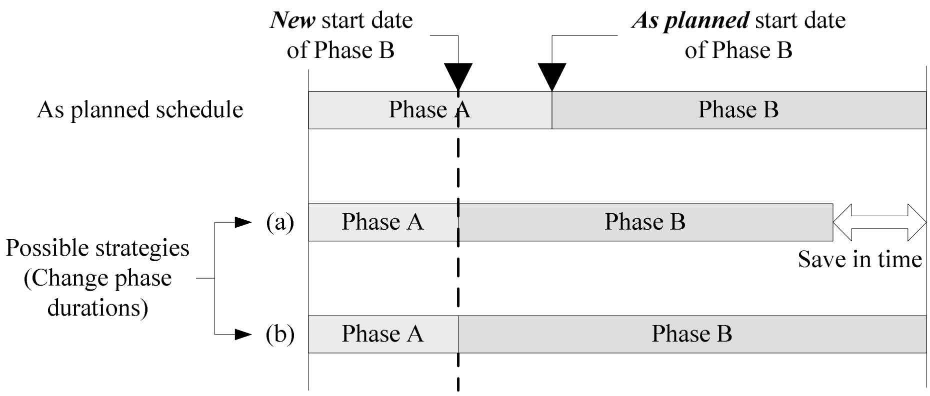


Figure 6.13 Change phase duration(s)

Modify the PDS. The decision-maker can also choose to modify the PDS to meet the new start date of Phase B. In Figure 6.14, the decision-maker can start Phase B before Phase A is completed and continue Phase B as is to save time. This action changes the sequence of project phases. Phase A and Phase B are now overlapped rather than being implemented in a sequential order. One such example is to begin the construction procurement phase before the design phase is completed in DBB. This changes "traditional sequential DBB" to "DBB with early procurement".

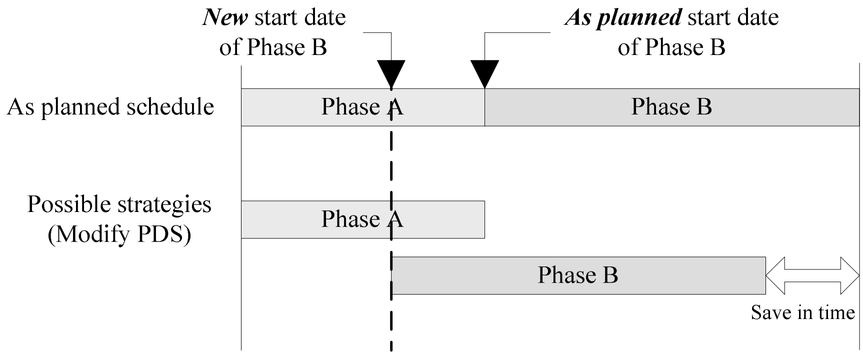


Figure 6.14 Modify the PDS

Modify the PDS and change phase duration(s). The decision-maker can also combine the above strategies: to modify the PDS and change phase duration(s). As shown in Figure 6.15, the decision-maker can start Phase B earlier by overlapping Phase A and Phase B, and extend the duration of Phase B to meet the original established completion date in trading off with cost. Time/cost trade-off rules are also needed here for making the time and cost adjustments.

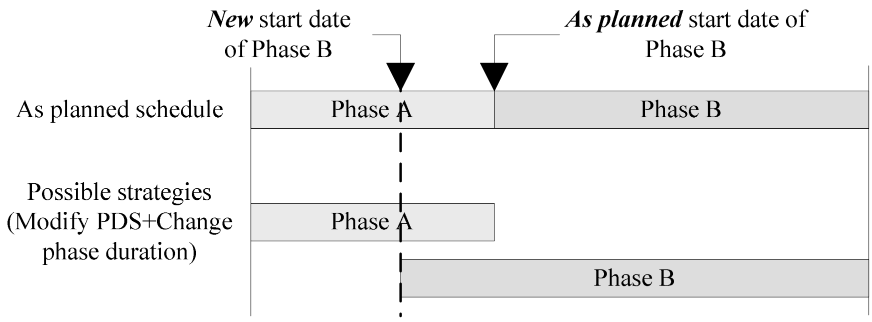


Figure 6.15 Modify the PDS and change phase duration(s)

6.4.4.2 Later than planned

Project dependencies may cause Phase B (or a time point in Phase B) to start later than planned, as shown in Figure 6.16. In this case, a decision-maker can choose from several strategies: (1) change phase duration(s); (2) split/separate project phases; (3) modify the PDS; (4) combine any of the above three strategies.

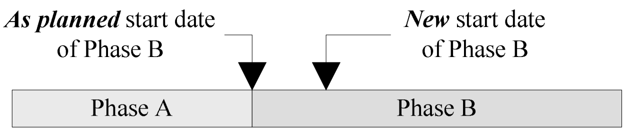


Figure 6.16 Later than planned

Change phase duration(s). The decision-maker can change duration(s) of one or multiple project phases. As shown in Figure 6.17, the decision-maker can: (a) extend the duration of Phase A to meet the new start date of Phase B and continue Phase B as is, which will result in a delay in project completion; or (b) extend the duration of Phase A to meet the new start date of Phase B and shorten the duration of Phase B to meet the original planned project completion date.

Both strategies will have impacts on project schedule and cost. The decision-maker needs time/cost trade-off rules here to make necessary time and cost adjustments.

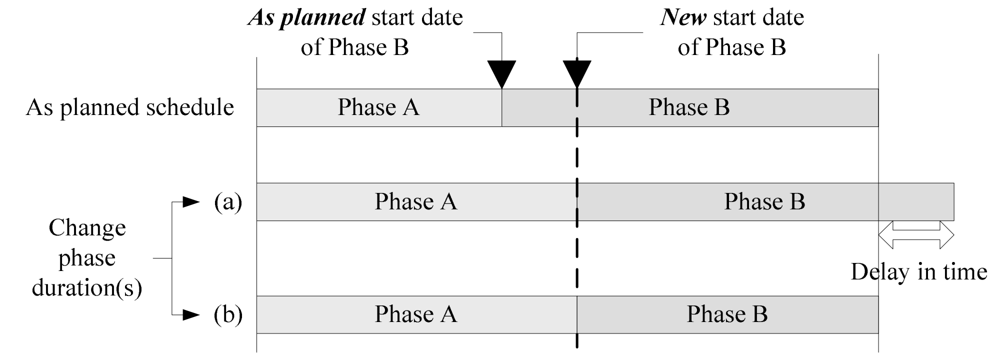


Figure 6.17 Change phase duration(s)

Split/separate project phases. The decision-maker can also choose to split a project phase into several sub-phases, or to separate two sequential phases with a time interval. Figure 6.18 shows two examples of this type of strategy. In (a), the decision-maker first starts Phase A as planned. When Phase A is completed, the project is temporarily put on hold to meet the new start date of Phase B. Both Phase A and Phase B are implemented according to their original planned durations. This will, however, result in a delay in project completion. In (b), the decision-maker splits Phase A into two phases (Phase A(1) and Phase A(2)) without changing its total duration. The project is then put on hold when Phase A(1) is completed. Phase B is implemented as is. This strategy will also delay project completion. The strategy to split/separate project phases normally has less impact on project cost because no changes in phase durations are involved.

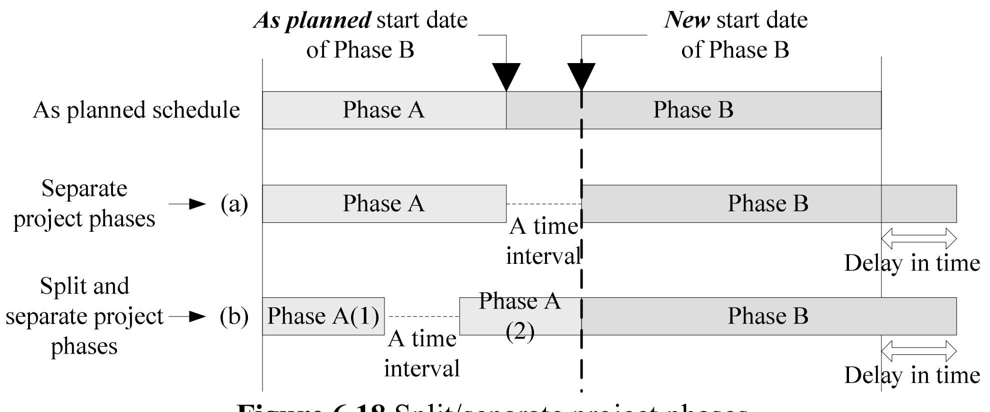


Figure 6.18 Split/separate project phases

Modify the PDS. The decision-maker can also modify a PDS for various needs. As shown in Figure 6.19, the decision-maker first delays the start date of Phase A and continues Phase A as is. The decision-maker then divides Phase B into to sub-phases (Phase B(1) and Phase B(2)) and implements them in parallel to meet the original planned project completion date. One example is to change "traditional sequential DBB" to "DBB with multiple contractors."

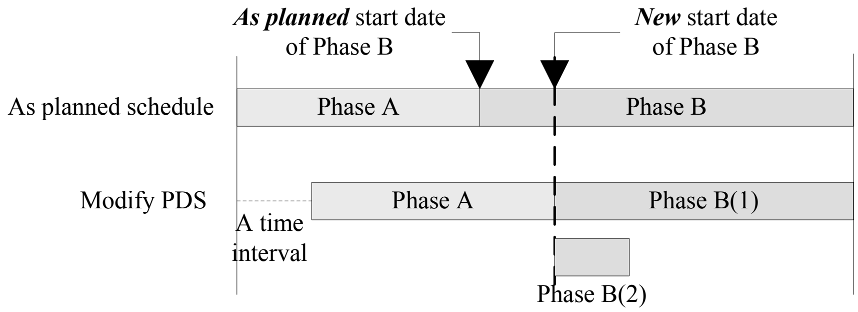


Figure 6.19 Modify the PDS

A combination of any of the above strategies. The decision-maker can also use a combination of any of the above strategies. Figure 6.20 shows two examples where the decision-maker separates/splits project phases and changes phase duration(s). In (a), the decision-maker decides to implement Phase A as is. After Phase A is completed, the decision-maker puts the project temporarily on hold to meet the new start date of Phase B. The decision-maker also shortens the duration of Phase B to meet the original planned project completion date. The situation in (b) is similar to (a) except that Phase A is now divided into two sub-phases (Phase A(1) and Phase A(2)) and the project is put on hold after Phase A(1) is completed. Because this set of strategies involves changes in phase duration(s), time/cost trade-off rules are needed for making necessary schedule and cost adjustments.

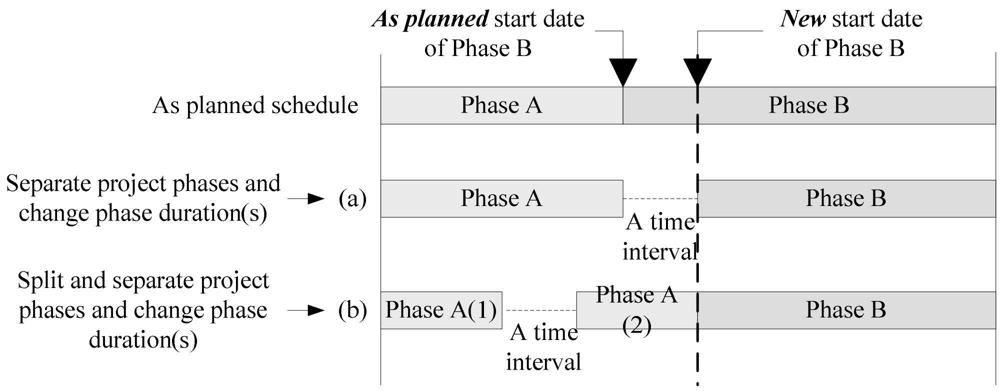


Figure 6.20 Split/separate project phases and change phase duration(s)

Figure 6.21 shows the examples where the strategies of separating/splitting project phases and modifying the PDS are combined. In (a), the decision-maker decides to implement Phase A as is, and puts the project on hold for a time period after Phase A is completed. Next, the decision-maker divides Phase B into Phase B(1) and Phase B(2) and implements the two sub-phases in parallel to meet the as planned project completion date. The situation in (b) is similar to (a) except that Phase A is now divided into two sub-phases (Phase A(1) and Phase A(2)) and a time interval is placed between the two sub-phases. Because this set of strategies does not involve a direct change in phase duration, it has minimum impact on project cost.

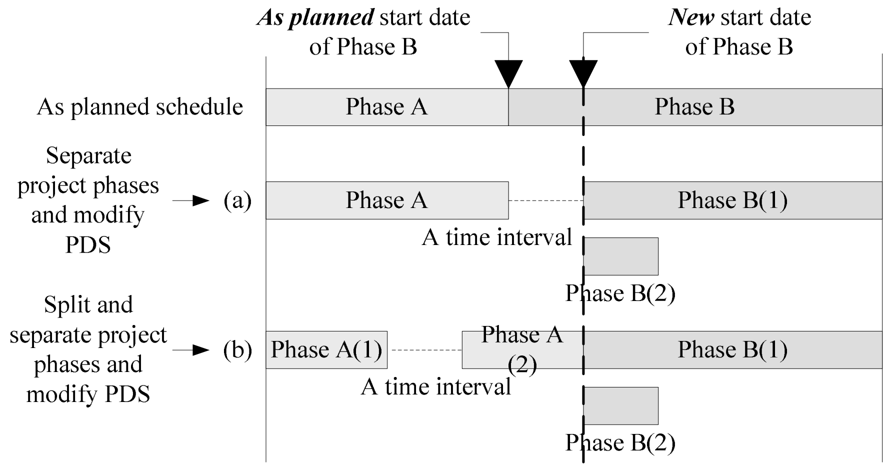


Figure 6.21 Split/separate project phases and modify the PDS

Figure 6.22 shows an example where the strategies of changing phase duration(s) and modifying PDS are combined together. In this case, the decision-maker decides to extend the duration of Phase A in trading off with the project cost to meet the new start date of Phase B. Time cost trade-off rules are required to make this adjustment. The decision-maker also divides Phase B into two sub-phases and has them implemented in parallel to meet the as-planned project completion date.

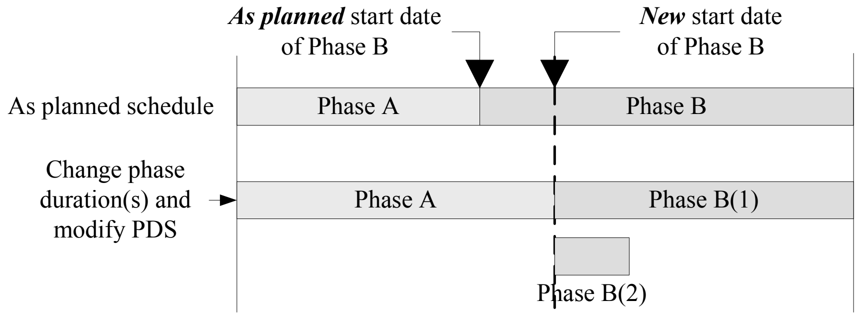


Figure 6.22 Change phase duration(s) and modify the PDS

6.4.5 Procedure outputs

The final procedure output is a performance profile that shows the new project's adjusted times and costs, and its initial estimated quality levels in different PDSs, as shown in Figure 6.23.

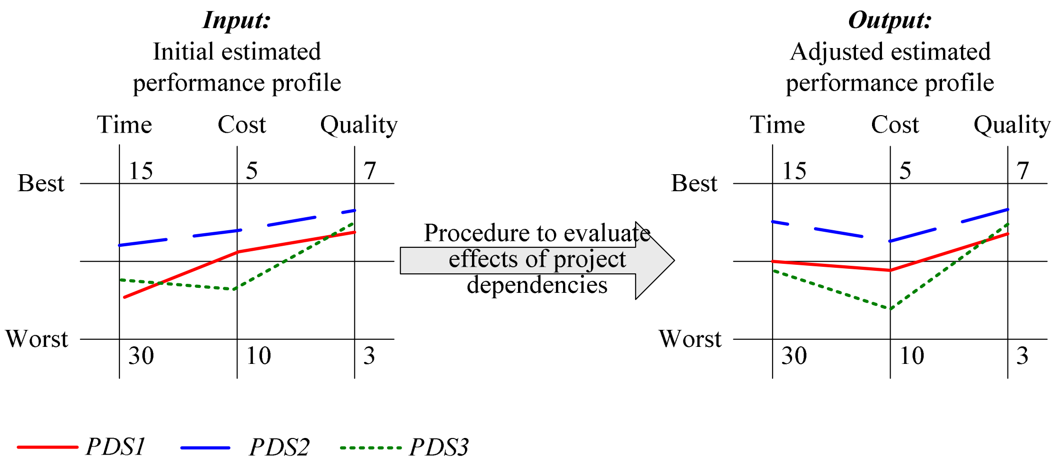


Figure 6.23 Procedure input and final output

6.5 An Illustrative Example

The illustrative example presented in this section is based on data collected from a wastewater treatment plant project in Taiwan (Case Project). Detailed descriptions of the Case Project and the data collection process and methodology can be found in Chapter 7. This section presents only the application of the proposed project dependency evaluation procedure to the Case Project in two PDSs: DBB and DB. (The public agency in charge of the Case Project is referred to as the Agency.)

6.5.1 The basic information of the Case Project

The initial estimated project timelines and costs, and the time/cost trade-off rules in DBB and DB, are needed for the procedure application. This information should have been generated in the previous stages of the PDS decision-support framework. Detailed explanations about how project timelines and costs are estimated, and how the time/cost trade-off rules are derived, can be found in Section 5.4. This section only relists some tables that provide the required information. Tables 6.3 and 6.4 summarize the Case Project's initial estimated timelines in DBB and DB; Tables 6.5 and 6.6 show the estimated costs in DBB and DB. Tables 6.7 and 6.8 summarize time/cost trade-off rules in DBB and DB.

Table 6.3 Estimated phase durations in DBB

Project phase	Duration (month)
Planning	6
Procurement (for design)	2[1]
Design	20
Procurement (for construction)	4[2]
Construction	29
Operation/Maintenance (test)	6
Operation/Maintenance (official)	293
Total[3]	360

[1]One month is for document preparation; the other month is for public advertising and designer selection.
[2]Three months are for document preparation; the other month is for public advertising and contractor selection.

Table 6.4 Estimated phase durations in DB

Project phase	Duration (month)
Planning	9
Procurement (for design/builder)	6[1]
Design/Build	34
Operation/Maintenance (test)	6
Operation/Maintenance (Official)	305
Total	360

[1]Four months are for document preparation; two months are for public advertising and design/builder selection.

Table 6.5 Estimated cost/revenue distribution in DBB

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917[1]	$52,700,000×0.5%=$263,500; $263,500/6=$43,917/m
	Procurement	8,783[2]	$52,700,000×0.1%=$52,700; $52,700/6=$8,783/m
	Design	135,000[3]	5.4%[1]×$50,000,000=$2,700,000; $2,700,000 /20=$135,000/m.
	Construction	1,724,138	40,000CMD×$1,250/CMD=$50,000,000; $50,000,000/29=$1,724,138/m
	Operation/ Maintenance	271,849[4]	7.15 (NTD/m^3)×1,460 (10,000m^3/year)=10,439 million NTD/year=$271,849/m
Operation Revenue		778,395[5]	830,288 (NTD/day)×30days/m=24,908,640 NTD/m=$778,395 /m.

[1]Estimated to be 0.5% of the sum of the design and construction cost; the estimated duration of planning phase is 6 months.
[2]Estimated to be 0.1% of the sum of the design and construction cost. The cost including the procurement costs of two procurement phases (for design and for construction). Thus, the total duration is 6 months (two for design procurement and four for construction procurement).
[3]The % is specified in "Regulations for Selection and Fee Calculation of Technical Services Providers Entrusted by Entities," Public Construction Commission Executive Yuan, 2002, Taiwan. The design duration is 20 months.
[4]The operation/maintenance cost and revenue are estimated based on data from past wastewater treatment plant project; $1=32 NTD.
[5]There is no revenue income during the test operation/maintenance phase.

Table 6.6 Estimated cost/revenue distribution in DB

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB.
	Procurement	8,783	Same as in DBB.
	Design/Build	1,457,000	40,000CMD×$1,175/CMD[1]=$47,000,000; 5.4%×$47,000,000=$2,538,000; $47,000,000 +$2,538,000=$49,538,000; $49,538,000/34= $1,457,000/m
	Operation/ Maintenance	271,849	Same as in DBB.
Operation Revenue		778,395	Same as in DBB.

[1] It is estimated that the unit cost in DB is 6% less than it is in DBB (Konchar and Sanvido, 1998).

Table 6.7 Time/cost trade-off rules between design and construction phases in DBB

		Design		Construction	
		Duration (D_D)	Cost (D_C)	Duration (C_D)	Cost (C_C)
Design	Duration (D_D)	NA	- $270,000/m	-1.32	-$280,000/m
	Cost (D_C)	NA	NA	-$355,263/m	-0.96
Construction	Duration (C_D)	NA	NA	NA	-$362,069/m
	Cost (C_C)	NA	NA	NA	NA

Table 6.8 Time/cost trade-off rules between D/B duration and D/B cost in DB

		Design/Build	
		Duration (D/B_D)	Cost (D/B_C)
Design/Build	Duration (D/B_D)	NA	- $384,647/m
	Cost (D/B_C)	NA	NA

6.5.2 Evaluation of project dependencies

6.5.2.1 State 1: Identify interrelated projects

To avoid revealing confidential information through deductive disclosure, all interrelated projects identified in this section are kept anonymous and are referred to as "Project A," "Project B," and "Project C," etc. The aim of the Case Project is to meet the area's increasing wastewater treatment need. As the wastewater in the area mainly comes from industrial factories, the development schedule of the Case Project should take into account the progress of the nearby ongoing industrial factory projects. Four major industrial factories are identified, and their data are summarized in Tables 6.9 to 6.12.

The Case Project is the second phase wastewater treatment plant project. The first phase project (Project E) is now in its test operation/maintenance phase. The Case Project is interrelated with Project E in two ways. First, the starting time of the Case Project's planning phase had been delayed for six months partially because the Case Project's project manager was occupied by Project E. Since this is a past event, it has no impact on the Case Project's future anticipated schedule. The second dependency is that the test operation/maintenance results of Project E can be used as a reference for the design of the Case Project. This information, however, is not a necessity.

The implementation of the Case Project will also be affected by the approval of the new land use. The original land-use class of the site does not allow it to be used for a wastewater treatment plant. The Agency is currently in the process of changing the site's land-use designation, and this process is expected to be completed in 04/2010. The approval of the new environmental code will also affect the implementation of the Case Project. The new environmental code will require the Case Project to meet a higher wastewater treatment standard. The Agency is expected to have more certain information about this new code in 07/2010. The approval of new land-use and the new environmental code are defined as "non-physical" interrelated projects because they do not involve the construction of any physical facilities.

Table 6.9 An interrelated project: Project A

Project Name	Project A		
Project Type	A high-tech factory that manufactures wafers.		
Scale	14,147 M^2		
Estimated Cost	$9.4 million		
PDS	■ DBB □ DB □ CM at Risk □ Others		
Current Status	The construction phase just began in 01/2010.		
Project Schedule	Start	End[1]	Note
Planning	NA	10/2009	
Procurement (design)[2]	NA	NA	
Design	10/2009	01/2010	
Procurement (build)[2]	NA	NA	
Build	01/2010	08/2010*	
Operation/maintenance (18)[3]	08/2010*	02/2012*	

NA: Not available; [1] "*" indicates expected schedule; [2]because this is a private project, there are no clear separate procurement phases; [3]because the factory will normally achieve its full manufacturing capacity in 1.5-2 years. Therefore, this specific time point is also indicated as it will affect the desired completion date of the Case Project.

Table 6.10 An interrelated project: Project B

Project Name	Project B		
Project Type	A high-tech factory that manufactures lithium-ion battery cells.		
Scale	36,620 M^2		
Estimated Cost	$34.4 million		
PDS	■ DBB □ DB □ CM at Risk □ Others		
Current Status	The project is temporarily on hold.		
Project Schedule	Start	End[1]	Note
Planning	NA	08/2008	
Procurement (design)[2]	NA	NA	
Design	08/2008	12/2008	
Procurement (build)[2]	12/2008	04/2009	
Build	04/2009	02/2010*	
Operation/maintenance (18)[3]	02/2010*	08/2011*	

NA: Not available; [1] "*" indicates expected schedule; [2]because this is a private project, there are no clear separate procurement phases; [3]because the factory will normally achieve its full manufacturing capacity in 1.5-2 years. Therefore, this specific time point is also indicated as it will affect the desired completion date of the Case Project.

