DEVELOPMENT OF A MULTI-OBJECTIVE STRATEGIC MANAGEMENT APPROACH TO IMPROVE DECISIONS FOR PAVEMENT MANAGEMENT PRACTICES IN LOCAL AGENCIES

A Dissertation

by

CARLOS MARTIN CHANG ALBITRES

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2007

Major Subject: Civil Engineering

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Approved by:

Chair of Committee, Roger E. Smith
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ABSTRACT

Development of a Multi-Objective Strategic Management Approach to Improve Decisions for Pavement Management Practices in Local Agencies.

(May 2007)

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Multiple objectives are often used by agencies trying to manage pavement networks. Often alternative investment strategies can accomplish the agencies' target objectives. If the goal is to achieve the target objectives at the minimum cost, an approach is needed to assist agencies in identifying investment strategies capable of meeting the targets while minimizing costs.

The approach used by the agency should not be limited to an analytical method to mathematically solve the funding allocation problem. Finding mechanisms to ensure the sustainability and efficiency of the investment strategy over time is a great challenge that needs to be addressed by the approach. The challenge is even greater for local agencies where resources are usually limited.

This research develops a multi-objective strategic management approach oriented to improving decisions for pavement management practices in local agencies. In this approach, target objectives are tied to key pavement network parameters in the management process. A methodology to identify the best combination of projects to meet target objectives at the minimum cost while maximizing treatment effectiveness is provided as a result of the research.

Concepts from the pavement management program (PMP) of the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area were used as a basis for developing the methodology. Four pavement network parameters are considered for setting the target objectives over the agency's planning horizon: the average network pavement condition index (PCI), average network remaining life, percent of the pavement network in good condition, and percent of the pavement network in poor and very poor condition.

Results from a case study show that funding allocation methods influence the allocation of preservation and rehabilitation funds among pavement network groups, affecting budget estimates and future condition of the pavement network. It is also concluded that the use of mechanisms that facilitate data integration and the flow of knowledge across management levels can contribute to making better informed decisions. Hence, the adoption of the multi-objective strategic pavement management approach developed in this dissertation should lead to identifying more efficient investment strategies for achieving the pavement network state desired by a local agency at a minimum cost.

DEDICATION

This dissertation is dedicated to my daughters, Ana Cristina and Karla Ianina, my lovely wife, Blanca, for her patience and support along these years, and to my parents, Alicia and Carlos, for their endless love.

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A deep sense of gratitude is owed to Dr. Roger E. Smith, chairman of my advisory committee and mentor, for his guidance, unreserved support, and continued encouragement during the development of this dissertation. His ingenious ideas, time, and effort to complete this work are highly appreciated. Special thanks are due to Dr. Amy Epps Martin, Dr. Francisco Olivera, and Dr. Donald R. Smith for their efforts to improve the quality of this dissertation.

My gratitude to the Texas Transportation Institute (TTI) for being a part of this great organization, to the Texas Department of Transportation (TxDOT) for the different research projects in which I have been involved, and to the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area in California for their support during my graduate studies.

My thanks to Mr. Raúl Delgado Sayán, President and CEO of CESEL S.A