Table 6.11 An interrelated project: Project C

Project Name	Project C		
Project Type	High-tech factory. Examples of products include specialty panels for automobile applications, building integrated photovoltaic (BIPV) modules and standard PV modules.		
Scale	42,380M^2		
Estimated Cost	$46.9 million		
PDS	■ DBB □ DB □ CM at Risk □ Others		
Current Status	The project is temporarily on hold.		
Project Schedule	Start	End[1]	Note
Planning	NA	07/2008	
Procurement (design)[2]	NA	NA	
Design	07/2008	12/2008	
Procurement (build)[2]	NA	NA	
Build	12/2008	04/2011*	Due to the poor economic environment, the project was temporarily on hold after 8-month construction. The construction is expected to be restarted in 08/2010.
Operation/maintenance (18)[3]	04/2010*	10/2012*	

NA: Not available; [1] "*" indicates expected schedule; [2]because this is a private project, there are no clear separate procurement phases; [3]because the factory will normally achieve its full manufacturing capacity in 1.5-2 years. Therefore, this specific time point is also indicated as it will affect the desired completion date of the Case Project.

Table 6.12 An interrelated project: Project D

Project Name	Project D		
Project Type	High-tech factory. Examples of products include polarizer, color filter, and AL target.		
Scale	49,000 M^2		
Estimated Cost	$62.5 million		
PDS	■ DBB □ DB □ CM at Risk □ Others		
Current Status	The fifth month of construction phase.		
Project Schedule	Start	End[1]	Note
Planning	NA	07/2008	
Procurement (design)[2]	NA	NA	
Design	07/2008	11/2008	
Procurement (build)[2]	NA	NA	
Build	08/2009	10/2010*	Due to the poor economic environment, after the design phase, the project was temporarily on hold for 9 months.
Operation/maintenance (18)[3]	10/2010*	04/2012*	

NA: Not available; [1] "*" indicates expected schedule; [2]because this is a private project, there are no clear separate procurement phases; [3]because the factory will normally achieve its full manufacturing capacity in 1.5-2 years. Therefore, this specific time point is also indicated as it will affect the desired completion date of the Case Project.

6.5.2.2 Stage 2: Define project dependencies

The types, the strengths and the precedence relationships of the dependencies between the Case Project and its interrelated projects are defined and summarized in Table 6.13.

Table 6.13 Case Project's project dependencies

No.	Interrelated Project	Type of PD	Strength of PD[1]	Precedence Type	Description
PD(1)	Project E	Resource (Human)	Somewhat dependent	F_BS_P	Partially due to the shortage of staff, the starting time of the Case Project's planning phase was scheduled at (or after) the time when the construction of Project E was completed.
PD(2)	Project E	Resource (Information)	Slightly dependent	F_TS_D	Project E's test operation/maintenance results can be used as a basis for the design of the Case Project.
PD(3)	Approval of new land-use	Resource (information)	Highly dependent	FS_{ProD}	The Case Project's procurement (for design) phase cannot start until the new land-use of the site is approved.
PD(4)	New environmental code	Resource (information)	Highly dependent	FS_D	The Case Project's design phase cannot start until more information on the new environmental codes is available.
PD(5)	Project D	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project D is operated for 18 months.
PD(6)	Project C	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project C is operated for 18 months.
PD(7)	Project B	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project B is operated for 18 months.
PD(8)	Project A	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project A is operated for 18 months.

[1]Strength of PD: (1) Slightly dependent (can be successful without linkage project deliverables); (2) Somewhat dependent (without linkage project deliverables, schedule delays possible); (3) Highly dependent (cannot proceed without deliverables from linkage projects).

[2]FS: Finish-to-Start; FF: Finish-to-Finish; B: Build; P: Plan; T: Test Operation/Maintenance; D: Design; ProD: Procurement for design; O/M(18): 18 months of Operation/Maintenance. For example, F_BS_P indicates a finish-to-start relationship between the build phase of the interrelated project and the planning phase of the Case Project.

6.5.2.3 Stage 3: Evaluate impacts caused by project dependencies on the new project's estimated schedule, given a PDS

A project dependency diagram for each of the considered PDSs is created to visualize the project timelines and dependencies. Figures 6.24 and 6.25 show the project dependency diagrams in DBB and DB. Impacts of the indentified dependencies on the Case Project's estimated schedule in DBB and DB are summarized in Table 6.14.

Table 6.14 Impacts of project dependencies on the Case Project's estimated schedule

PDSs / No. of PDs	DBB	DB
PD(1)	PD(1) caused the Case Project's planning phase to be started later than planned.	
PD(2)	None[1]	
PD(3)	The procurement (for design) phase of the Case Project will have to be started later than planned.	None[2]
PD(4)	The design phase of the Case Project will have to be started later than planned.	None[3]
PD(5)~PD(8)	Due to these dependencies, the Case Project's construction phase will need to be completed earlier than planned.	

[1]Project A's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependency will not cause any changes to the Case Project's estimated schedule.
[2]The approval of the new land-use is expected to be completed before the estimated starting date of the Case Project's procurement (for design) phase in DB. Therefore, this dependency will not cause any changes on the Case Project's estimated schedule in this case.
[3]The information is expected to be available before the estimated starting date of the Case Project's design phase in DB. Therefore, this dependency will not cause any changes on the Case Project's estimated schedule in this case.

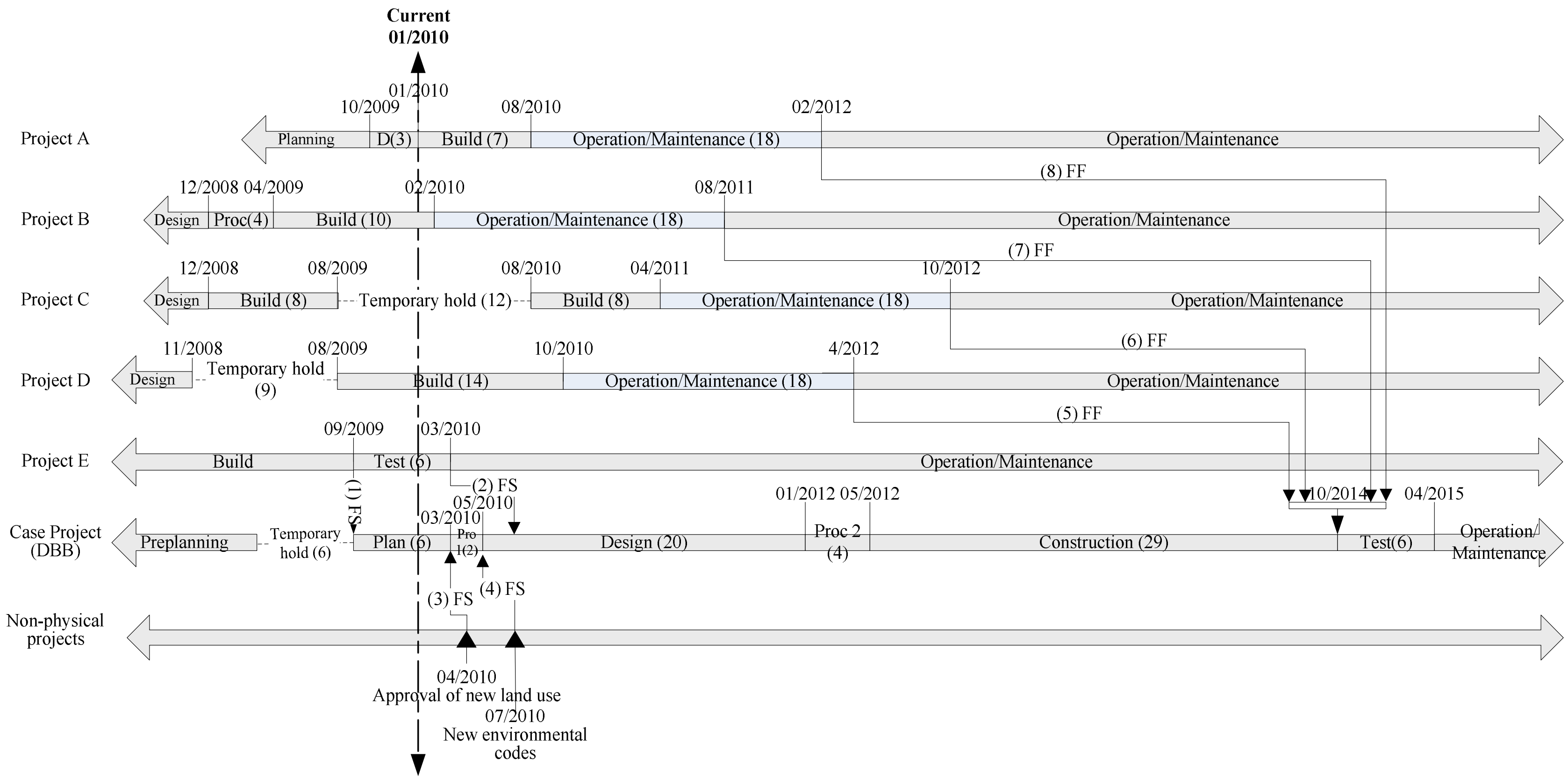


Figure 6.24 Case Project's dependence diagram in DBB

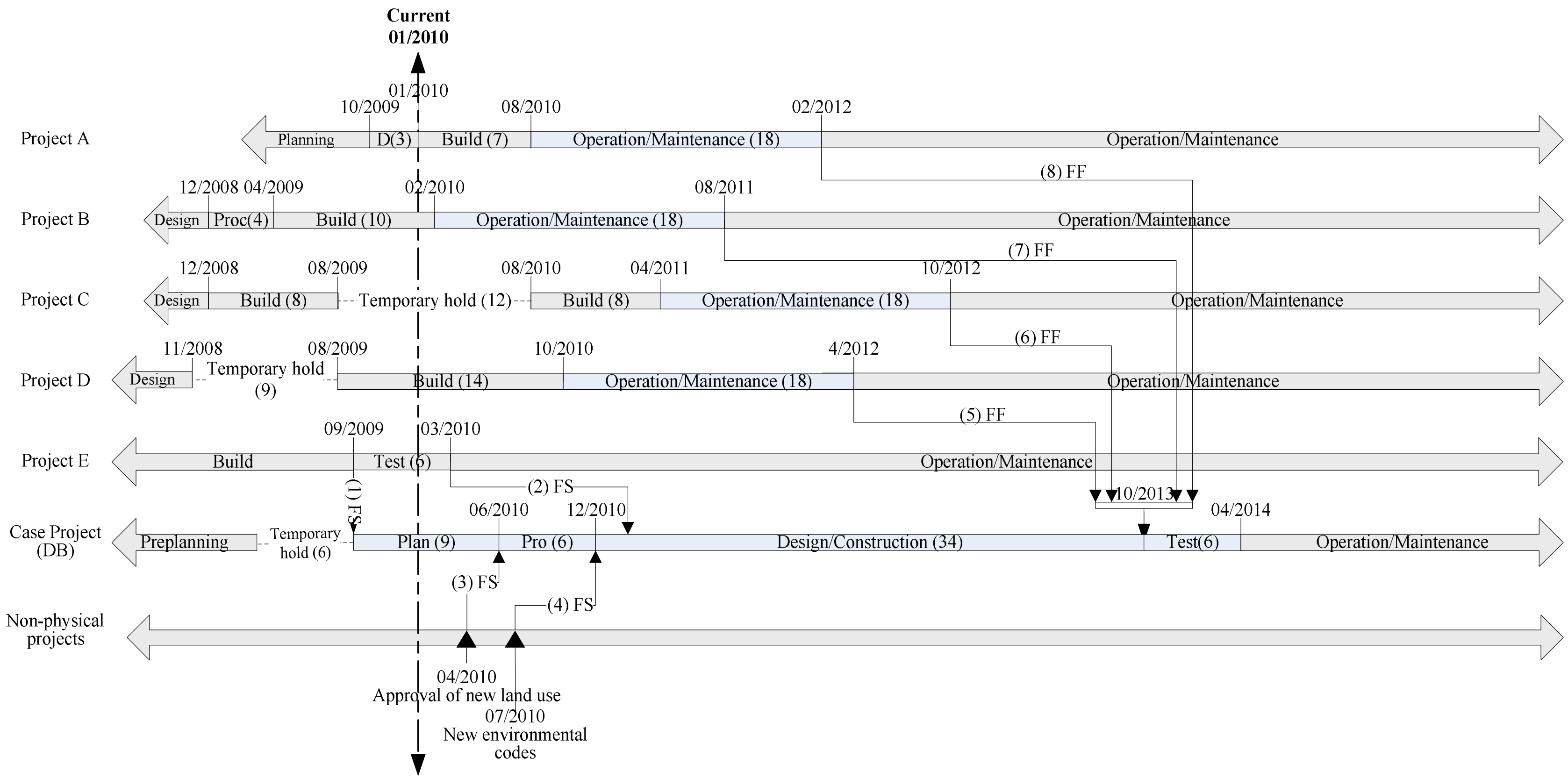


Figure 6.25 Case Project's dependence diagram in DB

6.5.2.4 Stage 4: Choose response strategies and adjust the estimated schedule and cost

To accommodate impacts caused by the project dependencies on the new project's schedule, a decision-maker can choose to: (1) split/separate project phases, (2) change phase duration(s), (3) modify the PDS, or (4) combine any of the three strategies. The response management strategies taken by the Case Project's project manager and their impacts on the project's estimated schedules and costs in the cases of DBB and DB are described below.

Response management strategies taken in DBB. Table 6.15 summarizes the response strategies taken by the project manager in DBB along with the time/cost trade-off involved. The Case Project's initial and adjusted estimated schedules are presented together in Figure 6.26.

For PD(1). PD(1) had caused the starting date of the Case Project's planning phase to be delayed for 6 months to 09/2009. Since this is a past event, it will not affect the Case Project's future estimated schedule.

For PD(2). PD(2) is due to the fact that the test operation/maintenance results of the first-phase wastewater treatment plant can be used as a reference for the design of the Case Project. This information is not a necessity, however, and hence it is a slight dependency. This means that, even without this information, the Case Project can still be implemented as planned. Furthermore, as shown in Figure 6.24, the test results are expected to be available before the estimated starting date of the Case Project's design phase. Thus, even if this information is a necessity, PD(2) will not affect the Case Project's estimated schedule. For this reason, no response action is required.

For PD(3). PD(3) requires the Case Project's procurement (for design) phase to be started at (or after) the time when the new land-use is approved. The new land-use is expected to be approved in 04/2010, while the initial estimated starting date of the Case Project's procurement (for design) phase is 03/2010. To accommodate this effect, the project manager decided to temporarily hold the project for one month after its planning phase is completed. This change has moved the estimated starting date of the Case Project's procurement (for design) phase to 04/2010.

For PD(4). PD(4) requires the Case Project's design phase to be started at (or after) the time when more information about the new environmental code is available, which is expected to be in 07/2010. The initial estimated starting date of the Case Project's design phase is in 05/2010, and this date has been delayed for one month to 06/2010 because of the response strategy taken for PD(3). To meet the 07/2010 constraint caused by PD(4), the Case Project's project manager decided to extend the current on-hold period between the planning and procurement (for design) phase for another month.

For PD(5)~PD(8). PD(5)~PD(8) restrict the completion date of the Case Project's construction phase. As shown in Figure 6.24, it is estimated that the construction of the four interrelated projects, Projects A, B, C and D, will be completed between 02/2010~04/2011. Based on past experience, these factory facilities are estimated to reach their full capacities in 1.5 to 2 years following the completion of their construction. For this reason, the project manager decided that the Case Project is desired to be completed between 08/2011 and 10/2012.

The Case Project's initial estimated construction completion date in DBB is 10/2014. This has been delayed for two months to 12/2014 due to the previous response strategies taken for PD(3) and PD(4). In this case, in order to meet the new desired construction completion date, the design and construction phase together will need to be shortened by approximately 24 months. Based on his experience, the project manager decided that it is not possible to achieve this level of duration reduction by simply trading time and cost at the risk of project quality. He thus decided to modify "traditional DBB" to "DBB with early procurement and multiple contractors". Below are detailed adjustments involved in this response strategy.

The project manager first divided the Case Project into two parts. The first-part and second-part project are desired to be completed, respectively, by 02/2012 and 10/2012. The durations of the design, procurement (for construction) and construction phases are 10, 2 and 14 months for the first-part project, and 10, 2 and 15 months for the second-part project.

In this modified DBB, after the design of the first-part project is completed, the procurement phase (for the construction of the first-part project) begins. In the meantime, the designer will continue to design the second-part of the facility. Following the completion of the design of the second-part project is the procurement phase (for the construction of the second-part project). Even though the project duration is shortened through the modification of the PDS, it still cannot meet the desired project completion dates. Therefore, the project manager decided to further shorten the design and construction durations by trading them off with project cost. The design and construction phases of the first-part project are shortened, respectively, by three and four months to meet the desired 02/2012 completion date; the design and construction phases of the second-part project are also shortened, respectively, by three and four months to meet the desired 10/2012 completion date. Together, the design phases of the two sub-projects are shortened by six months and the construction phases are shortened by eight months.

From Table 6.7, it is seen that the trade-off rule between the design duration and design cost is \$270,000/m; the trade-off rule between the construction duration and construction cost is \$355,263/m. Based on these rules, for a 6-month reduction in the design duration, the project manager would be willing to pay an extra \$1,620,000 (\$270,000 /m×6m=\$1,620,000) in the design cost; for a 8-month reduction in the construction duration, he would be willing to pay an extra \$2,842,104 (\$355,263/m×8m=\$2,842,104) in the construction cost. These two combined increase the estimated total project cost by \$4,462,104. This has increased the estimated total project cost in DBB from \$53,016,200 to \$57,478,304.

Response management strategies taken in DB. Table 6.16 summarizes the response strategies taken in DB along with the time/cost trade-off involved. The Case Project's initial and adjusted estimated schedules are presented together in Figure 6.27.

For PD(1). The start date of the Case Project had been delayed for 6 months due to PD(1). Since this is a past event, it will not affect the Case Project's future estimated schedule.

For PD(2)~PD(4). For PD(2), the Project E's test operation/maintenance results is expected to be available before the starting date of the Case Project's design/build phase. For PD(3), the new land-use is expected to be approved before the estimated starting date of the Case Project's procurement (for design/build) phase. For PD(4), the Agency is expected to have more certain information about the new environmental code before the estimated starting date of the Case Project's design/build phase. These three project dependencies will not affect the Case Project's estimated schedule and therefore no response actions are required.

For PD(5)~PD(8). In order to meet the new desired project completion date, which is between 08/2011 and 10/2012, the duration of the design/build phase needs to be shortened by approximately 12~24 months. The project manager again decided that it is not possible to achieve this level of duration reduction by simply trading time and cost. He thus decided to modify "traditional DB" to "DB with multiple design/builders". Below are detailed adjustments involved in this response strategy.

First, the project manager divided the Case Project into two sub-projects. The durations of the design/build phase of these two sub-projects are both 17 months; the constructions of the first-part project and the second-part project are desired to be completed, respectively, by 02/2012 and

10/2012.

In this modified DB, the project manager would first spend 6 months to prepare the procurement for the first-part project. After the procurement for the first-part project is completed, the project manager would then prepare the procurement for the second-part project. Because documents prepared for the first-part project can be revised and reused, the duration of the procurement phase for the second-part project is reduced to 4 months. Even though the modification of DB can shorten project duration, further adjustments to the Case Project's estimated durations are still required.

In order to meet the new completion date of 02/2012, the duration of the first-part project's design/duration phase needs to be shortened by 3 months. Referring back to Table 6.8, it is found that the trade-off rule between the design/build duration and cost is \$384,647/m. Therefore, for a 3-month decrease in the design/build duration, the project manager would be willing to pay an extra \$1,153,941 (\$384,647/m ×3m=\$1,153,941) in design/build cost. As for the second-part project, its new estimated project completion date is one month earlier than the desired date. The project manager therefore decided to extend the design/build duration by one month in trading off with cost. By applying the above trade-off rule, for a one-month increase in design/build phase, the project manager needs to reduce the design/build cost by \$384,647/m (\$384,647/m ×1m=\$384,647/m). The above adjustments together have increased the estimated total project cost by \$769,294. This increases the estimated total project cost in DB from \$49,985,950 to \$50,755,244.

Table 6.15 Impacts of project dependencies and response strategies taken in DBB

No.	Impacts on initial estimated schedule	Response strategies	Descriptions of the action and impacts	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	PD(2) will not affect the Case Project's estimated schedule and no response action is required.	None
PD(3)	Case Project' procurement (for design) phase has to be started later than planned.	(b) Separate project phases	To temporarily hold the Case Project for one month after its planning phase is completed for the approval of the new land-use.	None
PD(4)	Case Project's design phase has to be started later than planned.	(c) Separate project phases	To extend the on-hold period between planning and procurement (for design) phases for another month for more certain information about the new environmental code.	None
PD(5)~ PD(8)	The Case Project's construction phase needs to be completed earlier than planned.	(d) Modify PDS and change phase durations	To change DBB to DBB with early procurement and with multiple contractors, and to shorten design and construction durations to meet the desirable earlier completion date.	Increase the total project cost by $4,462,104.[2]

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]A $1,620,000 increase in design cost and a $2,842,104 increase in construction cost.

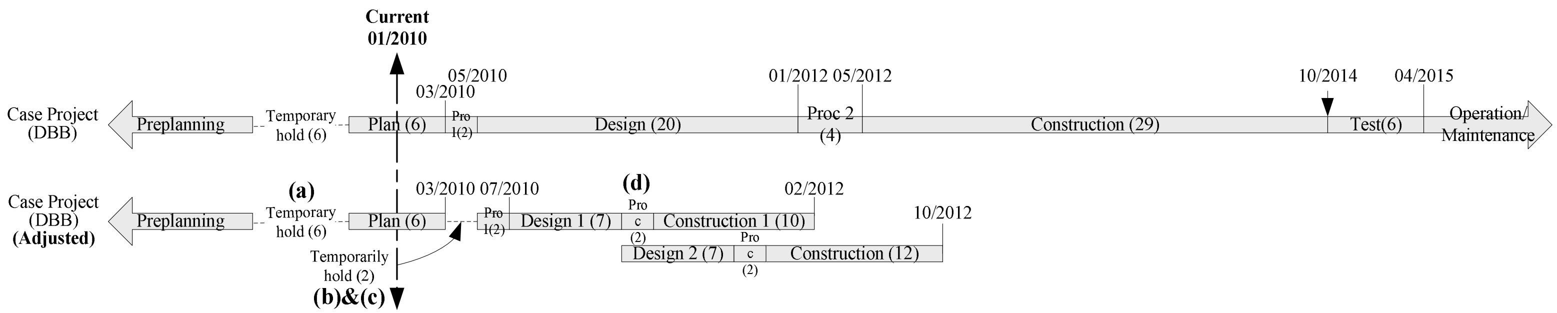


Figure 6.26 Case Project's initial and adjusted timelines in DBB

Table 6.16 Impacts of project dependencies and response strategies taken in DB

No of PD	Impacts on initial estimated schedule	Response strategy	Strategy description	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	No response strategy is required as PD(2) will not affect the Case Project's estimated schedule.	None
PD(3)	None[2]	None	The new land use is expected to be approved before the estimated starting date of the Case Project's procurement phase; and hence no response strategy is required.	None
PD(4)	None[3]	None	More certain information about the environmental codes is expected to be available before the starting date of the design/build phase; and hence no response strategy is required.	None
PD(5)~ PD(8)	The Case Project's construction phase needs to be completed earlier than planned.	(b) Modify PDS and change phase durations	To change traditional DB to DB with multiple design/builders; and to shorten design and construction durations.	Increase the total project cost by $ 769,294.

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]The approval of the new land-use is expected to be completed before the estimated starting date of the Case Project's procurement (for design) phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.
[3]The information is expected to be available before the estimated starting date of the Case Project's design phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.

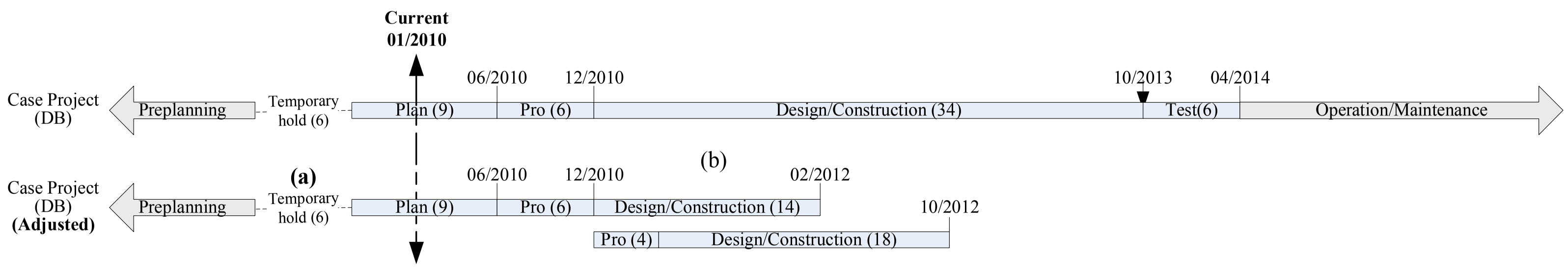


Figure 6.27 Case Project's initial and adjusted timelines in DB

6.6 Summary

Project dependencies can significantly affect project performance, and therefore should be taken into account in project planning. They should also be considered in designing and choosing a PDS. Unfortunately, currently available PDS selection methods do not fully integrate this consideration into their PDS evaluation processes. Even though some decision-makers may intuitively consider project dependencies in making a PDS choice, this evaluation process should be more explicit. The procedure proposed in this chapter provides a basis for doing so.

The proposed procedure provides a step-by-step guide to a systematic identification and evaluation of project dependencies. It helps a decision-maker: (1) identify projects that are interrelated with the new project; (2) define types, strengths and precedence relationships of project dependencies; (3) evaluate the impacts of the identified project dependencies on the new project's estimated schedule; (4) choose proper response strategies and make corresponding adjustments to the project's initial estimated schedule and cost, given a PDS.

This chapter is useful for both practitioners and researchers. The proposed procedure enables a structured consideration of project dependencies in the project planning and estimating. This allows a decision-maker to identify the potential implementation bottlenecks of the project and thereby to develop proactive management strategies to mitigate those difficulties. More realistic estimates of project schedules and costs in different PDSs can also facilitate a more informed PDS decision. This chapter also raises the need to consider project dependencies in planning a project, which can be an interesting direction for researchers to explore.

Chapter 7
Application of the PDS Decision-Support Framework

7.1 Introduction

In Chapter 4, a framework that can help a decision-maker design and evaluate regulation-authorized PDSs with respect to performance and general PDS criteria, while taking into account project dependencies and possible time/cost trade-offs, is proposed. Chapters 5 and 6, respectively, present a NPV-based method to derive time/cost trade-off rules and a procedure to assess the impacts of project dependencies on the new project's estimated timelines and costs in different PDSs. This chapter presents an application of the proposed framework, method and procedure to an infrastructure project in Taiwan.

First, the case study data collection process, methodology and limitations are described in Section 7.2. Section 7.3 provides an overview of the case study project. Section 7.4 illustrates the step-by-step application of the PDS decision-support framework. Lessons learned from the framework application are discussed in Section 7.5. A chapter summary is given in Section 7.6.

7.2 Case Study Data Collection

7.2.1 Data collection process and methodology

The process to collect data for framework application is composed of four stages: (1) search for public agency participants; (2) search for appropriate case projects; (3) collect required data; (4) implement the framework and write up framework application results. Actions and means in each of the stages are illustrated in Figure 7.1. To avoid revealing confidential information through deductive disclosure in the following sections, the participating public agency and the case study project are referred to as "the Agency" and "the Case Project."

Stage 1: Search for public agency participants. The search for potential public agency participants began in early 06/2009. Several public agencies in the US and Taiwan were considered for their appropriateness for this research. The consideration at this stage focused on whether the agencies were allowed to use alternative PDSs and whether they had potential case projects. Public agencies that are prohibited by regulations from using PDSs other than DBB are eliminated from further consideration. This search and screening process was performed mainly through a Web search.

In early 08/2009, three public agencies (including the Agency) in Taiwan were contacted. They were provided with a brief description of the study and consulted about their willingness to participate in the study. Because the application of the proposed framework requires some data that are sensitive in nature (e.g., budget constraints and cost estimates), the agencies expressed concerns about disclosing confidential project information. Only the Agency agreed to participate in the study.

The Agency is a Construction Management Division in a public agency in Taiwan. This particular agency was considered appropriate for the case study for two reasons (in addition to the availability of data). First, the Agency is responsible for planning and managing the implementation of a variety of infrastructure projects (e.g., wastewater and waste treatment systems, electricity and telecommunication systems, and roads). This multi-project environment provides a good opportunity for examining the impacts of project dependencies on the PDS decision-making. Second, the Agency had successfully implemented several infrastructure projects through alternative PDSs and has a positive attitude toward the consideration of alternative PDSs.

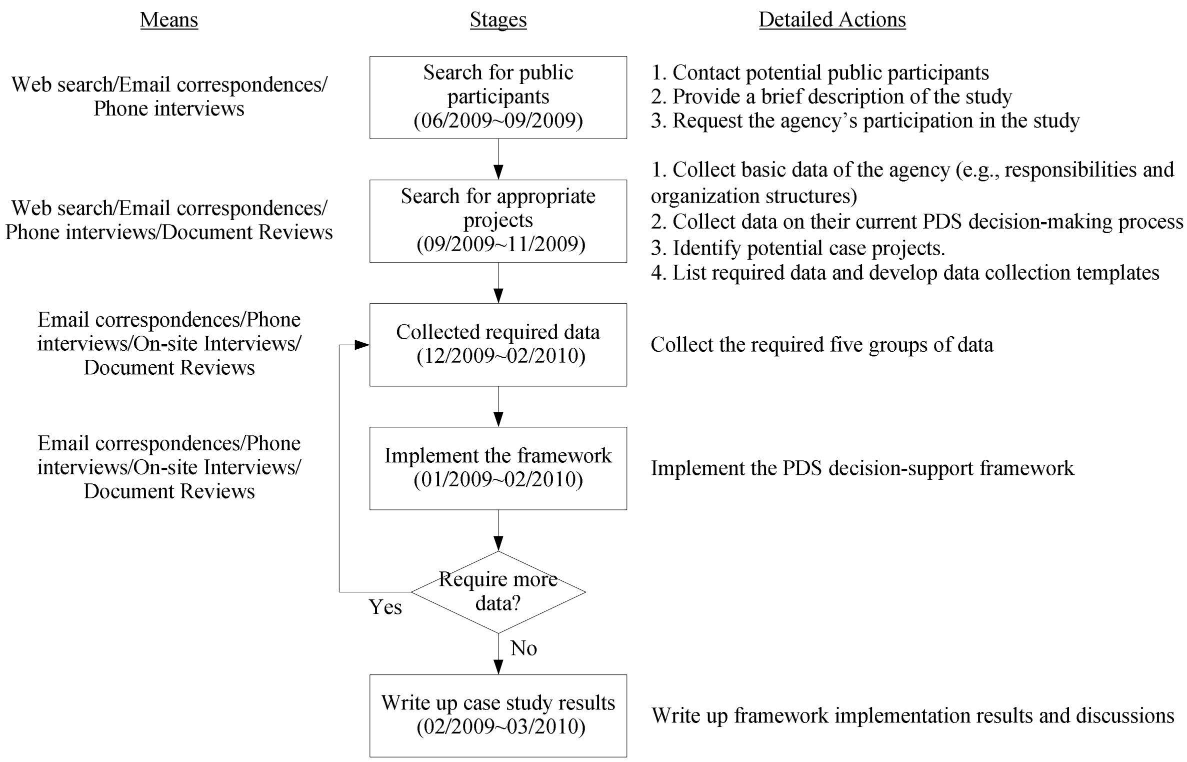


Figure 7.1 Case study data collection process

Stage 2: Search for an appropriate case project. After the consent of the participating agency was obtained, the search for potential case projects began. Main tasks in this stage included collecting basic data about the Agency (e.g., responsibility and organization structures), understanding the Agency's current PDS decision-making process, and identifying potential case project(s). Three criteria were used to determine an appropriate case study project. First, the project should be a new-build project in its planning phase (or at least the early design phase). Second, the project should be complex enough to enable consideration of project dependencies in the PDS decision-making process. Finally, its project manager should be experienced enough in the planning and management of public projects and preferably has experience with alternative PDSs. Based on these three criteria, a wastewater treatment plant project was selected as the Case Project. An overview of this project is presented in Section 7.3.

In this same stage, the data required for the framework implementation were also identified; templates that would assist in collecting and documenting data were developed.

Stage 3: Collect the required data. In early 12/2009, the process to collect data required for the framework application began. The required data can be classified into five groups, as shown in Figure 7.2. *Group A* data are those directly related to the Case Project itself. Such data include: (1) project description and scope, (2) project objectives/constraints, (3) a list of possible PDSs for the Case Project, (4) the Case Project's estimated project schedule, cost and quality level, given a PDS, (5) a set of PDS selection criteria, and (6) a list of interrelated projects (denoted as Project_x). *Group B* data are those relating to Project_x. Examples of such data include Project_x's: (1) basic information, (2) used PDS (if applicable), (3) current status, and (4) forecasted timelines (or milesones). *Group C* data are those that concern the dependencies between the Case Project and Project_x. Data that need to be collected are the types, strengths and precedence relationships of the project dependencies. The impacts of the project dependencies on the Case Project's estimated schedule, and the response management strategies taken to accommodate these impacts, are also data in this group. *Group D* data are agency-level data (e.g. special strategic considerations for the Case Project) and *Group E* data are external environmental data (e.g., external projects/environmental conditions).

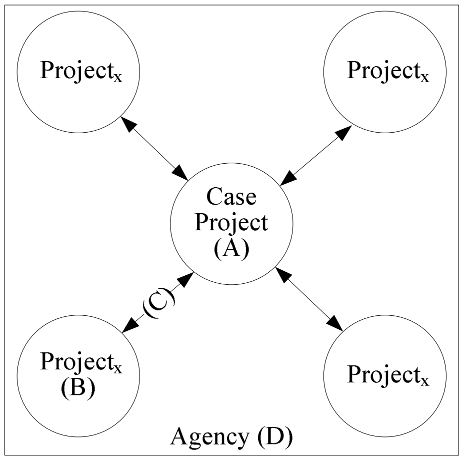


Figure 7.2 Five groups of required data

The above required data were collected through interviews, document reviews and personal observation. Two types of interviews, namely, semi-structured and structured interviews, were performed. First, semi-structured interviews were conducted via emails and telephone with the Case Project's project manager to understand the Case Project's background (e.g., its scopes and objectives/constraints). Next, structured face-to-face interviews were conducted to get deeper insights into the Case Project (e.g., estimated project schedule, cost and quality level given a PDS, and its relationships with other projects). In the structured interview, the Case Project's project manager was also asked to identify a list of possible PDSs, determine a set of PDS selection criteria and evaluate PDSs with respect to the chosen criteria. Structured interviews were also conducted with the project managers of the projects that are interrelated with the Case Project. Measures taken to secure data quality and reliability can be found in Chapter 3.

Document reviews were conducted to collect the agency-level (Group D) and external environment (Group E) data. Results of document reviews were also used to supplement and cross-check data collected through interviews.

Stage 4 and Stage 5: Implement the framework and write up the case study results. The collected data were then applied to the framework. A step-by-step presentation of the framework application is presented in Section 7.4. In this framework application process, project managers of the Case Project and its interrelated projects were contacted for missing data and for further information. Results produced by the framework were presented to the Case Project's project manager. Steps taken in the framework application process and assumptions associated with each of the steps were also carefully explained to the project manager. After the project manager's questions were addressed, he was asked to make a PDS decision based on the information presented and provide reasons for his PDS decision. Finally, the framework application results and lessons learned were documented.

7.2.2 Limitations of the data collection

The data collection was limited in three ways. First, some data were subjectively estimated by the Case Project's project manager based on his knowledge and experience. Such data might lack an objective basis. For example, the durations and costs of the project planning and procurement phases were needed for deriving time/cost trade-off rules. As these two project phases were performed by the Agency's in-house staff, which was simultaneously responsible for several other projects, it was difficult to determine the planning and procurement cost associated with a single project. For this reason, the project manager made the estimates subjectively based on his judgment. For these subjectively determined data, there is a higher level of uncertainty.

The second limitation is related to the data collection for the Case Project's external interrelated projects. Because not all project managers of these external projects were accessible for interviews, data of some external projects were collected indirectly from a staff member in the Agency who was familiar with and knowledgeable about those projects. Some uncertainties may exist in these data as well. Another limitation of the data was the possible reporting errors in interviewees' self-reported data.

Despite these limitations, the data collected served well to illustrate the application of the proposed PDS decision-support framework. The uncertainty associated with the collected data was addressed by a sensitivity analysis.

7.3 Case Project Overview

The Case Project is a second-phase wastewater treatment plant project, yet it is an individual project located in a different site. The first-phase plant was completed in 09/2009 and is now in its test operation/maintenance phase. These test results will be a valuable reference for the design of the Case Project.

The Case Project has two main objectives: (1) meet the area's increasing wastewater treatment need; (2) provide additional operational flexibility to the first-phase plant. The area's wastewater comes mainly from the operation of a variety of factories and their supporting facilities. There are several new factory projects under development in the area. The Case Project is desired to be completed before these factories achieve their full capacities.

The Case Project has a designated capacity of 40,000 cubic meters per day (CMD). It is situated on a site of 8.82 acres, where 4.95 acres will be occupied by the wastewater treatment facilities, and the remaining 3.87 acres will be reserved for environmental protection purposes. Because the original designated use of this site does not allow it to be used for a wastewater treatment project, the Agency is now in the process of changing the site's original designated use. This process is estimated to be completed in 04/2010. Furthermore, a new environmental code is under development. This new code will demand a higher wastewater treatment standard, which will affect the design of the Case Project. The Agency is expected to have more certain information about this code in 07/2010.

7.4 Framework Application

As described in Chapter 4, the PDS decision-support framework has five stages: (1) define project objectives/constraints; (2) identify regulation-authorized PDSs; (3) define evaluation criteria; (4) design and evaluate PDSs; (5) choose a PDS. This section presents a stage-by-stage application of the framework to the Case Project.

7.4.1 Stage 1: Define project objectives/constraints

The Case Project's objectives/constraints in terms of time, cost, quality and others are summarized below:

Time

- Estimated total project delivery time (including planning, procurement, design and construction phases) is 4 to 5.5 years.
- The project completion time should meet the area's anticipated increasing wastewater treatment need.

Cost

- Total project cost should not exceed the established budget of $55,000,000; the minimum cost is at $42,400,000.

Quality

- Meet the designated capacity of 40,000 CMD.
- Meet the new wastewater treatment quality standard.

- Meet (or exceed) all other performance specifications and design criteria.

Others

- Maximize the Agency's flexibility to effect changes.
- Minimize the Agency's involvement and risk level.
- Develop an environmentally responsible, durable and maintainable project while minimizing the impact on the environment.

7.4.2 Stage 2: Identify regulation-authorized PDSs

In Taiwan, public-funded infrastructure projects are permitted to be implemented through DBB or DB. A PCM team can be hired to assist the public agency in project implementation if necessary. This has created four PDS alternatives for the Case Project: DBB, DBB (with PCM), DB and DB (with PCM). Descriptions of DBB and DB can be found in Section 2.3.1. Brief descriptions of DBB (with PCM) and DB (with PCM) are given below.

DBB (with PCM). DBB (with PCM) is similar to DBB except that a PCM team will be hired to assist the Agency in implementing the Case Project. Due to the high complexity of the Case Project, the project manager decided that a PCM team is required to assist in both the design and construction of the Case Project. For this reason, the procurement for PCM will be held at the same time as the procurement for a designer. The selected PCM team will then help the Agency review design documents, prepare procurement documents for construction services and supervise (together with the designer) the construction process.

DB (with PCM). DB (with PCM) is similar to DB except that a PCM team will be hired before the procurement (for design/builder) phase to assist the Agency in preparing DB procurement documents. After the design/build contract is awarded, the PCM will also be responsible for the supervision of the design/builder.

7.4.3 Stage 3: Define PDS selection criteria

In choosing PDS selection criteria, the project manager agreed that PERF criteria, time, cost and quality were his main concerns. To assist the project manager in determining general PDS criteria, a list of commonly used general PDS criteria were presented for his reference. Each of the criteria was also clearly explained in the interview process. At the end, the project manager decided that all of the presented general PDS criteria should be considered for the Case Project. Table 7.1 provides the descriptions of these selection criteria.

Table 7.1 PERF and General PDS criteria for the Case Project

Group	Criterion	Description
PERF	Time (T)	The time taken to complete the project, including project planning, procurement, design and construction durations.
	Cost (C)	The cost required to complete the project, including project planning, procurement, design and construction costs.
	Quality level(QL)	The quality required of the completed project.
PDS	Time certainty (TC)	The certainty over the time for completion of the project.
	Cost certainty (CC)	The certainty over the cost for completion of the project.
	Flexibility (FL)	The ability and authority for the Agency to effect changes.
	Complexity (CO)	The suitability of the PDS to tackle complex projects.
	Risk transfer (RT)	The transfer of risk to the contactor.
	Price competition (PC)	The degree of price competition pertaining to the PDS.
	Point of responsibility (PR)	The clarity of allocation of responsibility.

7.4.4 Stage 4: Design and evaluate alternative PDSs

7.4.4.1 Deal with PERF criteria

The PERF criteria are dealt with through a three-step process: (1) estimate the Case Project's time (T), cost (C) and quality level (QL); (2) derive time/cost trade-off rules; (3) adjust estimated time and cost for project dependencies. This process is repeated for each of the four considered PDSs.

Step 1: Estimate the Case Project's time, cost and quality level, given a PDS

Time. In DBB, the Case Project is divided into the planning, procurement (for design), design, procurement (for construction), construction and test operation/maintenance phases. Based on information from past similar projects and his experience, the project manager estimated the durations of these phases, respectively, are 6, 2, 20, 4, 29 and 6 months. The project phases and their estimated durations in DBB (with PCM) are the same as those in DBB, with one difference. The duration of the first procurement phase in DBB (with PCM) is extended for one month because the procurement of a designer and a PCM team will be held simultaneously.

In DB, the Case Project is divided into planning, procurement (for design/builder), design/build, and test and official operation/maintenance phases. The durations of these phases are estimated to be, respectively, 9, 6, 34 and 6 months. The detailed estimation process can be found in Section 5.4.2. The project phases and their durations in DB (with PCM) are similar to those in DB with two differences. First, because the Agency can shift some of its responsibilities to the selected PCM team in the later project phases, the estimated duration of the project planning phase in DB (with PCM) was shortened to 6 months. In addition, a procurement (for PCM) phase was added after the project planning phase. The duration of this phase was estimated to be five months, in which three months were for document preparation and the other two months were for public advertising and PCM selection. The estimated project durations under the four considered PDSs are summarized in Tables 7.2 to 7.5.

Table 7.2 Estimated phase durations in DBB

Project phase	Duration (month)
Planning	6
Procurement (for design)	2[1]
Design	20
Procurement (for construction)	4[2]
Construction	29
Operation/Maintenance (Test)	6
Total (test operation/maintenance phase not included)	61
Total (test operation/maintenance phase included)	67

[1]One month is for document preparation; the one month is for public advertising and designer selection.
[2]Three months are for document preparation; one month is for public advertising and contractor selection.

Table 7.3 Estimated phase durations in DBB (with PCM)

Phases	Duration (Month)
Planning	6
Procurement (for design and PCM)	3[1]
Design	20
Procurement (for construction)	4[2]
Construction	29
Operation/Maintenance (Test)	6
Total (test operation/maintenance phase not included)	62
Total (test operation/maintenance phase included)	68

[1]Two months are for document preparation; one month is for public advertising and designer/PCM team selection (procurements for designer and PCM are held simultaneously).
[2]Three months are for document preparation; one month is for public advertising and contractor selection.

Table 7.4 Estimated phase durations in DB

Phases	Duration (Month)
Planning	9
Procurement (for design/builder)	6[1]
Design/Build	34
Operation/Maintenance (Test)	6
Total (test operation/maintenance phase not included)	49
Total (test operation/maintenance phase included)	55

[1]Four months are for document preparation; two months are for public advertising and design/builder selection.

Table 7.5 Estimated phase durations in DB (with PCM)

Phases	Duration (Month)
Planning Phase	6
Procurement (for PCM)	5[1]
Procurement (for design/builder)	6[2]
Design/Build	34
Operation/Maintenance Phase (Test)	6
Total (test operation/maintenance phase not included)	51
Total (test operation/maintenance phase included)	57

[1]Three months are for document preparation; two months are for public advertising and design/builder selection.
[2]Four months are for document preparation; two months are for public advertising and design/builder selection.

Cost. Cost/revenue estimating is similar to project duration estimating. The project manager first estimated project phase costs/revenues in DBB based on information from past similar projects and his experience. The cost/revenue distribution in DBB (with PCM) is similar to that in DBB except that an additional PCM fee was added. The estimates of cost/revenue distributions in DBB and DBB (with PCM) are summarized in Tables 7.6 and 7.7. The detailed estimation process can be found in Section 5.4.1.

Table 7.6 Estimated cost/revenue distribution in DBB

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917[1]	52,700,000×0.5%=263,500; 263,500/6=$43,917/m
	Procurement	8,783[2]	52,700,000×0.1%=52,700; 52,700/6=$8,783/m
	Design	135,000[3]	5.4%[1]×$50,000,000=$2,700,000; $2,700,000 /20=$135,000/m.
	Construction	1,724,138	40,000CMD×$1,250/CMD=$50,000,000; $50,000,000/29=$1,724,138/m
	Operation/ Maintenance	271,849[4]	7.15 (NTD/m^3)×1,460 (10,000m^3/year)=10,439 million NTD/year=$271,849/m
Operation Revenue		778,395[5]	830,288 (NT/day)×30days/m=24,908,640 NTD/m=$778,395/m.

[1]Estimated to be 0.5% of the sum of design and construction cost; the estimated duration of planning phase is 6 month.
[2]Estimated to be 0.1% of the sum of design and construction cost. The cost including the procurement costs of two procurement phases (for design and for construction). Thus, the total duration is 6 months (two for design procurement and four for construction procurement).
[3]The % is specified in "Regulations for Selection and Fee Calculation of Technical Services Providers Entrusted by Entities," Public Construction Commission Executive Yuan, 2002, Taiwan. The design duration is 20 months.
[4]The operation/maintenance cost and revenue are estimated based on data from past wastewater treatment plant project.
[5]There is no revenue income during the test operation/maintenance phase.

Table 7.7 Estimated cost/revenue distribution in DBB (with PCM)

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB
	Procurement	8,783	Same as in DBB
	Design	135,000	Same as in DBB
	Construction	1,724,138	Same as in DBB
	PCM Fee[1]	34,802	$52,700,000×3.5%=1,844,500 1,844,500/53[2]=$34,802/m
	Operation/Maintenance	271,849	Same as in DBB
Operation Revenue		778,395	Same as in DBB

[1]Estimated to be 3.5% of the sum of design and construction cost

[2]PCM service is provided in design, procurement (for construction) and construction phases. Total duration is 20+4+29=53 months.

Tables 7.8 and 7.9 summarize the estimated cost/revenue distributions in DB and DB (with PCM). The monthly planning, procurement, and operation/maintenance costs in DB are the same as those in DBB, and so is the monthly operation/maintenance revenue. The design/build cost in DB assumes that the unit cost in DB is about 6% less than it is in DBB (Konchar and Sanvido 1998). The cost/revenue distribution in DB (with PCM) is similar to that in DB except that an additional PCM fee was added. The detailed estimation process can be found in Section 5.4.2. The total estimated project costs given different PDSs are summarized in Table 7.10.

Table 7.8 Estimated cost/revenue distribution in DB

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB
	Procurement	8,783	Same as in DBB
	Design/Build	1,457,000	40,000CMD×$1,175/CMD[1]=$ 47,000,000; 5.4%×$47,000,000=$2,538,000; $47,000,000 +$2,538,000 =$49,538,000; $49,538,000/34= $1,457,000/m
	Operation/ Maintenance	271,849	Same as in DBB
Operation Revenue		778,395	Same as in DBB

[1]It is estimated that the unit cost in DB is 6% less than it is in DBB (Konchar and Sanvido 1998).

Table 7.9 Estimated cost/revenue distribution in DB (with PCM)

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB
	Procurement	8,783	Same as in DBB
	Design/Build	1,457,000	Same as in DBB
	PCM Fee[1]	$43,346	$49,538,000×3.5%=1,733,830; 1,733,830/40[2]=$43,346/m
	Operation/ Maintenance	271,849	Same as in DBB
Operation Revenue		778,395	Same as in DBB

[1]Estimated to be 3.5% of the sum of design and construction cost

[2]PCM service is provided in procurement (for design/builder) and design/build phases. Total duration is 6+34=40 months.

Table 7.10 Total estimated project costs given different PDSs

	DBB	DBB (with PCM)	DB	DB (with PCM)
Total cost ($) [1]	53,016,200	54,869,483	49,985,950	51,631,947

[1]The operation/maintenance cost is not included.

Quality Level. The project manager decided that the four considered PDSs can deliver a 40,000 CMD capacity wastewater treatment plant project that meets the new wastewater treatment standard. His evaluation on the quality level criterion was based on the PDSs' abilities to meet (or exceed) all other performance specifications and design criteria. This evaluation is on a 10-110 scale, where 10 represents the worst performance and 110 represents the best performance. The project manager first assigned 10 (110) to a PDS with the worst (best) performance on quality. He then scored the other two PDSs based on their performance relative to the two reference points.

The project manager assigned the highest score, 110, to DB (with PCM). His reasons are two-fold. First, the Case Project requires intensive coordination and integration of a wide range of specialized knowledge and skills. Because the Agency lacks the required expertise in-house, a PCM team is vital to ensure the project quality. In addition, DB can provide the design/builder opportunities to innovate. Such innovation, if properly supervised by PCM, could contribute to the improvement of the project quality. The project manager, however, also emphasized that this innovation could hamper the project quality if it is not properly supervised. This is the reason why he scored DB slightly lower than DBB (with PCM). Scores of the four considered PDSs on quality are presented in Table 7.11.

Table 7.11 Quality levels in the four considered PDSs

	DBB	DBB (with PCM)	DB	DB (with PCM)
Quality level score	10	90	80	110

The Case Project's estimated times, costs, and quality levels in the four considered PDSs are presented in the form of a performance profile, as shown in Figure 7.3. The estimated durations and costs in different PDSs were further adjusted for project dependencies in the following steps.

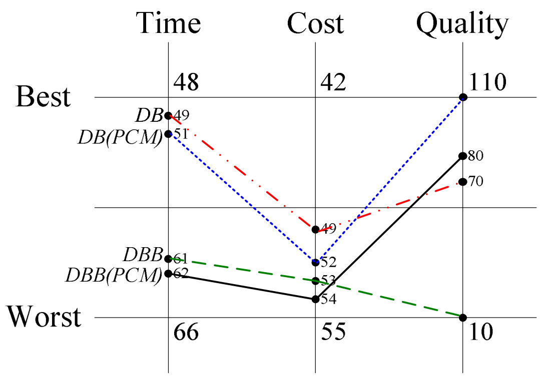


Figure 7.3 Initial performance profile on PERF criteria

Step 2: Develop time/cost trade-off rules, given a PDS

The NPV-based method proposed in Chapter 5 was used to derive time/cost trade-off rules in the four considered PDSs, as summarized in Tables 7.12 and 7.13. Detailed trade-off rule derivation processes can be found in Section 5.4 (for DBB and DB) and Appendix A (for DBB (with PCM) and DB (with PCM).

Table 7.12 Trade-off rules in DBB and DBB (with PCM)

DBB (with PCM)					
		Design		Construction	
		Duration (D_D)	Cost (D_C)	Duration (C_D)	Cost (C_C)
Design	Duration (D_D)	NA	- $270,000/m	-1.32	-$280,000/m
	Cost (D_C)	NA	NA	-$355,263/m	-0.96
Construction	Duration (C_D)	NA	NA	NA	-$362,069/m
	Cost (C_C)	NA	NA	NA	NA
DBB (with PCM)					
		Design		Construction	
		Duration (D_D)	Cost (D_C)	Duration (C_D)	Cost (C_C)
Design	Duration (D_D)	NA	- $258,660/m	-1.30	-$265,000/m
	Cost (D_C)	NA	NA	-$329,268/m	-0.957
Construction	Duration (C_D)	NA	NA	NA	-$348,276/m
	Cost (C_C)	NA	NA	NA	NA

Table 7.13 Trade-off rules in DB and DB (with PCM)

<table>
<tr><th colspan="4">DB</th></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Design/Build</td></tr>
<tr><td>Duration (D/B_D)</td><td>Cost (D/B_C)</td></tr>
<tr><td rowspan="2">Design/Build</td><td>Duration (D/B_D)</td><td>NA</td><td>- $384,647/m</td></tr>
<tr><td>Cost (D/B_C)</td><td>NA</td><td>NA</td></tr>
<tr><th colspan="4">DB (with PCM)</th></tr>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Design/Build</td></tr>
<tr><td>Duration (D/B_D)</td><td>Cost (D/B_C)</td></tr>
<tr><td rowspan="2">Design/Build</td><td>Duration (D/B_D)</td><td>NA</td><td>- $370,078/m</td></tr>
<tr><td>Cost (D/B_C)</td><td>NA</td><td>NA</td></tr>
</table>

Step 3: Adjust estimated time and cost for project dependencies

The procedure proposed in Chapter 6 was followed to adjust the initial estimated time and cost given a PDS for project dependencies. Detailed stage-by-stage illustrations of how project dependencies are evaluated in the cases of DBB and DB can be found in Section 6.5. Interested readers can also refer to Appendix B in the cases of DBB (with PCM) and DB (with PCM). Provided below is a summary of the procedure application results.

Case Project's interrelated projects and project dependencies. The Case Project is interrelated with five physical projects and two non-physical projects. Table 7.14 summarizes the dependencies between these projects and the Case Project.

Impacts of project dependencies on Case Project's estimated schedule. Project dependencies illustrated in Table 7.14 can be visualized in a project dependency diagram. Project dependency diagrams in the four considered PDSs are shown in Figures 7.4 to 7.7. Impacts caused by the identified project dependencies on the Case Project's initial estimated schedule are given in Table 7.15.

Table 7.14 Case Project's project dependencies

No.	Interrelated Project	Type of PD	Strength of PD[1]	Precedence Type	Description
PD(1)	Project E	Resource (Human)	Somewhat dependent	F_BS_P	Partially due to the shortage of staff, the starting time of the Case Project's planning phase was scheduled at (or after) the time when the construction of Project E was completed.
PD(2)	Project E	Resource (Information)	Slightly dependent	F_TS_D	Project E's test operation/maintenance results can be used as a basis for the design of the Case Project.
PD(3)	Approval of new land-use	Resource (information)	Highly dependent	FS_{ProD}	The Case Project's procurement (for design) phase cannot start until the new land-use of the site is approved.
PD(4)	New environmental code	Resource (information)	Highly dependent	FS_D	The Case Project's design phase cannot start until more information on the new environmental codes is available.
PD(5)	Project D	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project D is operated for 18 months.
PD(6)	Project C	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project C is operated for 18 months.
PD(7)	Project B	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project B is operated for 18 months.
PD(8)	Project A	Strategic (outside)	Highly dependent	$F_{O/M(18)}F_B$	The Case Project's construction is expected to be completed before (or at) the time when Project A is operated for 18 months.

[1]Strength of PD: (1) Slightly dependent (can be successful without linkage project deliverables); (2) Somewhat dependent (without linkage project deliverables, schedule delays possible); (3) Highly dependent (cannot proceed without deliverables from linkage projects).

[2]FS: Finish-to-Start; FF: Finish-to-Finish; B: Build; P: Plan; T: Test Operation/Maintenance; D: Design; ProD: Procurement for design; O/M(18): 18 months of Operation/Maintenance. For example, F_BS_P indicates a finish-to-start relationship between the build phase of the interrelated project and the planning phase of the Case Project.

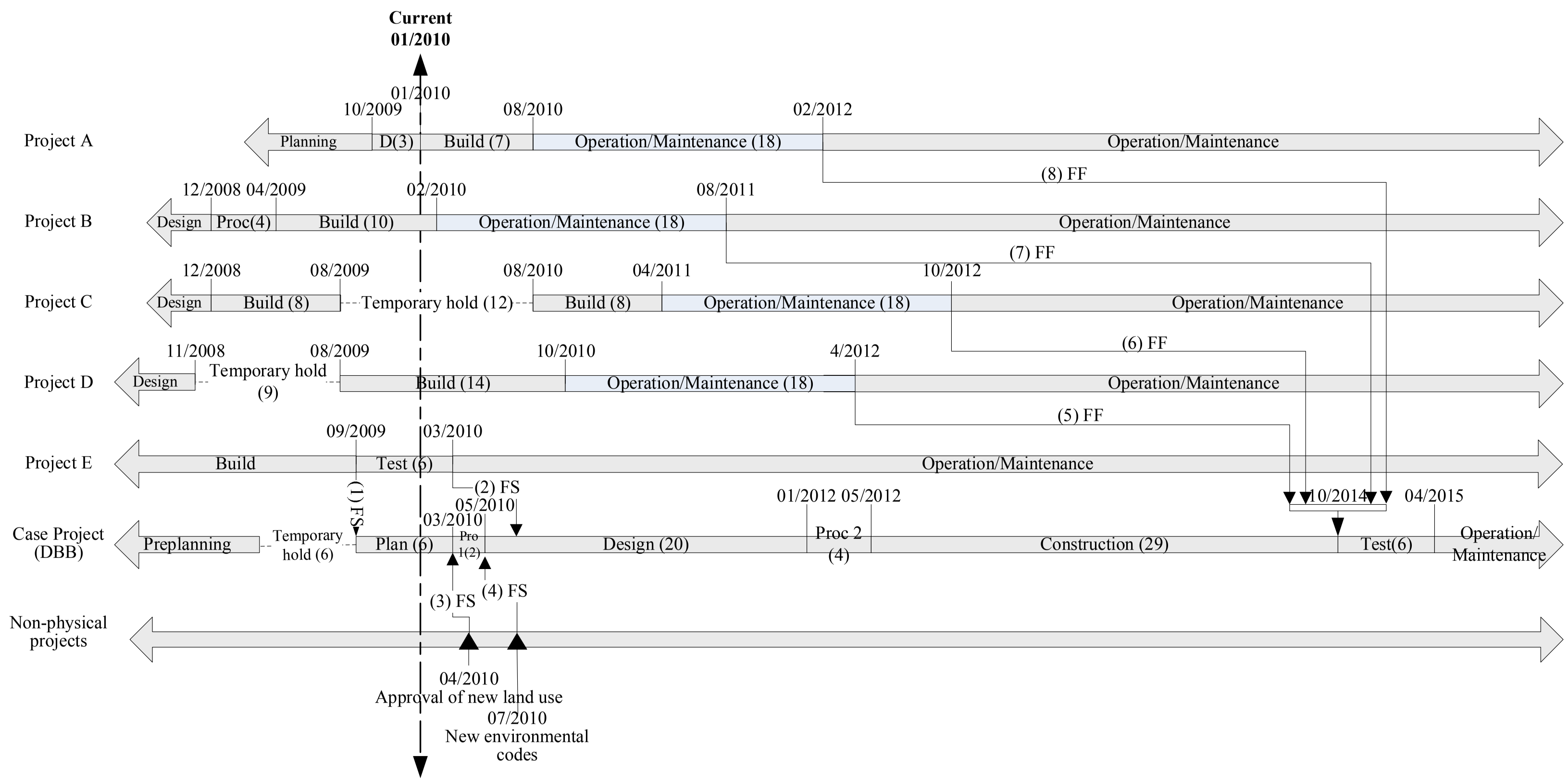


Figure 7.4 Project dependence diagram in DBB

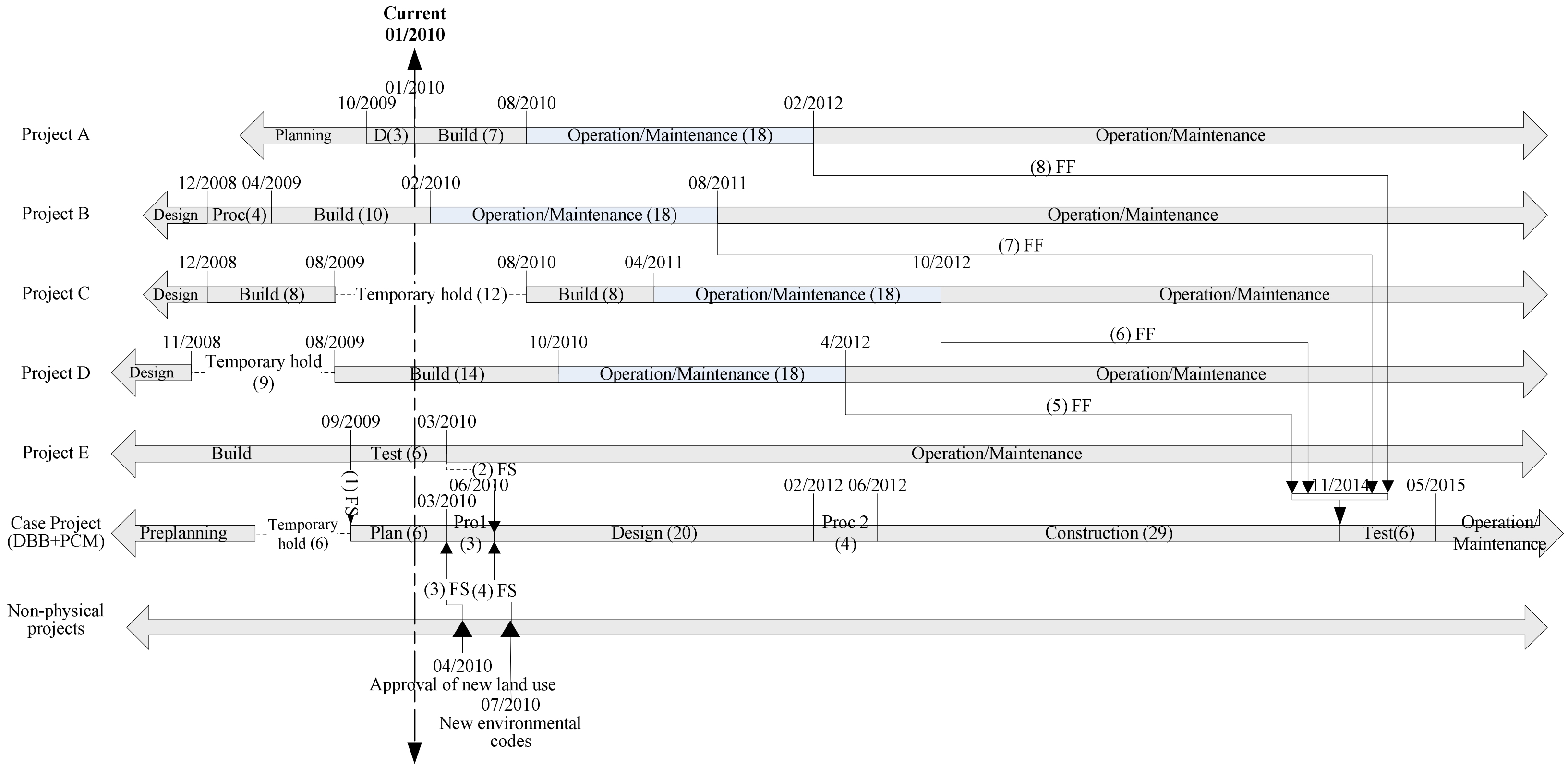


Figure 7.5 Project dependence diagram in DBB(with PCM)

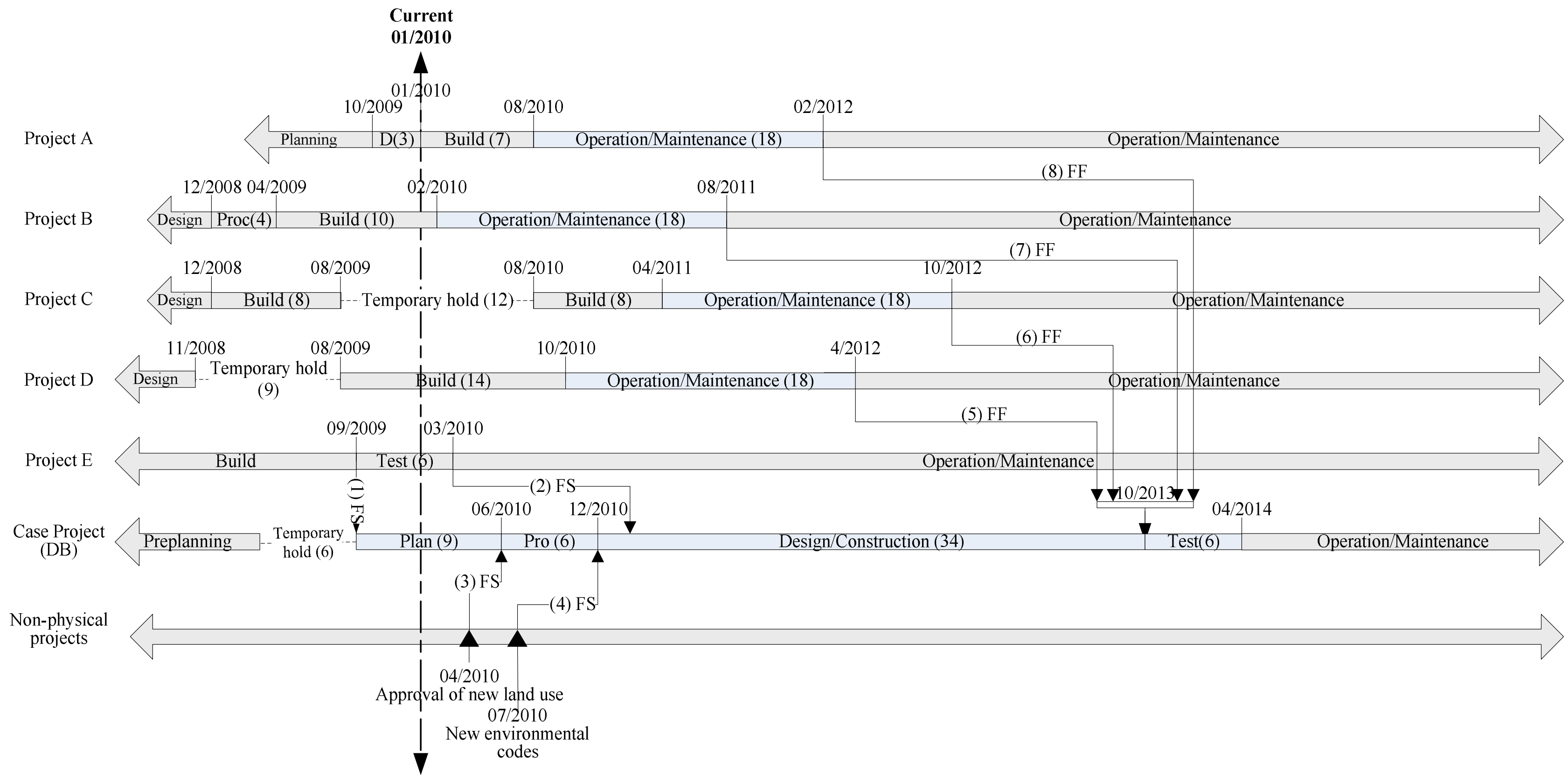


Figure 7.6 Project dependence diagram in DB

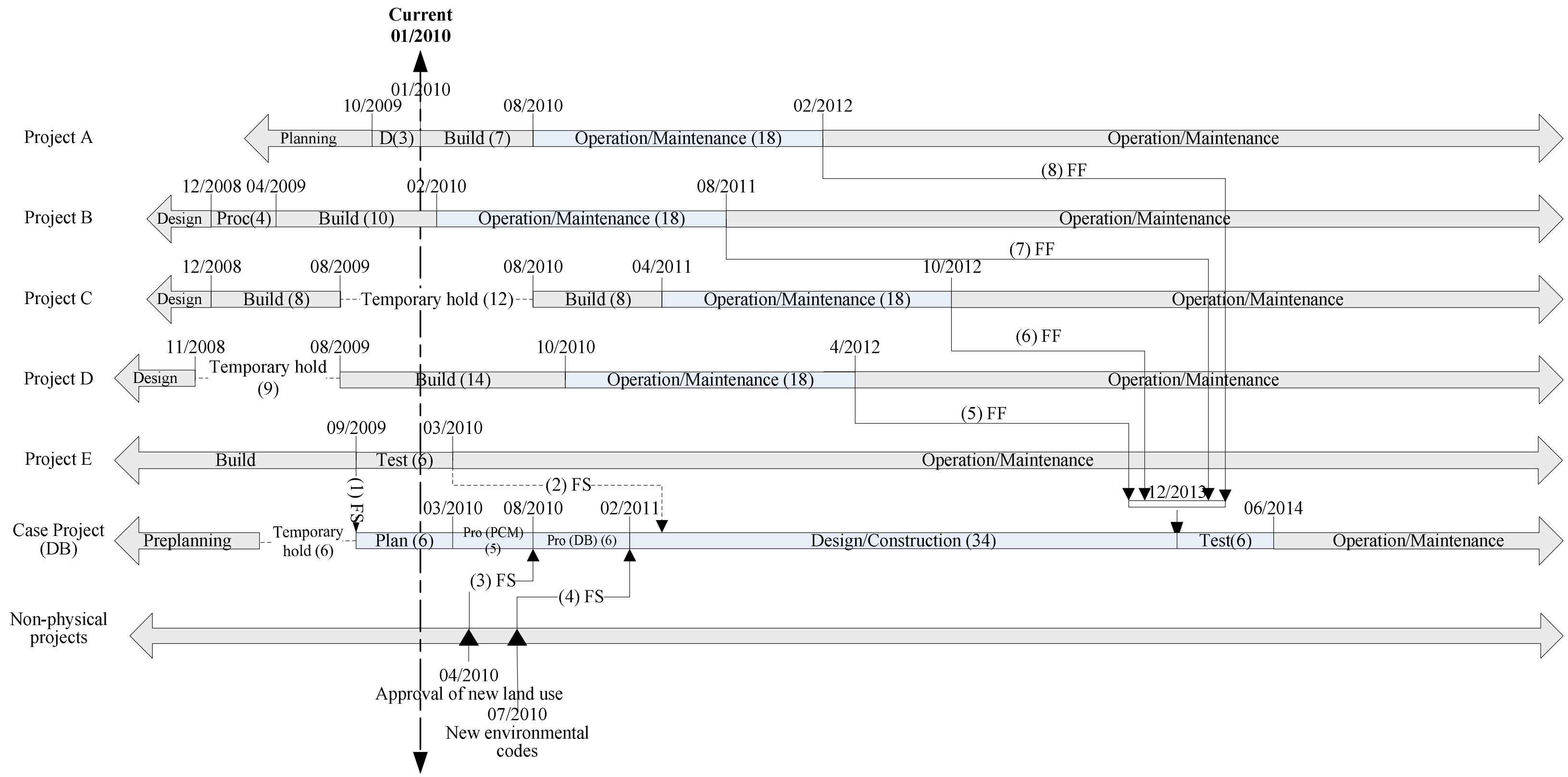


Figure 7.7 Project dependence diagram in DB(with PCM)

Table 7.15 Impacts of project dependencies on the Case Project's estimated schedule

	DBB	DBB (with PCM)	DB	DB (with PCM)
PD(1)	PD1 caused the Case Project's planning phase to start later than planned.			
PD(2)	None[1]			
PD(3)	The procurement (for design) phase of the Case Project will have to start later than planned.		None[2]	
PD(4)	The design phase of the Case Project will have to start later than planned.		None[3]	
PD(5)~PD(8)	Due to these dependencies, the Case Project's construction phase will need to be completed earlier than planned.			

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependency will not cause any changes on the Case Project's estimated schedule.
[2]The approval of the new land-use is expected to be completed before the estimated starting date of the Case Project's procurement (for design) phase in DB and DB (with PCM) scenarios. Therefore, this dependency will not cause any changes on the Case Project's estimated schedule in these two cases.
[3]The information is expected to be available before the estimated starting date of the Case Project's design phase in DB and DB (with PCM) scenarios. Therefore, this dependency will not cause any changes on the Case Project's estimated schedule in these two cases.

Choose response strategies and adjust Case Project's estimated schedule and cost. Tables 7.16 to 7.19 summarize the response strategies taken by the Case Project's project manager to accommodate the impacts caused by the project dependencies. These response strategies are also visualized in Figures 7.8 to 7.11. With certain response management strategies, the four considered PDSs can deliver the Case Project within its new desired deadlines. These strategies however have resulted in different levels of increase in the estimated total project cost. The Case Project's estimated total project durations and costs before and after being adjusted for project dependencies in the four considered PDSs are summarized in Table 7.20. The after-adjusted performance profile on PERF criteria is shown in Figure 7.12.

Table 7.16 Impacts of project dependencies and response strategies taken in DBB

No.	Impacts on initial estimated schedule	Response strategies	Descriptions of the strategy and impacts	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	PD(2) will not affect the Case Project's estimated schedule and no response strategy is required.	None
PD(3)	Case Project' procurement (for design) phase has to be started later than planned.	(b) Separate project phases	To temporarily hold the Case Project for one month after its planning phase is completed for the approval of the new land-use.	None
PD(4)	Case Project's design phase has to be started later than planned.	(c) Separate project phases	To extend the on-hold period between planning and procurement (for design) phases for another month for more certain information about the new environmental code.	None
PD(5)~ PD(8)	The Case Project's construction phase needs to be completed earlier than planned.	(d) Modify PDS and change phase durations	To change DBB to DBB with early procurement and with multiple contractors, and to shorten design and construction durations to meet the desirable earlier completion date.	Increase the total project cost by $4,462,104.[2]

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]A $1,620,000 increase in design cost and a $2,842,104 increase in construction cost.

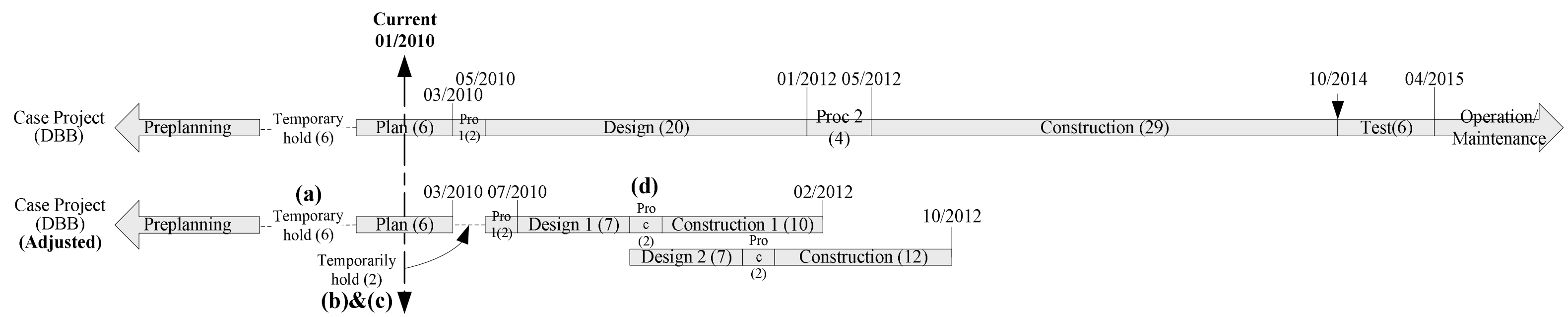


Figure 7.8 Case Project's initial and adjusted timelines in DBB

Table 7.17 Impacts of project dependencies and the response strategies taken in DBB (with PCM)

No of PD	Impacts on initial estimated schedule	Response Strategy	Descriptions of the strategy and impacts	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	PD(2) will not affect the Case Project's estimated schedule and no response strategy is required.	None
PD(3)	Case Project' procurement (for design &PCM) phase has to be started later than planned.	(b) Separate project phases	To temporarily hold the Case Project for one month after its planning phase is completed for the approval of the new land-use.	None
PD(4)	Case Project's design phase has to be started later than planned.	None	Because the Case Project is temporarily on hold for one month after its planning phase is completed in response to previous PD(3), the new starting date of the Case Project can now satisfy the restriction caused by PD(4). Hence, no further adjustment is required.	None
PD(5)~PD (8)	The Case Project's construction phase needs to be completed earlier than planned.	(c) Modify PDS and change phase durations	To change DBB (with PCM) to DBB (with PCM) with early procurement and with multiple contractors, and to shorten design and construction durations to meet the desirable earlier completion date.	Increase the total project cost by $3,900,276.[2]

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]A $$1,810,620 increase in design cost and a $2,089,656 increase in construction cost.

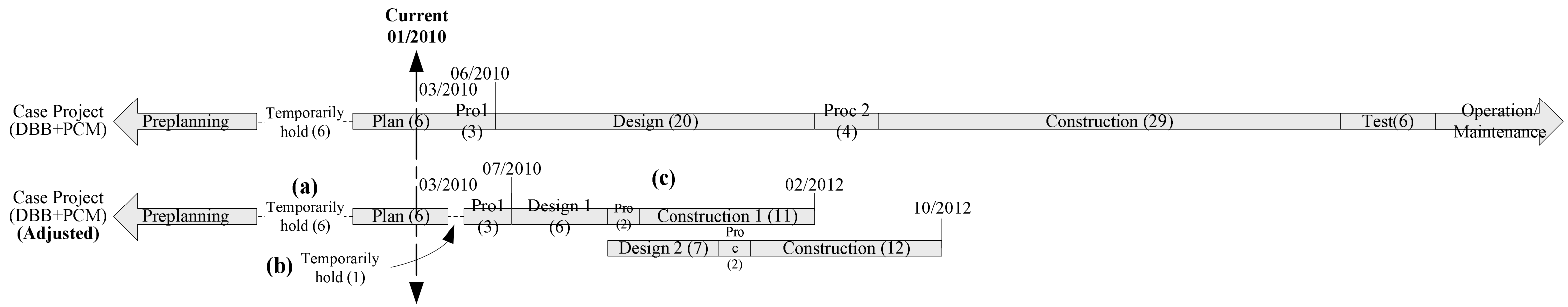


Figure 7.9 Case Project's initial and adjusted timeline in DBB (with PCM)

Table 7.18 Impacts of project dependencies and response strategies taken in DB

No of PD	Impacts on initial estimated schedule	Response strategy	Strategy description	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	No response strategy is required as PD(2) will not affect the Case Project's estimated schedule.	None
PD(3)	None[2]	None	The new land use is expected to be approved before the estimated starting date of the Case Project's procurement phase; and hence no response strategy is required.	None
PD(4)	None[3]	None	More certain information about the environmental codes is expected to be available before the starting date of the design/build phase; and hence no response strategy is required.	None
PD(5)~ PD(8)	The Case Project's construction phase needs to be completed earlier than planned.	(b) Modify PDS and change phase durations	To change traditional DB to DB with multiple design/builders; and to shorten design and construction durations.	Increase the total project cost by $ 769,294.

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]The approval of the new land-use is expected to be completed before the estimated starting date of the Case Project's procurement (for design) phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.
[3]The information is expected to be available before the estimated starting date of the Case Project's design phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.

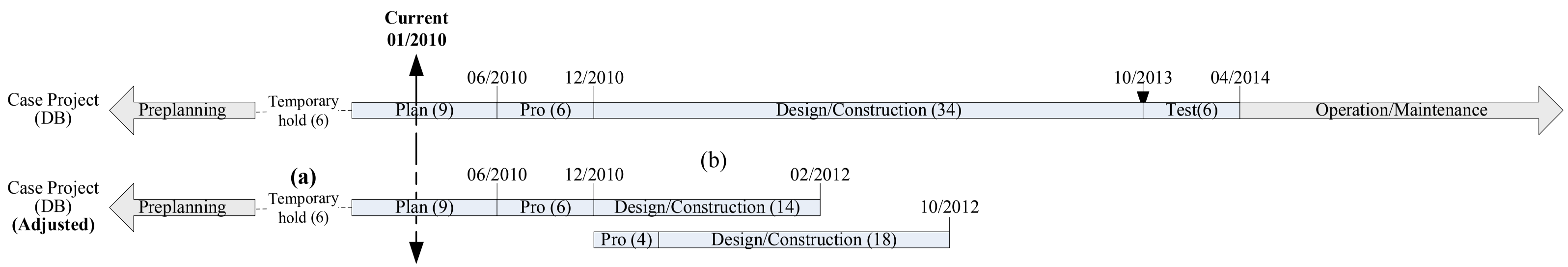


Figure 7.10 Case Project's initial and adjusted timelines in DB

Table 7.19 Impacts of project dependencies and the response strategies taken in DB (with PCM)

No of PD	Impacts on initial estimated schedule	Response Strategy	Strategy Description	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	No response strategy is required as PD(2) will not affect the Case Project's estimated schedule.	None
PD(3)	None[2]	None	The new land use is expected to be approved before the estimated starting date of the Case Project's procurement phase; and hence no response strategy is required.	None
PD(4)	None[3]	None	More certain information about the environmental codes is expected to be available before the starting date of the design/build phase; and hence no response strategy is required.	None
PD(5)~PD (8)	The Case Project's construction phase needs to be completed earlier than planned.	(b) Modify PDS and change phase durations	To change traditional DB (with PCM) to DB (with PCM) with multiple design/builders; and to shorten design and construction durations.	Increase the total project cost by $ 2,220,468.

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]The approval of the new land-use is expected to be completed before the estimated starting date of the Case Project's procurement (for design) phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.
[3]The information is expected to be available before the estimated starting date of the Case Project's design phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.

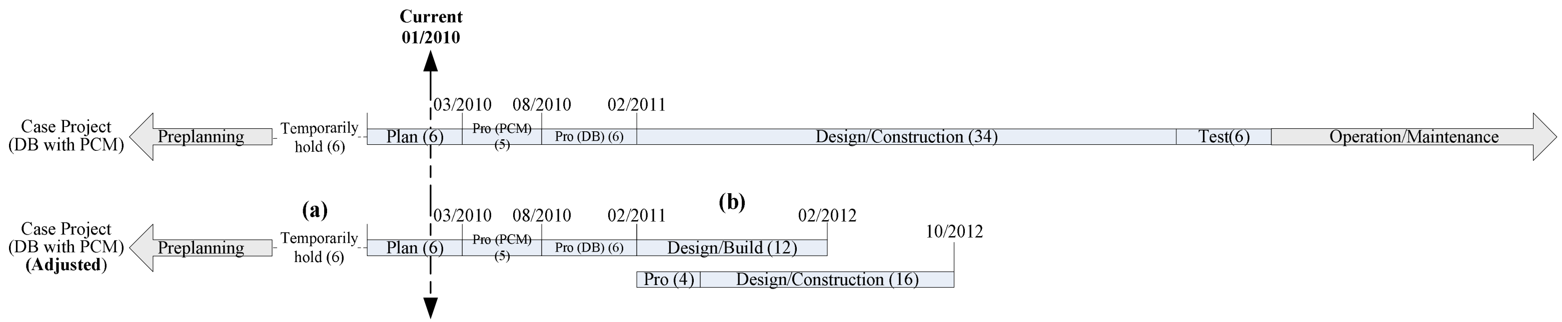


Figure 7.11 Case Project's initial and adjusted timeline in DB (with PCM)

Table 7.20 Case Project's initial and adjusted total project durations and costs[1]

	Estimated project duration(month)[2]		Estimated project cost($)[3]	
	Initial	After-adjusted	Initial	After-adjusted
DBB	61	37	$53,016,200	$57,478,304
DBB (with PCM)	62	37	$54,869,483	$58,769,759
DB	49	37	$49,985,950	$50,755,244
DB (with PCM)	51	37	$51,631,947	$53,852,415

[1]Under 4% discount rate.

[2]Estimated duration here refers to the total project duration starting from the beginning of the project planning phase to the end of the construction phase.

[3]Estimated project cost here refers to the total project cost including project planning, design, procurement and construction costs.

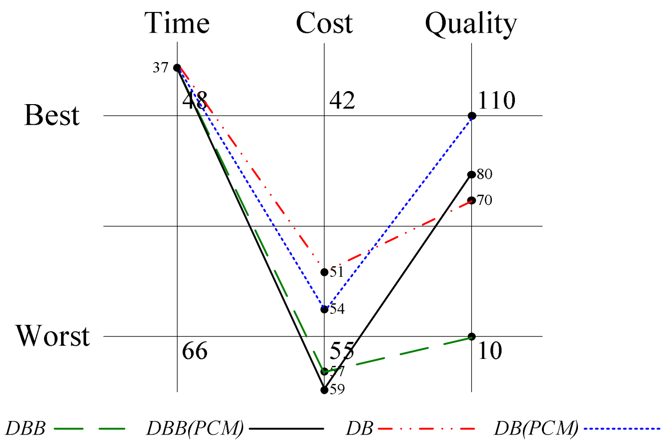


Figure 7.12 Adjusted performance profile on PERF criteria

7.4.4.2 Deal with general PDS criteria

The Case Project's project manager evaluated the four considered PDSs on general PDS criteria using a weighted score approach. A 10-110 scale is used for both the weighting of the criteria and scoring of the PDSs. The higher the number, the more important the criterion/the better the performance of the PDS. The scores of the four considered PDSs on general PDS criteria are presented in Table 7.21. Figure 7.13 shows the four considered PDSs' overall performance profiles on the general PDS criteria. Because PDSs with similar total weighted scores can have different performance profiles, a breakdown performance profile that shows PDSs' performance on individual criteria is also generated (as shown in Figure 7.14).

Table 7.21 Considered PDSs' performance on general PDS criteria

General PDS criteria	Rank	Wi	DBB		DBB+PCM		DB		DB+PCM	
			Score	W. S.	Score	W. S.	Score	W. S.	Score	W. S.
Complexity (CP)	(1)	0.23	10	2.3	60	14.0	100	23.4	110	25.7
Flexibility (F)	(2)	0.21	100	21.3	110	23.4	10	2.1	30	6.4
Time certainty (TC)	(3)	0.19	10	1.9	40	7.7	110	21.1	100	19.1
Risk transfer (RT)	(4)	0.15	10	1.5	30	4.5	100	14.9	110	16.4
Cost certainty (CC)	(5)	0.11	10	1.1	20	2.1	110	11.7	100	10.6
Point of responsibility (PR)	(6)	0.09	10	0.9	50	4.3	100	8.5	110	9.4
Price competition (PC)	(7)	0.02	110	2.3	80	1.7	40	0.9	10	0.2
Total		1		31.3		57.7		82.6		87.9

Wi: Normalized weight; W.S.: Weighted score.

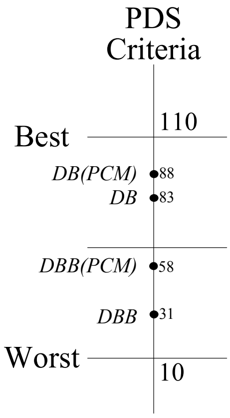


Figure 7.13 The performance profile on general PDS criteria

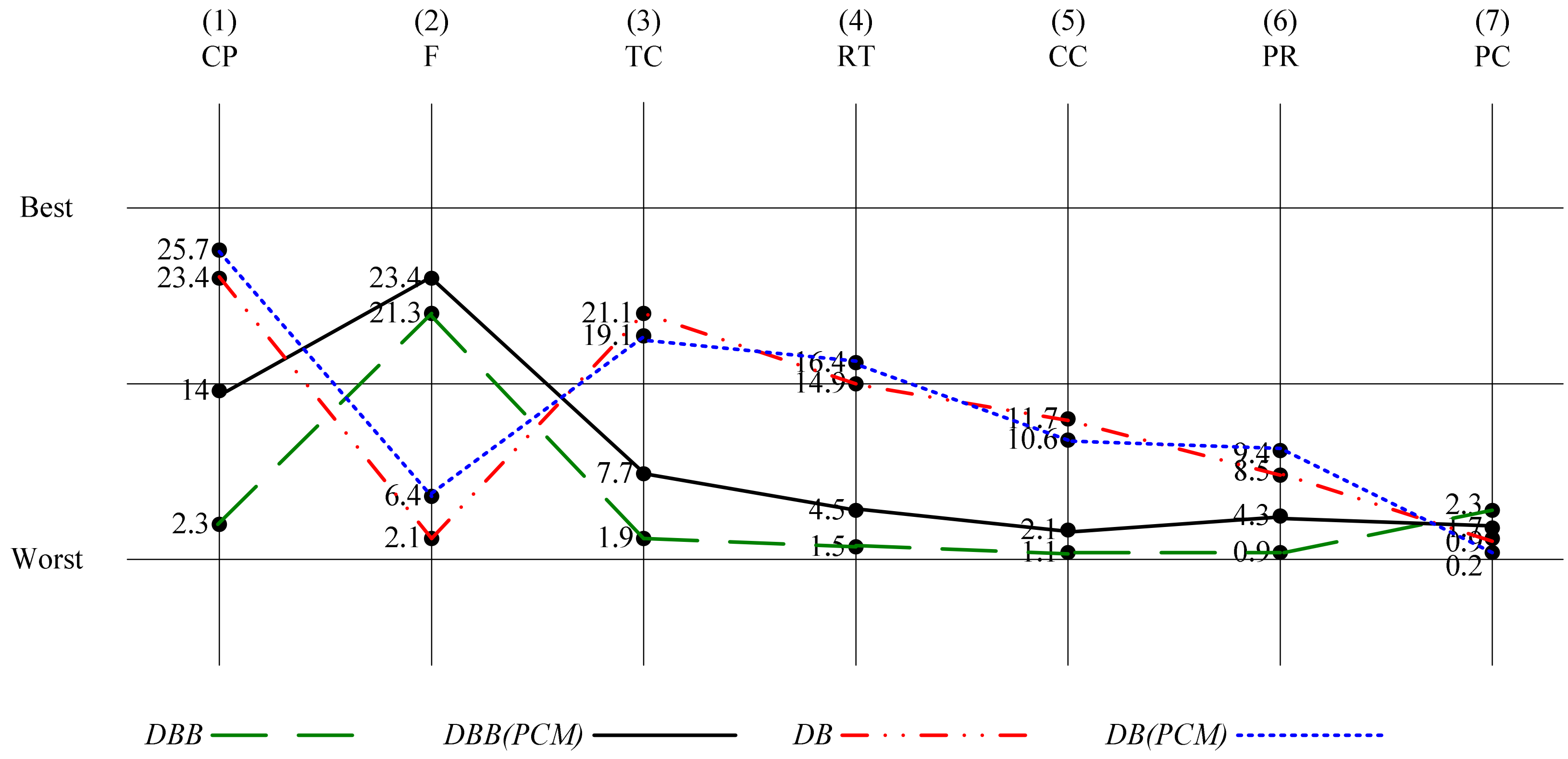


Figure 7.14 Breakdown performance profile on individual general PDS Criteria

7.4.5 Stage 5: Choose a PDS

The performance profiles of the four considered PDSs on PERF and general PDS criteria are combined into a single performance profile, as shown in Figure 7.15. This figure, along with the breakdown performance profile on general PDS criteria (Figure 7.14), were presented to the project manager for his PDS decision-making.

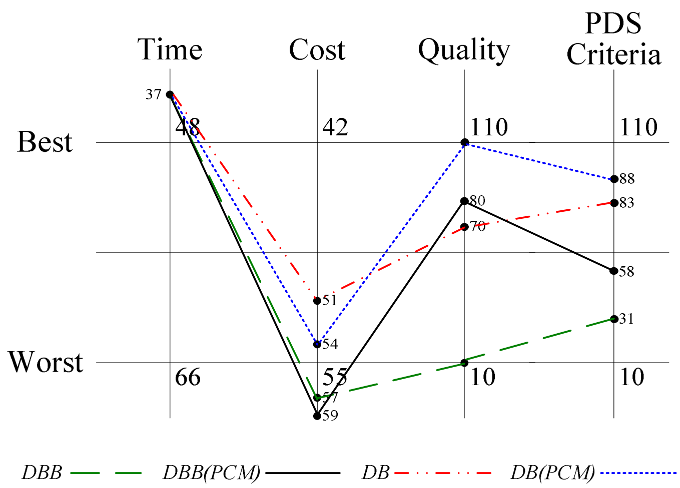


Figure 7.15 Overall performance profile of the four considered PDSs

7.4.5.1 Decision-making rational

The project manager selected DB (with PCM) as the most appropriate PDS for the Case Project based on the following decision-making rationale:

- DBB and DBB (with PCM) were eliminated from further consideration because the Case Project's total cost in these two PDSs will exceed the budget limit. DB and DB (with PCM) were considered by the project manager to perform equally on the cost criterion despite the fact that the project cost in DB (with PCM) is higher than in DB. This is due to two reasons. First, for a public project, as long as its cost falls within the budget constraint, it is less important to the decision-maker whether the cost is higher or lower. Furthermore, the extra cost in DB (with PCM) is the PCM fee, which was considered to be a reasonable expense.

- A similar consideration is also applied to the quality criterion. Whether a PDS can deliver a public project at a higher quality level than another is not the project manager's primary concern, as long as the delivered project can fulfill its designated functions and standards. For this reason, even though DB (with PCM) performs better than DB on the quality criterion, it is not a sufficient reason for the project manager to make his decision.

- Time is the project manager's primary concern for the Case Project. Both DB and DB (with PCM), with certain modifications and time/cost trade-off adjustments, can deliver the Case Project's within the new desired project deadline. The project manager thus further examined the two PDSs' performance on time certainty criterion; he found that DB performs better than DB (with PCM). However, because the weighted scores of the two PDSs on time certainty are relatively close, it is difficult to determine whether their performance significantly differs.

- The project manager's next serious concern about the Case Project was its complexity. Whether a PDS can tackle a complex project is therefore an important factor to consider. In terms of complexity criterion, DB (with PCM) performs better than DB;PCM can provide the expertise and skills that the Agency does not have.

- The project manager was also concerned about the Agency's ability to effect changes, the Agency's level of involvement and the level of risk bared. These three are evaluated by the criteria of flexibility, risk transfer and point of responsibility. As shown in Figure 7.14, DB (with PCM) performs better than DB on all three criteria.

- Figure 7.14 also shows that DB performs better than DB (with PCM) on cost certainty and price competition. These two criteria, however, were considered by the project manager as the least important criteria. As mentioned earlier, as long as the project cost falls within the budget constraint, cost variations are acceptable. In addition, the Agency itself has a separate funding pool that can pay for project cost-overruns should they occur. In this case, cost certainty is a less important criterion as compared with others. As for the price competition, due to the high project complexity and scale, the Agency would rather have the most qualified bidders than have "many" bidders. For this reason, the price competition criterion is also not an important issue.

In sum, DBB and DBB (with PCM) were considered infeasible because the total project cost in these two PDSs will exceed the budget constraint. Both DB and DB (with PCM) can deliver the Case Project within the desired completion date, within the budget constraint and with a satisfactory quality level. However, DB (with PCM) performs better than DB on almost all general PDS criteria, except time certainty, cost certainty and price competition. Because cost certainty and price competition are the two least important criteria for the Case Project, the disadvantage of DB (with PCM) on these two criteria does not make it a worse PDS. Even though time certainty is also an important criterion, the disadvantage of DB (with PCM) on this criterion is outweighed by its advantages on other important criteria (e.g., complexity, flexibility and risk transfer). On the basis of this rationale, the project manager chose DB (with PCM) as the most appropriate PDS for the Case Project.

7.4.5.2 Proactive management strategies

In the above reasoning process, the project manager also identified three important criteria that DB (with PCM) performs poorly: flexibility, time certainty and cost certainty. He then developed management strategies to improve DB (with PCM)'s performance on these three criteria.

As previously discussed, the project manager divided the Case Project into two sub-projects to be implemented by different design/builders. This changed "DB (with PCM)" to "DB (with PCM) with multiple design/builders". This strategy could shorten the Case Project's duration to meet its new desired completion date, and it could improve the Agency's flexibility to effect changes in the future. For example, if the need of the wastewater treatment increases slower than expected in the future, the Agency can choose to stop the development or change the scope of the second-part project. The project manager also decided to build more flexibility into contracts by including a termination (or reduction) for convenience clause in its contracts with the contractor. This clause will provide the Agency the flexibility to terminate the Case Project (in whole or in part) or change its scope.

DB (with PCM) performs slightly worse than DB on time certainty and cost certainty. This is mainly because of the intensive coordination and communication involved in DB (with PCM). Such coordination and communication, if not properly managed, can cause significant project delay and cost overrun. To prevent or minimize this possibility, the project manager decided to emphasize the review of the communication plans in the PCM bidders' proposals.

7.4.6 Sensitivity analysis

The use of different discount rates can affect the time/cost trade-off rules, and thus the Case Project's adjusted schedules and costs. This section presents a sensitivity analysis on two additional discount rates, namely 2% and 6%, and discusses how they may affect the project manager's PDS decision. Table 7.22 summarizes the time/cost trade-off rules under different discount rates in the four considered PDSs.

Many other factors may also affect the Case Project's estimated timelines and costs in different PDSs. Some examples include: the Case Project's initial estimated project timelines and cost distributions, the interrelated projects' anticipated timelines, and the project manager's choices of response strategies. If necessary, a decision-maker can also conduct a sensitivity analysis on each of the factors (or a group of factors) to investigate how changes in these factors would affect PDS decisions.

Table 7.22 Time/cost trade-off rules given different discount rates

		Discount Rates		
		2%	4%	6%
DBB	D_D vs. D_C	- $382,590/m	- $270,000/m	- $167,400/m
	D_D vs. C_D	-1.11	-1.32	-1.69
	D_D vs. C_C	-$380,000/m	-$280,000/m	-$180,000/m
	D_C vs. C_D	-$411,962/m	-$355,263/m	-$280,432/m
	D_C vs. C_C	-1.0	-0.96	-0.93
	C_D vs. C_C	-$420,690/m	-$362,069/m	-$306,896/m
DBB (with PCM)	D_D vs. D_C	-$368,550/m	- $258,660/m	-$157,410/m
	D_D vs. C_D	-1.109	-1.30	-1.7
	D_D vs. C_C	-$365,000/m	-$265,000/m	-$170,000/m
	D_C vs. C_D	-$408,348/m	-$329,268/m	-$267,538/m
	D_C vs. C_C	-1.04	-0.957	-0.93
	C_D vs. C_C	-$403,793/m	-$348,276/m	-$293,103/m
DB	D/B_D vs. D/B_C	- $445,842/m	- $384,647/m	- $323,454/m
DB (with PCM)	D/B_D vs. D/B_C	- $430,106/m	- $370,078/m	-$308,884/m

Note: columns marked in grey are the trade-off rules that are currently in use.
D_D: Design Duration; D_C: Design Cost; C_D: Construction Duration; C_C: Construction Cost; D/B_D: Design/Build Duration; D/B_C: Design/Build Cost.

7.4.6.1 PDS decision-making given a 2% discount rate

The same procedure as outlined in Section 7.4.5 was used to obtain the Case Project's adjusted estimated durations and costs in the four considered PDSs, given a 2% discount rate. The results are presented in Table 7.23. The performance profile of the four considered PDSs in 2% discount rate is shown in Figure 7.16.

The analysis result shows that when the discount rate is reduced from 4% to 2%, the estimated total project costs in all the four considered PDSs increase. The estimated total project costs in DBB and DBB (with PCM) still exceed the budget limit; these two PDSs are again considered infeasible. Because the change of discount rate does not change the scores of the considered PDSs on quality level and general PDS criteria, the project manager still considered DB (with PCM) as the most appropriate PDS for the Case Project. His decision-making rationale in this case was the same as that presented in Section 7.4.5.

Tabl2 7.23 Case Project's initial and adjusted total project durations and costs, given 2% discount rate

	Estimated project duration(month)[1]		Estimated project cost($)[2]	
	Initial	After-adjusted	Initial	After-adjusted
DBB	61	37	$53,016,200	$58,677,260[3]
DBB (with PCM)	62	37	$54,869,483	$59,872,091[4]
DB	49	37	$49,985,950	$50,877,634[5]
DB (with PCM)	51	37	$51,631,947	$54,212,583[6]

[1]Estimated duration here refers to the total project duration starting from the beginning of the project planning phase to the end of the construction phase.
[2]Estimated project cost here refers to the total project cost including project planning, design, procurement and construction costs.
[3]Shorten the design phase by 6 months and construction phase by 8 months.
[4]Shorten the design phase by 7 months and construction phase by 6 months.
[5]Shorten the design/build phase by 2 months in total.
[6] Shorten the design/build phase by 6 months.

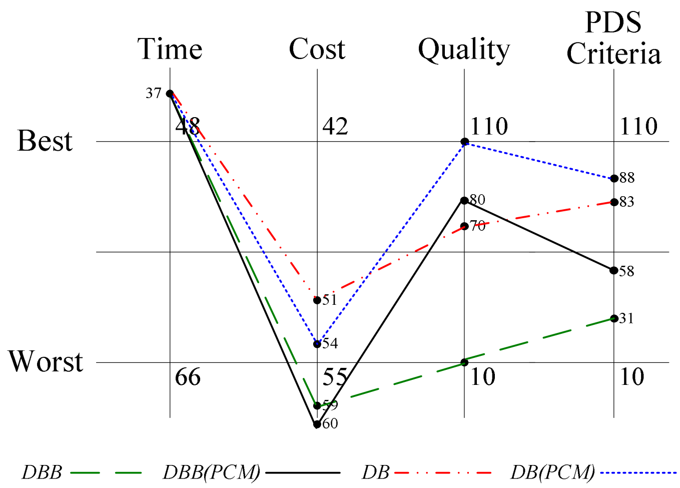


Figure 7.16 Performance profile, given 2% discount rate

7.4.6.2 PDS decision-making given 6% discount rate

Table 7.26 summarizes the Case Project's initial and adjusted timelines and costs in the four considered PDSs given a 6% discount rate, and Figure 7.17 shows the performance profile. The analysis result shows that as the discount rate increases from 4% to 6%, the estimated total project costs in the four considered PDSs all decrease. Even though the estimated total project costs in DBB and DBB (with PCM) still exceed the budget limit, the estimated total project cost in DBB is very close to the budget limit. Considering the uncertainty associated with the estimates, the project manager decided to also include DBB in his further consideration.

It can be seen from Figure 7.17 that DBB performs poorly relative to DB and DB (with PCM) on both the quality level and general PDS criteria. The project manager further examined the three PDSs' performance on individual general PDS criteria. Referring back to Figure 7.14, it is found that DBB performs better than DB and DB (with PCM) on flexibility but poorly on all the other general PDS criteria. Even though flexibility is also very important to the project manager, he decided that either DB or DB (with PCM) should be used from a holistic perspective. The project manager finally also selected DB (with PCM) for the Case Project based on the reasons presented in Section 7.4.5.

Tabl2 7.24 Case Project's initial and adjusted total project durations and costs, given 6% discount rate

	Estimated project duration(month)[1]		Estimated project cost($)[2]	
	Initial	After-adjusted	Initial	After-adjusted
DBB	61	37	$53,016,200	$56,475,768[3]
DBB (with PCM)	62	37	$54,869,483	$57,732,581[4]
DB	49	37	$49,985,950	$50,632,858[5]
DB (with PCM)	51	37	$51,631,947	$53,485,251[6]

[1]Estimated duration here refers to the total project duration starting from the beginning of the project planning phase to the end of the construction phase.
[2]Estimated project cost here refers to the total project cost, including project planning, design, procurement and construction costs.
[3]Shorten the design phase by 6 months and construction phase by 8 months.
[4]Shorten the design phase by 7 months and construction phase by 6 months.
[5]Shorten the design/build phase by 2 months in total.
[6]Shorten the design/build phase by 6 months.

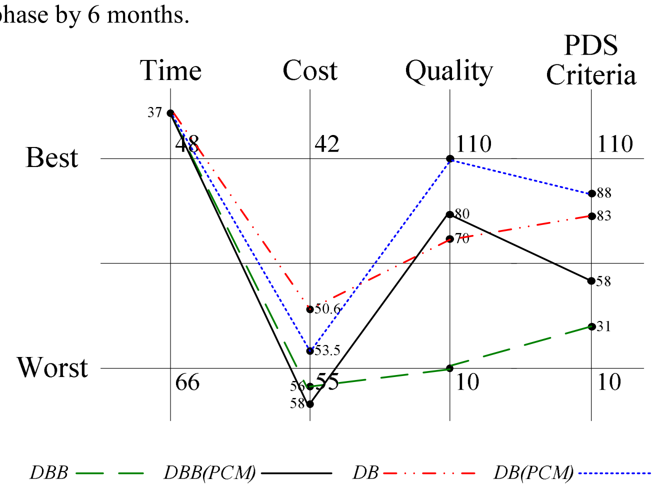


Figure 7.17 Performance profile, given 6% discount rate

7.5 Lessons Learned

Several lessons are learned from the framework application.

The PDS decision-support framework is useful in facilitating an informed and rational PDS decision. The Agency currently does not have a structured PDS decision-making process. A project manager chooses PDSs solely based on his/her experience with certain PDSs and intuitive judgment. The problems of this decision-making behavior are two-fold. First, the project manager tends to select PDSs that he/she is familiar with instead of the ones that are most suitable for projects. It is also difficult for the project manager to justify his/her PDS decisions to others.

When the framework was first introduced, the Case Project's project manager was hesitant to use it because he was unfamiliar with certain concepts (e.g., time/cost trade-off rules and the determination of project dependencies). After explanation, however, the project manager quickly learned the involved concepts and methods. He also agreed that the proposed PDS decision-support framework is useful in facilitating a structured and informed PDS decision. Information collected and analyzed in the framework allowed him to better justify his PDS decision for the Case Project to others. These pieces of information also provided him a basis for future project planning and control.

Proper documentation and knowledge management systems are important for the application of the PDS decision-support framework. The framework application relies heavily on information from past similar projects. It also requires the knowledge of the Case Project's interrelated projects (e.g., their current status and anticipated future timelines). These pieces of information can be collected more efficiently if there is a structured system that traps essential project information and manages past knowledge. When the proposed framework was applied, the Case Project's project manager had little difficulty collecting historical data from past similar projects and information on other ongoing projects because the Agency had maintained a comprehensive project database. The existence of this project database significantly contributed to the effectiveness of the framework implementation.

An effective communication structure is critical to the successful implementation of the PDS decision-support framework. Identifying projects that are interrelated with the Case Project, defining project dependencies, and determining the impacts of the identified project dependencies on the Case Project's estimated timelines and costs in different PDSs are critical steps in the framework application process. All these steps require intensive communication between the project managers of the Case Project and its interrelated projects.

Currently, project managers in the Agency plan and implement their projects individually. They only report the project information and status to the head of the Agency. The communication and coordination among them are limited. A project manager thus may not be aware of the scopes, the objectives and the status of the Agency's other ongoing projects. For this reason, when the proposed framework was applied, the project manager had difficulty identifying the projects that are interrelated to the Case Project. To resolve this problem, the project manager first retrieved a list of the Agency's ongoing projects from the project database. He then went through the projects individually to consider their possible relationship to the Case Project. For projects that he was not aware of, the project manager consulted with those projects' managers to collect more detailed information. This process consumed a significant amount of time and caused a delay in the framework application process. This application problem indicates the importance of a structured communication system.

The competence of the project manager is critical to the successful framework application. The application of the proposed framework requires the project manager's judgments in several areas, such as the range of estimated project durations and costs, and the management strategies to accommodate the impacts of project dependencies. A project manager's competence in making such judgments can significantly affect the efficiency of the framework application and the quality of a PDS decision. Thus, the public agency should periodically provide training courses to its project managers. Such training courses in the short-term can focus on the concepts and skills required for the implementation of the PDS decision-support framework. In the long-term, topics of these training courses can be expanded to include, but not be limited to, lessons learned from the framework implementation, the introduction to innovative PDSs and the uses of different PDSs in industry.

Top management support is essential for a structured PDS decision-making culture. To establish and implement a structured PDS decision-support framework in a public agency is a difficult task. It may involve significant changes in how project managers think about PDS decision-making and how they perform their work. For example, to use the proposed framework, a decision-maker has to consider project dependencies. This would require the decision-maker to change a mindset from a single-project consideration to a multi-project consideration. Additionally, a formal PDS decision-making process usually represents a more detailed information collection and analysis process, which requires much more effort. The project manager may also need to take some training courses to learn the concepts and skills required for the framework implementation. All these changes may encounter initial resistance from staff, and thus a strong and visible commitment from upper-level management is important.

7.6 Summary

This chapter presents the application of the proposed framework to a wastewater treatment plant project in Taiwan. The framework helped the Case Project's project manager design and evaluate four regulation-authorized PDSs with respect to performance and general PDS criteria; also taken into account were the dependencies between the Case Project and its interrelated projects, and possible time/cost trade-offs. The framework also helped the project manager identify areas where the selected PDS may perform poorly and allowed him to develop proactive management strategies.

The Case Project's project manager agreed that the proposed PDS decision-support framework is useful in facilitating a structured and informed PDS decision. With the information generated by the framework, he could better justify his choice of a PDS. The project manager also agreed that the concepts and skills required for the framework implementation are easy to understand and apply.

This application experience, however, also revealed a disadvantage of the framework. The implementation of the framework could be more time-consuming than some of the available PDS selection methods (e.g., the weighted sum approach). This longer implementation time was in part the result of the unfamiliarity of the project manager with the proposed framework, and thus could be reduced through proper training. Some difficulties associated with data collection (e.g., identifying interrelated projects and defining project dependencies) also caused a delay in the implementation process. These difficulties, however, could be mitigated in the future if a public agency establishes proper documentation and knowledge management systems, develops an effective communication structure, and provides proper training to enhance its staff's competence. Strong support from upper-level management is also critical to the successful framework implementation.

Chapter 8
Conclusions and Recommendations

8.1 Introduction

This chapter presents a research summary, contributions and discusses limitations and future research directions. These are separately described in the following sections: Section 8.2 summarizes research findings; Section 8.3 presents research contributions; Section 8.4 discusses research limitations and provides future research recommendations.

8.2 Research Summary

8.2.1 The PDS decision-making problem and practices

Designing and choosing a PDS in a multi-project environment is a difficult task for several reasons. First, the decision is made in the early project planning phase when only limited and imprecise information is available. Second, the choice of PDS involves the consideration of multiple objectives (e.g., time, cost and quality) and a variety of PDS alternatives (e.g., DBB and DB). The selection objectives can conflict. The considered PDSs can vary in different aspects. A PDS that performs better in some aspects may perform poorly in others. These have made a comparison of PDSs difficult. Complex dependencies existing among projects in a multi-project environment further complicates the PDS decision-making process.

A structured method can improve the quality of PDS choice. Unfortunately, in practice, a PDS choice is often made intuitively or not in a structured way. This unstructured behavior may increase the chance that an inappropriate PDS is selected. This may not only impede the realization of certain anticipated benefits associated with the designated PDS but also lead to project failure.

8.2.2 Available PDS selection methods

To help a decision-maker choose a PDS in a systematic way, researchers have proposed four groups of PDS selection methods: (1) guidance, (2) multi-attribute analysis, (3) knowledge- and experience-based, and (4) the mixed-method approaches. These methods vary in their knowledge bases, complexities and required information for implementation. They are also different in the ways in which a decision-maker's preferences are elucidated, expressed and measured. All of them have their own advantages and disadvantages. The choice of a suitable method should depend on a decision-maker's needs and decision-making circumstances.

Despite these differences, however, the available PDS selection methods share three similar limitations. First, they all inadequately address, if not entirely ignore, project dependencies in their PDS evaluation processes. In a multi-project environment, there exist complex interdependencies among projects. These project interdependencies may hinder a PDS's abilities to achieve expected benefits. A PDS may be selected based on an unrealistic expectation of its associated benefits if these project dependencies are not being considered. Furthermore, all of the available PDS selection methods do not allow decision-makers to explicitly consider possible time/cost trade-offs in their decision-making processes. These methods also do not provide decision-makers the opportunity to design, to a certain degree, a PDS to best meet project objectives. These three limitations, along with the unstructured PDS decision-making practices in industry, have inspired the development of the present decision-support framework.

8.2.3 The proposed PDS decision-support framework

8.2.3.1 The overall PDS decision-support framework

The proposed PDS decision-support framework can help a decision-maker design and evaluate regulation-authorized PDSs, specifically DBB, DB and CMR, with respect to two groups of criteria: PERF and general PDS criteria. It also integrates a NPV-based method for objectively determining time/cost trade-off rules and a procedure for systematically evaluating project dependencies. All these framework functions are built into a stage-gate structure that is composed of: (1) defining project objectives/constraints; (2) identifying regulation-authorized PDSs; (3) defining evaluation criteria; (4) designing and evaluating PDSs; (5) choosing a PDS.

A stage-gate structure has several benefits. First, the gates provide a decision-maker with opportunities to review, discuss and verify the stage outputs. This structure also allows a decision-maker to add, remove or modify certain stages and gates to tailor it various needs. Furthermore, with each stage and gate clearly outlined, a decision-maker can move easily and logically from one stage and gate to the next.

8.2.3.2 The NPV-based method

The proposed NPV-based process is composed of three main stages: (1) create a baseline NPV (given a PDS); (2) calculate impacts of variable variations on the baseline NPV; (3) convert the results to time/cost trade-off rules. This method is beneficial to a decision-maker in several ways. First, it helps the decision-maker objectively derive trade-off rules between time and cost within a single phase and across different phases. The visualization of time/cost trade-offs provides the decision-maker information about what to give up on one objective (e.g., time) for a performance increase on the other objective (e.g., cost). This information is useful in establishing project schedule and cost objectives. The derived trade-off rules also allow the decision-maker to conduct a scenario analysis for different sets of project durations and costs and to examine how these different situations affect project performance in a PDS.

8.2.3.3 A procedure to evaluate project dependencies

A structured procedure is also proposed to help a decision-maker evaluate impacts of project dependencies on the new project's estimated timelines and cost distributions in different PDSs. In this procedure, the decision-maker first identifies projects that are interrelated with the new project. Next, the decision-maker defines the types, the degrees and the precedence relationships of the indentified project dependencies. The decision-maker then determines the impacts of the identified project dependencies on the new project's estimated timelines in different PDSs and takes proper dependency management strategies. Finally, the decision-maker makes adjustments to the new project's estimated costs by applying the predetermined time/cost trade-off rules. Such a systematic consideration of project dependencies can help the decision-maker make more realistic estimates of project timelines and costs under different PDSs, which is expected to enable a more informed PDS decision.

8.2.3.4 Framework application

When applied to the Case Project, the PDS decision-support framework is shown to be useful in facilitating a structured and informed PDS decision. Information collected and analyzed in the framework not only enables a better justification for why a particular PDS is selected for the Case Project, but also provides a basis for future project planning and control.

This application, however, reveals a problem with the framework: its implementation can be more time-consuming than some other PDS selection methods. This longer implementation time is in part the result of the unfamiliarity of the Case Project's project manager with the proposed framework, and thus can be reduced through proper training. Some difficulties associated with collecting required information for the framework implementation (e.g., identifying interrelated projects and defining project dependencies) also contribute to this longer implementation time. To mitigate these difficulties and ensure a more effective framework implementation in the future, public agencies are urged to: (1) establish proper documentation and knowledge management systems, (2) develop an effective communication structure, and (3) provide proper training to enhance the project manager's competence. Strong support from upper-level management is also critical to a successful framework implementation.

8.3 Research Contributions

This research contributes to both the project planning and PDS decision-making practices, as discussed below:

8.3.1 Contributions to the project planning

This research raises the need to consider project interdependencies in project planning. Project interdependencies can significantly affect project performance. By considering these interdependencies in the project planning process, a project manager could make more realistic estimates of project schedule and cost; the project manager could also develop proactive management strategies to avoid (or at least mitigate) possible negative impacts caused by the interdependencies. The structured project interdependency evaluation procedure proposed in this research can help project owners systematically evaluate impacts of project interdependencies.

Time/cost trade-off analysis is a critical aspect of project planning and management. This research proposed a NPV-based method to help project owners objectively make time/cost trade-off decisions in the early project planning phase.

8.3.2 Contributions to PDS decision-making

The proposed PDS decision-support framework can also facilitate a more realistic and informed PDS decision. This is achieved in several ways.

First, the framework incorporates estimates of project schedule and cost into the PDS decision-making process. It also helps a decision-maker consider project dependencies and assess their impacts on project performance. These pieces of information can provide the decision-maker with an early indication of project performance on time and cost under different PDSs; in addition, such information can also be used as a basis for further project planning and controlling.

Second, the framework encourages the consideration of proactive project management strategies in addition to PDS decision-making. This can help avoid some potential project implementation difficulties or mitigate potential negative impacts caused by these problems. For example, the framework provides a decision-maker the opportunities to "design" a PDS to improve its performance on certain project objectives. The decision-maker can also develop proactive management strategies to enhance the selected PDS's performance on certain criteria.

Third, the framework allows the decision-maker to consider different scenarios in the decision-making process. A high level of uncertainty is involved in the environment where the project is implemented and in the estimates of project information. The proposed framework allows the decision-maker to perform a sensitivity analysis to investigate how these uncertainties may affect PDS decisions.

Finally, the framework provides a transparent and step-by-step assessment of alternative PDSs. The decision-maker has the opportunities to choose techniques used in each step and to discuss and verify the outputs of each step. This transparency allows the decision-maker to better justify PDS decisions to others. Additionally, the evaluation results are presented in the form of a performance profile, which provides the decision-maker a basis for group discussions.

8.4 Limitations and Future Research

The decision-support framework was developed for a public agency that is required by regulations to choose from regulation-authorized PDSs, namely, DBB, DB and CMR. It is assumed that the public agency has limited flexibility to adapt these PDSs to the specific circumstances of individual projects. It is also assumed that decisions on project management strategies, such as methods of contractor selection (e.g., price-based, value-based), compensation (e.g., cost plus and fixed fee, or cost plus a percentage) and project government methods, are made after the basic form of PDS is determined. Due to these two restrictions, the yielded PDS may not be the best PDS for the specific project, but the one that is the best suited for the decision-making circumstances. Future research is recommended to expand consideration of basic forms of PDSs to include decisions on project management strategies.

In addition, due to difficulty in data collection, the proposed framework is only applied to a wastewater treatment plant project in Taiwan. Even though this application has provided some valuable insights, more applications of the framework to projects in different infrastructure sectors and countries will be useful in improving the quality and the applicability of the framework.

The proposed framework is also limited in that it only allows a decision-maker to consider PDSs for one new project at a time. For example, the framework helps a decision-maker choose a PDS for a new infrastructure project, taking into account its dependencies on other ongoing projects. Future research can expand this framework to enable simultaneous consideration of PDSs for multiple new projects. Such evaluation will involve consideration of different combinations of the PDSs considered for each of the projects. Consider a decision-maker choosing PDSs for two new projects: Project A and Project B. Consider further that the number of PDSs under consideration for Project A and Project B are both two (e.g., DBB and DB). The number of combinations to be evaluated is thus four (e.g., DBB and DBB; DBB and DB; DB and DBB; and DB and DB). When the number of projects and possible PDSs increases, the evaluation process will become more complex. In this case, better computational models are needed.

Future research is also needed to address the dynamic nature of the estimates involved in the decision-making process. The proposed framework mainly uses static information to perform PDS evaluation and to address the uncertainty issue by performing a sensitivity analysis. The sensitivity analysis is limited in the sense that only variations in one parameter at a time are studied. Even though variations of a combination of multiple parameters can still be studied in the sensitivity analysis, its analysis process can become very complex and may require the assistance of computer algorithms. Future studies on the dynamic nature of the estimates can be helpful in enhancing the capability of the framework.

References

Aaker, D. A. and Tyebjee, T. T. (1978). “A model for the selection of interdependent R&D projects.” *IEEE Transactions on Engineering Management*, 25(2), 30–36.

Abdullah, A. M. and Vickridge, I. G. (1999). “Best practice for MPM in the construction industry.” In *Proceedings of RICS COBRA 1999 Conference – The Challenge of Change: Construction and Building for the New Millennium*, University of Salford, Salford, UK.

Abowitz, D. A. and Toole, T. M. (2010). “Mixed method research: fundamental issues of design, validity, and reliability in construction research.” *Journal of Construction Engineering and Management*, ASCE, 136(1), 108-116.

ACI, ACC and AGC (2006). *Airport Owners’ Guide to Project Delivery Systems*, available at: http://www.agc.org/galleries/projectd/ACI%20ACC%20AGC%20Project%20Delivery%20System%20White%20Paper.doc (assessed 18 April 2010).

Alhazmi, T. and McCaffer, R. (2000). “Project procurement system selection model.” *Journal of Construction Engineering and Management*, ASCE, 126(3), 176-184.

Al Khalil, M. I. (2002). “Selecting the appropriate project delivery method using AHP.” *International Journal of Project Management*, 20(6), 469-474.

Ambrose, M. D. and Tucker, S. N. (1999). “Matching a procurement system to client and project needs: a procurement system evaluator,” in *Bowen, P.A. and Hindle R. D. (Eds), CIB W92 Proceedings: “Customer satisfaction: a focus for research and practice in construction” Procurement Systems Symposium*, University of Cape Town, Cape Town, 280-288.

Ballard, G. (2008). “LPDS Update”. *Lean Construction Journal,* 2008. Available at www.leanconstructionjournal.org.

Barrie, D. S. and Paulson, Jr., B. C. (1992). *Professional Construction Management: including CM, Design-construct, and General Contracting*, McGraw-Hill, New York.

Beard, J. L., Loulakis, M. C. and Wundram, E. C. (2001). *Design-Build: Planning Through Development*, McGraw-Hill, New York, NY.

Belton, V. and Stewart, T. J. (2002). *Multiple criteria decision analysis: an integrated approach*, Springer.

Birnie, J. (1997). “Risk allocation to the construction firm within a Private Finance Initiative (PFI) project.” In *Proceedings of ARCOM Conference*, 1997, 527-534.

Bouyssou, D., Perny, P., Pirlot, M., Tsoukias, A., and Vincke, P. (1993). “A manifesto for the new MCDA era.” *Journal of Multi -Criteria Decision Analysis*, 2, 125-127.

Bouyssou, D. (1996). “Outranking relations: do they have special properties?” *Journal of Multi -Criteria Decision Analysis*, 5, 99-111.

Bryman, A. (2004). *Social research methods* (2nd Ed.). Oxford: Oxford University Press.

Burns, S., Liu, L. and Feng, C. (1996). “The LP/IP hybrid method for construction time/cost trade-off analysis.” *Construction Management and Economics*, 14, 265-276.

Carr, V. and Tah, J. H. M. (2001). “A fuzzy approach to construction project risk assessment and analysis: construction project risk management system.” *Advances in Engineering Software*, 32(10-11), 847-857.

Chinyio, E. A., Olomolaiye, P. O., and Corbett, P. (1998). “An evaluation of the projects needs of UK building clients.” *International Journal of Project Management*, 16(6), 385-391.

Cheung, S. O., Lam, T. I., Wan, Y. W. and Lam, K. C. (2001). “Improving objectivity in procurement selection.” *Journal of Management in Engineering*, ASCE, 17(3), 132-239.

Chan, A. P. C., Scott, D. and Lam, W. M. (2002). "Framework of success criteria for design/build projects." *Journal of Management in Engineering*, 18(3), 120-128.
Chang, A. S. T. (2002). "Reasons for cost and schedule increase for engineering design projects." *Journal of Management in Engineering*, ASCE, 18(1), 29-36.
Chan, D. W. M., and Kumaraswamy, M. M. (2002). "Compressing construction durations: lessons learned from Hong Kong building projects." *International Journal of Project Management*, 20, 23-35.
Chan, C. T. W. (2007). "Fuzzy procurement selection model for construction projects." *Construction Management and Economics*, 25(6), 611-618.
CIRC (2001). *Construct for Excellence*. Report of the Construction Industry Review Committee (CIRC), Hong Kong SAR Government, Hong Kong, 207pp.
Contractual Arrangements (Report A-7). (1982). Business Roundtable, New York.
Cooper, R. G. (1990). "Stage-gate systems: a new tool for managing new products." *Business Horizons*, 33(3), 44-53.
Construction Round Table (1995). *Thinking About Building*. London: The Business Round Table.
Construction Industry Institute (1997). *Project Delivery Systems: CM at Risk, Design-Build, Design-Bid-Build*, Executive Summary, RS133-1.
Construction Industry Institute (2003). *Owner's Tool for Project Delivery and Contract Strategy Selection User's Guide*, Research Summary IR165-2.
Construction Industry Institute (2003). *Project delivery and contract strategy selection: A tool for owners.* Implementation resource 165-2, 2nd Ed., The Univ. of Texas at Austin Press, Austin, Tex.
Dahl, P., Horman, M., Pohlman, T. and Pulaski, M. (2005). "Evaluating design-build-operate-maintain delivery as a tool for sustainability." In *Proceedings of Construction Research Congress*, April 5-7, San Diego, California.
De Maio, A., Verganti, R., Corso, M. (1994). "A multi-project management framework for new product development." *European Journal of Operational Research*, 78, 178-191.
Dvir, D., Raz, T. and Shenhar, A. J. (2003). "An empirical analysis of the relationship between project planning and project success." *International Journal of Project Management*, 21, 89-95.
Gransberg, D. D., Koch, J. A. And Molenaar, K. R. (2006). *Preparing for Design-Build Projects : a Primer for Owners, Engineers, and Contractors*, American Society of Civil Engineers, Reston, VA.
Goodman, A. S. and Hastak, M. (2006). *Infrastructure Planning Handbook: Planning, Engineering and Economics*. New York, ASCE Press, McGraw-Hill.
Einstein, A. and Infeld L. (1938). *The Evolution of Physics*. Simon and Schuster, New York, 1938.
Elmaghraby, S. E. and Herroelen, W. S. (1990). "The scheduling of activities to maximize the net present value of projects." *European Journal of Operational Research*, 49, 35-49.
Elmagraby, S. E. (1993). "Resource allocation via dynamic programming in activity networks." *European Journal of Operational Research*, 64, 199-215.
Eskerod, P. (1996). "Meaning and action in a multi-project environment." *International Journal of Project Management*, 14(2), 61-65.
Evaristo, R. and van Fenema, P.C. (1999). "A typology of project management: emergence and evolution of new forms." *International Journal of Project Management*, 17(5), 275-281.

Ferns, D. C. (1991). “Developments in programme management.” *International Journal of Project Management*, 9(3), 148-156.
Feng, C., Liu, L., and Burns, S. (1997). “Using genetic algorithms to solve construction time/cost trade-off problems.” *Journal of Computing in Civil Engineering*, 11(3), 184-189.
Federal Highway Administration (FHWA) (2008), PPP Case Studies, US Department of Transportation (available at http://www.fhwa.dot.gov/ppp/case_studies.htm)
Fox, G. E., Baker, N. R. and Bryant, J. L. (1984). “Economic models for R&D project selection in the presence of project interactions.” *Management Science*, 30, 890-902.
Friend, J. (1989). *The strategic choice approach*. In Rosenhead, 121-157.
Franks, J. (1990). *Building procurement Systems: a guide to building project management*, Charted Institute of Building, Ascot.
French, S. (1995). “Uncertainty and imprecision: modeling and analysis.” J*ournal of the Operational Research Society*, 46, 70-79.
Garvin, M. J. (2003). “Role of project delivery systems in infrastructure improvement.” In *Proceedings of Construction Research Congress*, March 19-21, Honolulu, Hawaii.
Gear, T. E. and Cowie, G. C. (1980). “A note on modeling project interdependency in research and development.” *Decision Science*, 11, 738-748.
Ghavamifar, K. and Touran, A. (2008). “Alternative project delivery systems: applications and legal limits in transportation projects.” *Journal of Professional Issues in Engineering Education and Practice*, ASCE, 134(1) 106-111.
Giachetti, R. E. (2006). “Understanding interdependency in enterprise systems: a model and measurement formalism.” In *Proceedings of Business Process Management 2006 Workshops*, J. Eder, S.Dusdar, et al. (Eds), Springer-Verlag, Berlin Heidelberg, 257-268.
Gray, R. (1997). “Alternative approaches to programme management.” *International Journal of Project Management*, 15(1), 5-9.
Guitouni, A. and Martel, J. M. (1998). “Tentative guidelines to help choosing an appropriate MCDA method.” *European Journal of Operational Research*, 109, 501-521.
Herbsman, Z. J., Chen, W. T., and Epstein, W. C. (1995). “Time is money: innovative contracting methods in highway construction.” *Journal of Construction Engineering and Management*, ASCE, 121(3), 273-281.
Hegazy, T. (1999). “Optimization of construction time/cost trade-off analysis using genetic algorithms.” *Canadian Journal of Civil Engineering*, 26, 685-697.
Hirst, I. (2001). *Investment appraisal for shareholder value*, Financial Times, Prentice-Hall, London.
HM Treasury, Central Unit on Purchasing (1992). *Guidance Document No.36: Contract Strategy Selection for Major Projects*, London: HMSO.
Howell, G., Ballard, G., and Hall, J. (2001). "Capacity utilization and wait time: a primer for construction." In *Proceedings of the 9th Annual Meeting of the International Group for Lean Construction*, Singapore.
Ibbs, C. W. and Crandall, K. C. (1982). “Construction risk: multi-attribute approach.” *Journal of the Construction Division*, ASCE, 108(C02) , 187-200.
Ibbs, C. W., Kwak, Y. H., Ng, T. and Odabasi, M (2003). “Project delivery systems and project change: quantitative analysis.” *Journal of Construction Engineering and Management*, ASCE, 129(4), 382-387.
Iyer, K. C. and Jha, K. N. (2005). “Factors affecting cost performance: evidence from Indian construction projects.” *International Journal of Project Management*, 23, 283-295.

Iyer, K. C. and Jha, K. N. (2006). "Critical factors affecting schedule performance: evidence from Indian construction projects." *Journal of Construction Engineering and Management*, ASCE, 132(8), 871-881.

Jick, T.D. (1983). "Mixing qualitative and quantitative methods: triangulation in action." In *Qualitative Methodology*, Van Maanen J. (Ed.),. Beverly Hills, CA: Sage Publications, 135-148.

Kelly, J. E. Jr. (1961). "Critical path planning and scheduling: mathematical basis." *Operations Research*, 9(3), 167-179.

Keeney, R. L. and Raiffa, H. (1972). "A critique of formal analysis in public sector decision making." In *Analysis of Public Systems*, Drake, A. W., Keeney, R. L., and Morse, P. M., (Ed.), MIT Press, Cambridge, Mass., 64-75.

Kerzner, H. (2003). *Project Management: a Systems Approach to Planning, Scheduling and Controlling*. John Wiley & Sons, Inc.

Kiggundu, M. N. (1981). "Task interdependency and the theory of job design." *Academy of Management Review*, 6(3), 499-508.

Kometa, S. T., Olomolaiye, P. O., and Harris, F. C. (1995). "An evaluation of clients' needs and responsibilities in the construction process." *Engineering Construction and Architect Management*, 2(1), 57-76.

Konchar, M. and Sanvido, V. (1998). "Comparison of U.S. project delivery systems." *Journal of Construction Engineering and Management*, ASCE, 124(6) 435-444.

Koppinen, T. and Lahdenpera, P. (2004), *The Current and Future Performance of Road Project Delivery Systems,* VTT Technical Research Centre of Finland.

Kumaraswamy, M. and Dissanayaka, S. (2001). "Developing a decision-support system for building project procurement." *Building and Environment*, 36(3), 337-349.

Leedy, P. (1993). *Practical research: planning and design*. Merrill, Columbus, Ohio.

Levy, N. and Globerson, S. (1997). "Improving multiproject management by using a queuing theory approach." *Project Management Journal*, 28(4), 40-46.

Li, H. and Love, P. (1997). "Using improved genetic algorithms to facilitate time/cost optimization." *Journal of Construction Engineering and Management*, ASCE, 123(3), 233-237.

Li, B., Akintoye, A., Edwards, P. J. and Hardcastle, C. (2005). "The allocation of risk in PPP/PFI construction projects in the UK," *International Journal of Project Management,* 23, 25-35.

Love, P. E. D, Skitmore, M. and Earl, G. (1998). "Selecting a suitable procurement method for a building project." *Construction Management and Economics*, 16(2), 221-233.

Luu, D. T., Ng, S. T. and Chen, S. E. (2003a). "Parameters governing the selection of procurement system-and empirical survey." *Engineering, Construction and Architectural Management*, 10(3), 209-218.

Luu, D. T., Ng, S. T. and Chen, S. E. (2003b). "A case-based procurement advisory system for construction." *Advances in Engineering Software*, 34, 429-438.

Luu, D. T., Ng, S. T. and Chen, S. E. (2005). "Formulating procurement selection criteria through case-based reasoning approach." *Journal of Computing in Civil Engineering*, ASCE, 19(3), 269-276.

Luu, D. T., Ng, S. T., Chen, S. E. and Jefferies, M. (2006). "A Strategy for evaluating a fuzzy case-based construction procurement selection system." *Advances in Engineering Software*, 37, 159-171.

Lucko, G. and Rojas, E. M. (2010). "Research validation: challenges and opportunities in the construction domain." *Journal of Construction Engineering and Management*, ASCE, 136(1), 127-135.

March, J. G. (1991). "How decisions happen in organizations." *Human-Computer Interaction*, 6, 95-117.

Masterman, J. W. E. and Gameson, R. (1994). "Client characteristics and needs in relation to their selection of procurement systems." in *Rowlinson, S. (Ed.) CIB-W92 Proceedings: "Ease meets West" Procurement Systems Symposium*, Hong Kong, 79-87.

Matthews, O. and Howell, G. A. (2005). "Integrated project delivery: an example of relational contracting." *Lean Construction Journal*, 2(1), 46-61.

Marshall, C. and Rossman, G. B. (1995). *Designing Qualitative Research*. Newbury Park, CA:Sage..

Masterman, J. W. E. (2002). *An Introduction to Building Procurement Systems*. Spon Press, 2nd Edition.

McCann, J. E. and Ferry, D. L. (1979). "An approach to assessing and managing inter-unit interdependency." *Academy of Management Review*, 4(1), 113-119.

Meredith, J. R. and Mantel, S. J. (2003). *Project Management: a Managerial Approach*. John Wiley & Sons, Inc.

Meyers, M. D. (2004). *Qualitative research.* Available at: http://www.qual.auckland.ac.nz/.

Miller, G. A. (1956). "The magical number seven plus or minus two: some limits on our capacity for processing information." *The Psychological Review*, 63, 81-97.

Miller, J. B. (1997). "Engineering sytems itegration for civil infrastructure projects." *Journal of Management in Engineering*, ASCE, 13(5), 61-69.

Miller, J. B. and Evje, R. H. (1999). "The practical application of delivery methods to project portfolios." *Construction Management and Economics*, 17, 669-677.

Miller, J. B., Garvin, M .J., Ibbs, C. W., and Mahoney, S. E. (2000). "Toward a new paradigm: simultaneous use of multiple project delivery methods." *Journal of Management in Engineering*, ASCE, 16(3), 58-67.

Moselhi, O. (1993). "Schedule compression using the direct stiffness method." *Canadian Journal of Civil Engineering*, 20, 65-72.

Molenaar, K. R. and Songer, A. D. (1998). "Model for public sector design-build project selection." *Journal of Construction Engineering and Management*, ASCE, 124(6), 467-479.

Molenaar, K. R., Songer, A. D. and Barash, M. (1999). "Public-sector design-build evolution and performance." *Journal of Management in Engineering*, ASCE, 54-62.

Morris, P. W. G. and Pinto, J. K. (2004). *The Wiley Guide to Managing Projects.* John Wiley & Sons, Inc.

Mulvey, D. (1997). "Trends in project delivery-a contractor's assessment." In *Proceedings of the 1997 ASCE Construction Conference*. 627-633.

Naoum, S. G. (1994). "Critical analysis of time and cost of management and traditional contracts." *Journal of Construction Engineering and Management*, ASCE, 120(4), 687-705.

National Institute of Sandards and Technology (2002). *Measuring the Impacts of Delivery System on Project Performance: Design-Build and Design-Bid-Build.* U.S. Department of Commerce, Technology Administration, available at: http://www.bfrl.nist.gov/oae/publications/gcrs/02840.pdf (assessed 21 April 2010).

Newan, G., Eschenbach, T. G., and Lavelle, J. P. (2004). *Engineering economic analysis*, Oxford University Press, New York.

Niekerk, F. and Voogd, H. (1999). "Impact assessment for infrastructure planning: some Dutch dilemmas." *Environment Impact Assessment Review*, 19(21), 21-36.
Ng, S. T. and Cheung, S. O. (2007) "Virtual project delivery system adviser." *Journal of Professional Issues in Engineering Education and Practice*, ASCE, 133(4), 275-284.
Ng, S. T., Luu, D. T., Chen, S. E. and Lam K. C. (2002). "Fuzzy membership functions of procurement selection criteria." *Construction Management and Economics*, 20, 285–296
Odeh, A. M. and Battaineh, H. T. (2002). "Causes of construction delay: traditional contracts." *International Journal of Project Management*, 20, 67-73.
Omar, M. F., Trigunarsyah, B and Wong, J. (2009). "Infrastructure project planning decision-making: challenges for decision support system applications." In *Proceedings of the 7th Asia Pacific Structural Engineering and Construction Conference & 2nd European Asian Civil Engineering Forum*, 4-6 August 2009, Awana Porto Malai, Langkawi.
Oyetunji, A. A. and Anderson, S. D. (2006). "Relative effectiveness of project delivery and contract strategies." *Journal of Construction Engineering and Management*, ASCE, 132(1), 3-13.
Padman, R. and Smith-Daniels, D. E. (1993). "Early-tardy cost trade-offs in resource constrained projects with cash flows: an optimization-guided heuristic approach." *European Journal of Operational Research*, 64, 295-311.
Patton, M. Q. (1999). *Qualitative evaluation and research methods* (2nd ed.). Newbury Park, CA: Sage.
Paek, J. H., Lee, Y. W. and Napier, T. R. (1992). "Selection of design/build proposal using fuzzy-logic system." *Journal of Construction Engineering and Management*, ASCE, 118(2), 303-317.
Payne, J. H. (1995). "Management of multiple simultaneous projects and state-of-art review." *International Journal of Project Management*, 13(3), 163-168.
Pellegrinelli, S. (1997). "Programme management: organizing project based change." *International Journal of Project Management*, 15(3), 141-149.
Pietroforte, R. and Miller, J. B. (2002). "Procurement methods for US infrastructure: historical perspectives and recent trends." *Building Research and Information*, 30(6), 425-434.
Platje, A. and Seidel, H. (1993). "Breakthrough in multiproject management: how to escape the vicious circle of planning and control." *International Journal of Project Management*, 11(4), 209-213.
Pollock, S. M., Rothkopf, M. H. and Barnett, A. (1994) (eds.). *Handbooks in operations research and management science*, volume 6: operations research and the public sector, North Holland.
Roschke, P. N. (1994). "Validation of knowledge-based system with multiple bridge rail experts." *Journal of Transportation Engineering*, ASCE, 120(5), 787-806.
Russell, A. H. (1970). "Cash flows in networks." *Management Science,* 16(5), 357-373.
Rwelamila, P. D. and Meyer, C. (1999). "Appropriate or default project procurement systems." *Cost Engineering*, 41(9), 40-44.
Sanvido V. and Konchar, M. (2005). *Selecting project delivery systems: comparing design-build, design-bid-build and construction management at risk.* The Project Delivery Institute, VA, USA.
Schmuck, R. (1997). *Practical action research for change*. Arlington Heights. IL:IRI/Skylight Training and Publishing.

Simens, N. (1971). "A simple CPM time/cost trade-off algorithm." *Management Science*, 17(6), 354-363.

Skitmore, R. M. and Marsden, D. E. (1988). "Which procurement system? Towards a universal procurement selection technique." *Construction Management and Economics*, 6, 71-89.

Smith-Daniels, D. E. and Smith-Daniels, V. L. (1987). "Maximizing the net present value of a project subject to materials and capital constraints." *Journal of Operations Management,* 7, 33-45.

Smith-Daniels, D. E. and Aquilano N. J. (1987). "Using a late-start resource-constrained project schedule to improve project net present value." *Decision Sciences,* 18, 617-630.

Solberg, J. J. (1992). "The power of simple models in manufacturing." *Manufacturing Systems: Foundations of World-Class Practice*, National Academy Press, Washington, DC, 215-23.

Songer, A. and Molenaar, K. R. (1997). "Project characteristics for successful public-sector design-build." *Journal of Construction Engineering and Management*, ASCE, 123(1), 34-40.

Songer A. D. and Molenaar, K. R. (2001). "Selecting design-build: public and private sector owner attitudes." *Journal of Management in Engineering*, 12(6), 47-53.

Sunde, L. and Lichtenberg, S. (1995). "Net-present-value cost/time tradeoff." *Internal Journal of Project Management*, 13(1), 45-49.

Suhr, J. (1999). *The Choosing by Advantages Decision Making System,* Quorum, Westport, CT. 281 p.

Talbot, F. B. (1982). "Resource-constrained project scheduling with time-resource tradeoffs: the nonpreemptive case." *Management Science*, 28(10), 1197-1210.

Touran, A., Molenaar, K. R., Gransberg, D. D. And Ghavamifar, K. (2009). "Decision support system for selection of project delivery method in transit." *Journal of Transportation Research Board*, 2111, 148-157.

Thiry, M. (2004). "Program management: a strategic decision management process." In *the Wiley Guide to Managing Projects*, Ed: Morris, P. W. G. and Pinto, J. K., John Wiley and Sons, Inc., Hoboken, New Jersey, USA.

Transportation Research Board (1999). *Glossary of Highway Quality*, (available online at http://ntl.bts.gov/lib/19000/19500/19532/PB2002107751.pdf)

Tsai, D. M. and Chiu, H. N. (1996). "Two heuristics for scheduling multiple projects with resource constraints." *Construction Management and Economics*, 14, 325-340.

Van der Heijden, K. (1996). *Scenarios: the art of strategic conversation*. John Wiley & Sons, Chichester.

Van der Merwe, A. P. (1998). "The history of project management: a search for world best practices." In *Proceedings of 14th World Congress on Project Management*, June 10-13, Slovenia, 260-70.

Yang, K. K., Talbot, F. B. and Patterson, J. H. (1992). "Scheduling a project to maximize its net present value: an integer programming approach." *European Journal of Operational Research*, 64, 188-198.

Ye, S. and Tiong, R. L. K. (2000). " NPV-at-risk method in infrastructure project investment evaluation." *Journal of Construction Engineering and Management*, ASCE, 126(3), 227-232.

Appendix A: Deriving time/cost trade-off rules in DBB (with PCM) and DB (with PCM)

1. Deriving time/cost trade-off rules in DBB (with PCM)

1.1 Stage 1: Create a baseline NPV

Step 1: Estimate project timelines in DBB (with PCM). Project phases and their estimated durations in DBB (with PCM) are the same as those in DBB, with one difference. The duration of the first procurement phase in DBB (with PCM) is extended for one month because the procurements for a designer and a PCM team will be held simultaneously. The estimated durations of each of the project phases in DBB (with PCM) are presented in Table 1.1. A 30-year life-span is used for the NPV calculation.

Table 1.1 Estimated phase durations in DBB (with PCM)

Project phase	Duration (Month)
Planning	6
Procurement (for design and PCM)	3[1]
Design	20
Procurement (for construction)	4[2]
Construction	29
Operation/Maintenance (test)	6
Operation/Maintenance (official)	292
Total[3]	360

[1]Two months are for document preparation; one month is for public advertising and designer/PCM team selection; [2]Three months are for document preparation; one month is for public advertising and contractor selection; [3]A 30-year life-span is used.

Step 2: Estimate cost/benefit parameters. The cost/revenue distribution in DBB (with PCM) is similar to that in DBB except that an additional PCM fee was added, as shown in Table 1.2. This PCM fee is estimated to be 3.5% of the sum of design and construction costs. It is assumed that the phase cost/revenue is equally distributed in that particular phase.

Table 1.2 Estimated cost/revenue distribution in DBB (with PCM)

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB
	Procurement	8,783	Same as in DBB
	Design	135,000	Same as in DBB
	Construction	1,724,138	Same as in DBB
	PCM Fee	34,802	$52,700,000×3.5%[1]=1,844,500; $1,844,500/53m[2]=$34,802/m
	Operation/Maintenance	271,849	Same as in DBB
Operation Revenue		778,395	Same as in DBB

[1]Estimated to be 3.5% of the sum of design and construction cost; [2]PCM service is provided in design, procurement (for construction) and construction phases.

Step 3: Determine a discount rate. The discount rate used for NPV calculation is 4%, and it is assumed to remain constant throughout the project life.

Step 4: Calculate project NPV. The cash flow diagram of the Case Project in DBB (with PCM) is shown in Figure 1.1. Given a 4% discount rate, the NPV is approximately $26.89 million.

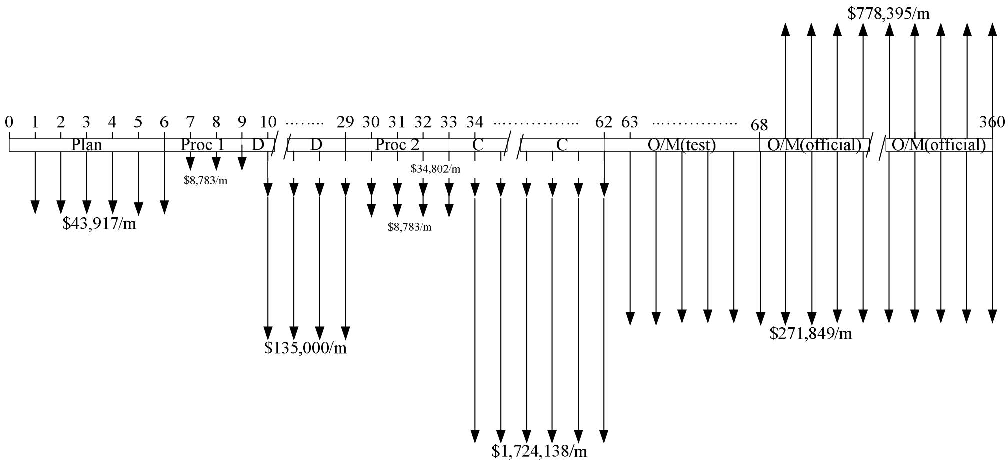


Figure 1.1 Case Project's cash flow diagram in DBB (with PCM)

1.2 Stage 2: Create NPV variants

This stage is to calculate variant NPVs with response to changes in time and cost parameters. Variant NPVs under changes in design duration (D_D), design cost (D_C), construction duration (C_D) and construction cost (C_C) are summarized in Table 1.3.

Table 1.3 Variant NPVs in DBB (with PCM)

Phase	Parameter	Changes in parameters	NPVs	Changes in the baseline NPV
Design	Time	10%	26,394,877	-1.85%
		5%	26,643,751	-0.93%
		0	26,893,463	0.00%
		-5%	27,144,014	0.93%
		-10%	27,395,409	1.87%
	Cost	10%	26,631,987	-0.97%
		5.0%	26,762,725	-0.49%
		0	26,893,463	0.00%
		-5%	27,024,201	0.49%
		-10.0%	27,154,939	0.97%
Construction	Time	10%	25,951,561	-3.50%
		5%	26,421,290	-1.76%
		0	26,893,463	0.00%
		-5%	27,368,091	1.76%
		-10%	27,845,188	3.54%
	Cost	4%	25,021,293	-6.96%
		2%	25,957,378	-3.48%
		0	26,893,463	0.00%
		-2%	27,829,548	3.48%
		-4%	28,765,632	6.96%

1.3 Stage 3: Derive time/cost trade-off rules

Trade-off rules between the durations and costs of the design and construction phases are summarized in Table 1.4, with details explained following the table.

Table 1.4 Time/cost trade-off rules between design and construction phases in DBB (with PCM)

		Design		Construction	
		Duration (D_D)	Cost (D_C)	Duration (C_D)	Cost (C_C)
Design	Duration (D_D)	NA	- \$258,660/m	-1.30	-\$265,000/m
	Cost (D_C)	NA	NA	-\$329,268/m	-0.957
Construction	Duration (C_D)	NA	NA	NA	-\$348,276/m
	Cost (C_C)	NA	NA	NA	NA

Design Duration (D_D) vs. Design Cost (D_C). From Table 1.3, it is found that a 5% increase in the design duration will result in a 0.93% decrease in the Case Project's baseline NPV. To offset the impact caused by this change in the design duration, the NPV needs to be increased by 0.93%. Referring to Table 1.3 again, it is found that to increase NPV by 0.93% the design cost needs to by a percentage between 5% and 10%. By performing an interpolation, this percentage is found to be 9.58%.

The design duration and design cost are 20 months and \$2,700,000. A 5% increase in the design duration means one extra month (20m×5%=1m); a 9.58% decrease in the design cost means an extra \$258,660 (\$2,700,000×9.58%=\$258,660). This makes the trade-off rule between the design duration and design cost \$258,600/m (\$258,600/1m=258,600/m). The relationship between the design duration and design cost is negative, meaning that an increase in the design duration will require a decrease in the design cost.

Design Duration (D_D) vs. Construction Duration (C_D). As indicated in Table 1.3, a 5% increase in the design duration will result in a 0.93% decrease in the Case Project's baseline NPV. If the project manager wishes to trade off the design duration against the construction duration, a percentage change of the construction duration should be found that can increase the baseline NPV by 0.93%. Referring back to Table 1.3, it is found that in order to increase the baseline NPV by 0.93%, the construction duration needs to be reduced by a percentage between 0% and 5%. By performing an extrapolation, this percentage is found to be 2.67%. In brief, if the project manager plans to increase the design duration by 5%, the construction duration should be shortened by 2.67% to prevent the baseline NPV from falling.

The design duration and construction duration are, respectively, 20 and 29 months, as shown in Table 1.1. A 5% increase in the design duration means one extra month (20m×5%=1m); a 2.67% decrease in the construction duration equals a reduction of 0.77 month (29m×2.67%=0.77m). This makes the trade-off rule between the design duration and construction duration a negative 1.30 (1m/0.77m=1.30). This trade-off rule indicates that if the project manager plans to increase the design duration by 1.30 months, the construction duration should be shortened by one month.

Design Duration (D_D) vs. Construction Cost (C_C). The same process is applied to determine the trade-off rule between the design duration and construction cost. It is known that a 5% increase in the design duration will result in a 0.93% decrease in the Case Project's baseline NPV. From Table 1.3, it is known that the construction cost needs to be reduced by a percentage between 0% and 2% to offset this impact. This percentage is found to be 0.53%. In other words, if the design duration is increased by 5%, the project manager will need to reduce construction cost by 0.53% to prevent the baseline NPV from falling.

The design duration and construction cost are 20 months and \$50,000,000. A 5% increase in the design duration means one extra month (20m×5%=1m); a 0.53% decrease in the construction cost means an extra \$265,000 (\$50,000,000×0.53%=\$265,000). This makes the trade-off rule between the design duration and construction cost negative \$265,000/m (\$265,000/1m=\$265,000m). In other words, if the project manager plans to increase design duration by one month, the construction cost should be reducedby \$265,000.

Design Cost (D_C) vs. Construction Duration (C_D). From Table 1.3, it is found that a 5% increase in the design cost will result in a 0.49% decrease in the Case Project's baseline NPV. To offset this impact, the construction duration needs to be reduced by a percentage between 0% and 5%. This percentage is found to be 1.43%. This means that if the project manager wishes to increase the design cost by 5% without affecting the baseline NPV, the construction duration should be reduced by 1.43%.

The design cost and construction duration are \$2,700,000 and 29 months. A 5% increase in the design cost means an extra of \$135,000 (\$2,700,000×5%=\$135,000); a 1.43% decrease in the construction duration equals a reduction of 0.41 month (29m×1.43%=0.41m). This makes the trade-off rule between the design cost and construction duration a negative \$329,268/m (\$135,000/0.41m=\$329,268/m). This trade-off rule indicates that if the project manager plans to increase the construction duration by one month, the design cost should be reduced by \$329,268 to prevent the baseline NPV from falling.

Design Cost (D_C) vs. Construction Cost (C_C). Table 1.3 shows that a 5% increase in the design cost will result in a 0.49% decrease in the Case Project's baseline NPV. To offset this impact, the construction cost needs to be reduced by a percentage between 0% and 2%. This percentage is found to be 0.282%. In sum, if the project manager plans to increase the design cost by 5%, the construction cost should be reduced by 0.282% to avoid the baseline NPV falling situation.

The design cost and construction cost are, respectively, \$2,700,000 and \$50,000,000. A 5% increase in the design cost equals an extra \$135,000 (\$2,700,000×5%=\$135,000); a 0.282% decrease in the construction cost equals a reduction of \$141,000 (\$50,000,000×0.28%=\$141,000). This makes the trade-off rule between the design cost and construction cost negative 0.957 (\$135,000/\$141,000=0.957). This trade-off rule means that if the project manager plans to increase the design cost by \$0.957, the construction cost should be reduced by \$1.

Construction Duration (C_D) vs. Construction Cost (C_C). A 5% increase in the construction duration will result in a 1.76% decrease in the Case Project's baseline NPV. Table 1.3 shows that the construction cost needs to be reduced by a percentage between 0% and 2% to offset this impact. This percentage is found to be 1.01%. This means that if the project manager plans to increase the construction duration by 5%, the construction cost should be decreased by 1.01% to prevent the baseline NPV from falling.

The construction duration and construction cost are 29 months and $50,000,000. A 5% increase in the construction duration represents an extra 1.45 months (29m×5%=1.45m); a 1.01% decrease in the construction cost equals a reduction of $505,000 ($50,000,000×1.01%=$505,000). This makes the trade-off rule between construction duration and construction cost negative $348,276/m ($505,000/1.45m=$348,276/m). This trade-off rule indicates that if the project manager plans to increase the construction duration by one month without affecting the baseline NPV, he the construction cost should be reduced by $348,276.

2. Deriving time/cost trade-off rules in DB (with PCM)

2.1 Stage 1: Create a baseline NPV

Step 1: Estimate project timelines in DB (with PCM). Project phases and their durations in DB (with PCM) are similar to those in DB, with two differences. First, because in DB (with PCM) the Agency could shift some of its responsibilities to the selected PCM team in the later phases, the duration of project planning phase in DB (with PCM) was estimated to be shortened to 6 months. In addition, a procurement (for PCM) phase was added after the project planning phase. The duration of this phase was estimated to be 5 months, in which 3 months are for document preparation and the other 2 months are for public advertising and PCM selection. Estimated durations of project phases in DB (with PCM) can be found in Table 2.1. A 30-year life-span is used for the NPV calculation.

Table 2.1 Estimated phase durations in DB (with PCM)

Project phase	Duration (month)
Planning	6
Procurement (for PCM)	5[1]
Procurement (for design/builder)	6[2]
Design/Build	34
Operation/Maintenance (test)	6
Operation/Maintenance (official)	303
Total[3]	360

[1]Three months are for document preparation; two months are for public advertising and design/builder selection.
[2]Four months are for document preparation; two months are for public advertising and design/builder selection.
[3]A 30-year life-span is used.

Step 2: Estimate cost/benefit parameters. The cost/revenue distribution in DB (with PCM) is similar to that in DB except that an additional PCM fee was added, as shown in Table 2.2. This PCM fee is estimated to be 3.5% of design/build cost.

Table 2.2 Estimated cost/revenue distribution in DB (with PCM)

Cost/Revenue		Unit ($/m)	Note
Cost	Planning	43,917	Same as in DBB
	Procurement	8,783	Same as in DBB
	Design/Build	1,457,000	Same as in DB
	PCM Fee	$43,346	$49,538,000×3.5%[1]=$1,733,830; $1,733,830/40[2]=$43,346/m
	Operation/ Maintenance	271,849	Same as in DBB
Operation Revenue		778,395	Same as in DBB

[1] Estimated to be 3.5% of the sum of design and construction cost

[2] PCM service is provided in procurement (for design/builder) and design/build phases. Total duration is 6+34=40 months.

Step 3: Determine a discount rate. The discount rate used for NPV calculation is 4%, and it is assumed to remain a constant throughout the project life.

***Step 4: Calculate project NPV**.* The cash flow diagram of the Case Project in DB is shown in Figure 2.1. Given a 4% discount rate, the NPV is approximately $32.3 million.

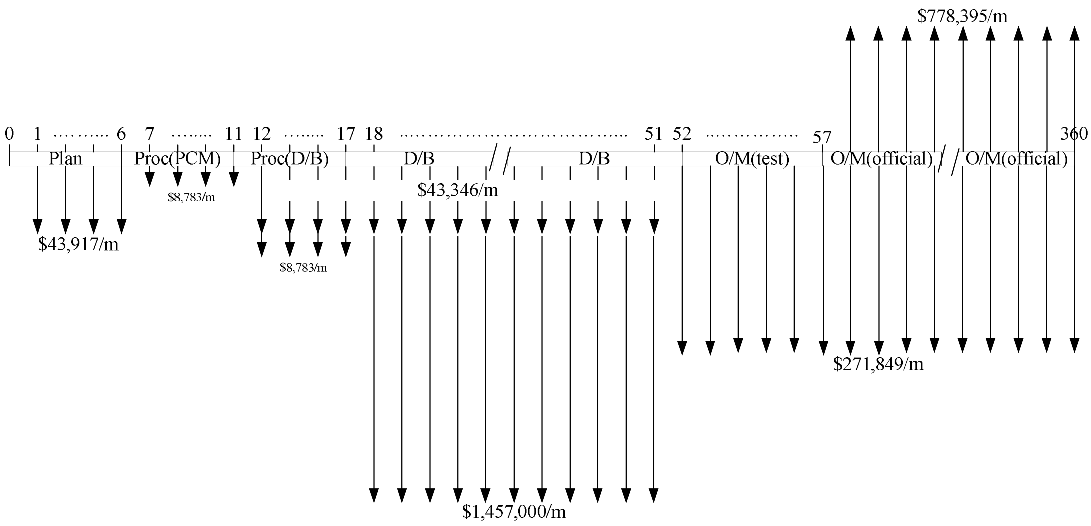


Figure 2.1 Case Project's cash flow diagram in DB (with PCM)

2.2 Stage 2: Create NPV variants

This step changes time and cost parameters, one parameter per time, to see how a particular change affects the baseline NPV. Variant NPVs under changes in the design/build duration (D/B_D) and design/build cost (D/B_C) are summarized in Table 2.3.

Table 2.3 Variant NPVs in DB (with PCM)

Phase	Parameter	Changes in parameters	NPVs	Changes in the baseline NPV
Design/Build	Time	10%	31,124,232	-3.58%
		5%	31,699,878	-1.79%
		0	32,279,066	0.00%
		-5%	32,861,818	1.81%
		-10%	33,448,156	3.62%
	Cost	4%	30,449,925	-5.67%
		2.0%	31,364,496	-2.83%
		0	32,279,066	0.00%
		-2%	33,193,637	2.83%
		-4.0%	34,108,207	5.67%

Note: columns marked in grey show the baseline NPV

2.3 Stage 3: Derive time/cost trade-off rules

From Table 2.3, it is found that a 5% increase in the D/B duration will result in a 1.79% decrease in the Case Project's baseline NPV. To offset this impact, the NPV needs to be increased by 1.79%. This can be achieved by reducing the D/B cost by a percentage between 0% and 2%. This percentage is found to be 1.27%. This means that if the project manager plans to increase the D/B duration by 5%, the D/B cost should be reduced by 1.27% to prevent the baseline from falling.

The D/B duration and D/B cost are 34 months and $49,538,000. A 5% increase in the D/B duration means an extra 1.7 months (34m×5%=1.7m); a 1.27% decrease in the D/B cost equals a reduction of $629,133 ($49,538,000×1.32%=$629,133). This makes the trade-off rule between the D/B duration and D/B cost $370,078/m ($629,133/1.7m=$370,078/m). The relationship between the D/B duration and D/B cost is negative. If the project manager plans to increase the D/B duration by one month without affecting the baseline NPV, the D/B cost should be reduced by $370,078. This trade off rule is illustrated in Table 2.4.

Table 2.4 Time/cost trade-off rules between D/B duration and D/B cost in DB (with PCM)

		Design/Build	
		Duration (D/B_D)	Cost (D/B_C)
Design/Build	Duration (D/B_D)	NA	- $370,078/m
	Cost (D/B_C)	NA	NA

Appendix B: Adjusting Case Project's estimated timelines and costs for project dependencies: in DBB (with PCM) and DB (with PCM)

1. DBB (with PCM)

Table 1.1 summarizes the response strategies taken in DBB (with PCM) with the time/cost trade-off involved. The Case Project's initial and adjusted estimated schedules are presented together in Figure 1.1.

For PD(1). PD(1) had caused the starting date of the Case Project's planning phase to be delayed for 6 month. Since this is past event, it will not affect the Case Project's future estimated schedule.

For PD(2). PD(2) relates to the fact that the test operation/maintenance results of the first-phase wastewater treatment plant can be used as a reference for the design of the Case Project. It is estimated that this information will be available before the starting date of the Case Project's design phase. For this reason, PD(2) will not affect the Case Project's estimated schedule; no response action is required.

For PD(3). PD(3) requires the Case Project's procurement (for design and PCM) phase to be started at (or after) the time when the new land-use is approved. The new land-use is expected to be approved in 04/2010;the initial estimated starting date of the Case Project's procurement (for design and PCM) phase is 03/2010. To accommodate this effect, the project manager decided to temporarily hold the project for one month after its planning phase is completed. Due to this change, the new scheduled starting date of the Case Project's procurement (for design and PCM) phase becomes 04/2010.

For PD(4). PD(4) requires the Case Project's design phase to be started at (or after) the time when more information about the new environmental code is available, which is expected to be in 07/2010. The initial estimated starting date of the Case Project's design phase is in 06/2010, and this date has been delayed for one month to 07/2010 because of the response action taken for PD(3). At that time, the information about the new environmental code is expected to be available. Therefore, no further response action is required.

For PD(5)~PD(8). PD(5)~PD(8) restrict the completion date of the Case Project's construction phase. The new desired completion date is between 08/2011 and 10/2012. The Case Project's initial estimated construction completion date in DBB (with PCM) is 11/2014. This has been delayed for one month to 12/2014 due to the response actions taken for PD(3). In this case, in order to meet the new desired construction completion date, the design and construction phase together will need to be shortened by approximately 24 months. Based on his experience, the project manager decided that it is not possible to achieve this level of duration reduction by simply trading time and cost without sacrificing the project quality. He thus decided to modify "traditional DBB (with PCM)" to "DBB (with PCM) with early procurement and multiple contractors". Below are detailed adjustments involved in this response strategy.

First, the project manager divided the Case Project into two parts. The first-part project is desired to be completed by 02/2012; the second-part project is desired to be completed by 10/2012. The durations of design, procurement (for construction) and construction phases are, respectively, 10, 2 and 14 months for the first-part project, and 10, 2 and 15 months for the second-part project. In this modified DBB (with PCM), after the design of the first-part project is completed, the procurement phase (for the first-part construction) begins. In the meantime, the designer continues to design the second-part project. Following the completion of the design of the second-part project is the procurement phase (for the second-part construction). By modifying the PDS, the total project delivery duration is shortened. However, it still cannot meet the desired project completion dates. Therefore, the project manager decided to further shorten the design and construction durations by trading them off them with costs. The design and construction phases of the first-part project are shortened, respectively, by 4 and 3 months to meet the desired 02/2012 completion date; the design and construction phases of the second-part project are also shortened, respectively, by 3 and 3 months to meet the desired 10/2012 completion date. Together, the design phases of the two sub-projects are shortened by 7 months and the construction phases are shortened by 6 months.

It is known that the trade-off rule between the design duration and design cost is $258,660/m, and the trade-off rule between the construction duration and construction cost is $348,276/m. Based on these rules, for a 7-month decrease in the design duration, the project manager will be willing to pay an extra $1,810,620 ($258,660/m×7m=$1,810,620) in the design cost; for a 6-month decrease in the construction duration, he will be willing to pay an extra $2,089,656 ($348,276/m×6m=$2,089,656) in the construction cost. These two together will increase the estimated total project cost by $3,900,276. This has increased the estimated total project cost in DBB (with PCM) from $54,869,483 to $58,769,759.

2. DB (with PCM)

Table 2.1 summarizes the response actions taken in DB (with PCM) along with the time/cost trade-off involved. The Case Project's initial and adjusted estimated schedules are presented together in Figure 2.1 .

For PD(1). PD(1) had caused the starting date of the Case Project's planning phase to be delayed for 6 months. Since this is a past event, it will not affect the Case Project's future estimated schedule.

For PD(2)~PD(4). The test results of the first-phase wastewater treatment plant project is estimated to be available before the starting date of the Case Project's design/build phase (PD(2)); the new land-used is estimated to be approved before the estimated starting date of the Case Project's procurement (for design/build) phase (PD(3)); the information about the new environmental code is estimated to be available before the design/build phase begins (PD(4)); therefore, these three project dependencies will not affect the Case Project's estimated schedule, and no response actions are required.

For PD(5)~PD(8). PD(5)~PD(8) restrict the completion date of the Case Project's construction phase. The Case Project's new desired completion date is now between 08/2011 and 10/2012. Its initial estimated construction completion date in DB (with PCM) is 12/2013. Thus, in order to meet the new desired construction completion date, the design/build phase needs to be shortened by approximately 12~24 months. The project manager decided that it is not possible to achieve this level of duration reduction by simply trading time and cost. He therefore decided to modify "traditional DB (with PCM)" to "DB (with PCM) with multiple design/builders". Below are detailed adjustments involved in this response strategy.

First, the project manager divided the Case Project into two sub-projects. The durations of the design/build phases of these two sub-projects are both 17 months; the constructions of the first-part project and the second-part project are desired to be completed, respectively, by 02/2012 and 10/2012. In this modified DB (with PCM), the project manager will first prepare the procurement for the first-part project. This procurement phase will take 6 months. After the procurement for the first-part project is completed, the project manager will prepare the procurement for the second-part project. Because documents prepared for the first-part project can be revised and reused for the procurement of the second-part project, the duration of the procurement phase (for the second-part project) is reduced from 6 months to 4 months. By modifying the PDS, the total project delivery duration is shortened. However, to meet the desired project completion dates, the Case Project's phase durations still need to be shortened. For the first-part project, in order to complete the design/build phase by 02/2012, the project manager shortened the duration of the design/duration phase by five months. Referring back to Table 6, it is found that the trade-off rule between the design/build duration and cost is \$370,078/m. Therefore, for a 5-month decrease in the design/build duration, the project manager will be willing to pay an extra \$1,850,390 (\$370,078/m ×5months=\$1,850,390) in design/build cost. As for the second-part project, its new estimated project completion date is 11/2012, which is one month after the desired date. The project manager therefore decided to shorten the design/build duration by one month in trading off with cost. By applying the above trade-off rule, the project manager will be willing to pay an extra \$370,078 (\$370,078/m ×1=\$370,078) in the design/build cost. These adjustments have increased the estimated total project cost by \$2,220,468. This has increased the estimated total project cost in DB (with PCM) from \$51,631,947 to \$53,852,415.

Table 1.1 Impacts of project dependencies and the response strategies taken in DBB (with PCM)

No of PD	Impacts on initial estimated schedule	Response Strategy	Descriptions of the strategy and impacts	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	PD(2) will not affect the Case Project's estimated schedule and no response strategy is required.	None
PD(3)	Case Project' procurement (for design &PCM) phase has to be started later than planned.	(b) Separate project phases	To temporarily hold the Case Project for one month after its planning phase is completed for the approval of the new land-use.	None
PD(4)	Case Project's design phase has to be started later than planned.	None	Because the Case Project is temporarily on hold for one month after its planning phase is completed in response to previous PD(3), the new starting date of the Case Project can now satisfy the restriction caused by PD(4). Hence, no further adjustment is required.	None
PD(5)~PD (8)	The Case Project's construction phase needs to be completed earlier than planned.	(c) Modify PDS and change phase durations	To change DBB (with PCM) to DBB (with PCM) with early procurement and with multiple contractors, and to shorten design and construction durations to meet the desirable earlier completion date.	Increase the total project cost by $3,900,276.[2]

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]A $$1,810,620 increase in design cost and a $2,089,656 increase in construction cost.

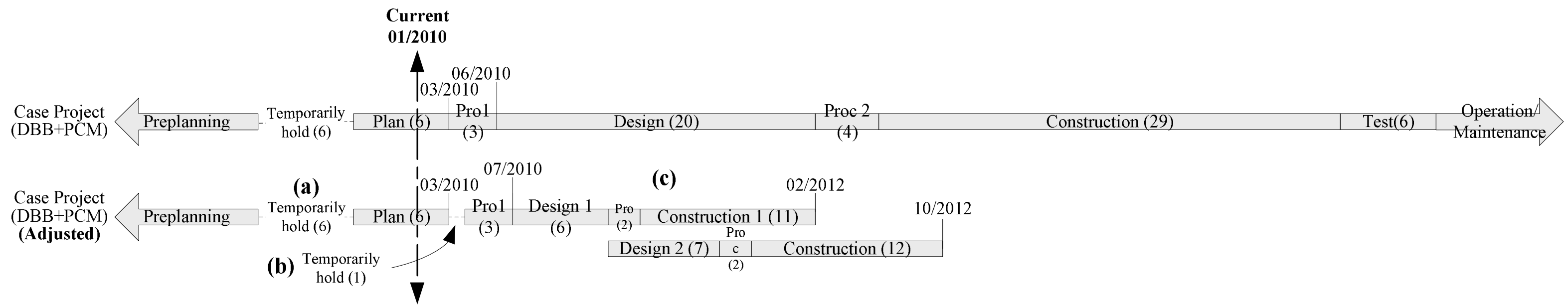


Figure 1.1 Case Project's initial and adjusted timeline in DBB (with PCM)

Table 2.1 Impacts of project dependencies and the response strategies taken in DB (with PCM)

No of PD	Impacts on initial estimated schedule	Response Strategy	Strategy Description	Time-cost trade-off
PD(1)	Caused the Case Project's planning phase to be started later than planned.	(a) Separate project phases	Temporarily hold the project for 6 month and began the Case Project's planning phase in 09/2009. This has no impact on Case Project's future estimated schedule because it is an occurred event.	None
PD(2)	None[1]	None	No response strategy is required as PD(2) will not affect the Case Project's estimated schedule.	None
PD(3)	None[2]	None	The new land use is expected to be approved before the estimated starting date of the Case Project's procurement phase; and hence no response strategy is required.	None
PD(4)	None[3]	None	More certain information about the environmental codes is expected to be available before the starting date of the design/build phase; and hence no response strategy is required.	None
PD(5)~PD (8)	The Case Project's construction phase needs to be completed earlier than planned.	(b) Modify PDS and change phase durations	To change traditional DB (with PCM) to DB (with PCM) with multiple design/builders; and to shorten design and construction durations.	Increase the total project cost by $ 2,220,468.

[1]Project E's test operation/maintenance results will be available before the estimated starting date of the Case Project's design phase in all PDS scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule.
[2]The approval of the new land-use is expected to be completed before the estimated starting date of the Case Project's procurement (for design) phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.
[3]The information is expected to be available before the estimated starting date of the Case Project's design phase in DB and DB (with PCM) scenarios. Therefore, this dependence will not cause any changes on the Case Project's estimated schedule in these two cases.

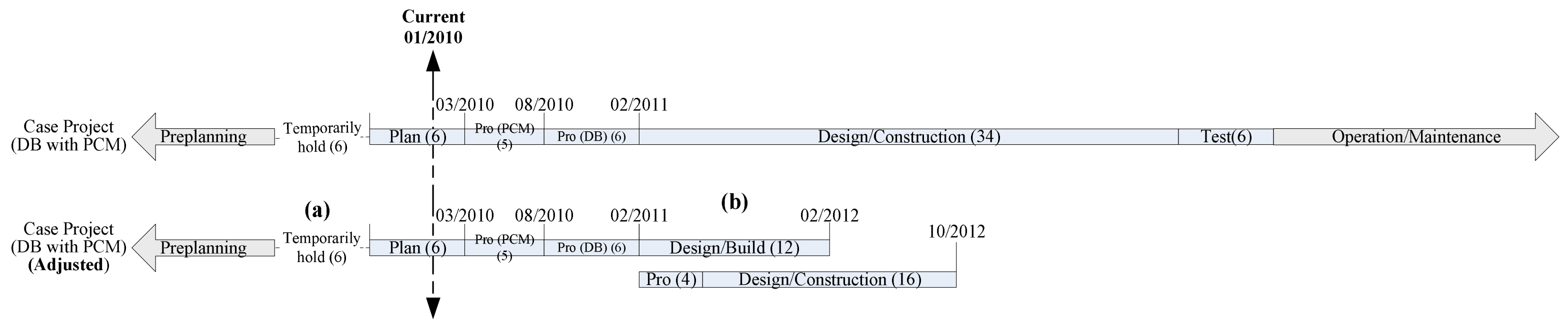


Figure 2.1 Case Project's initial and adjusted timeline in DB (with PCM)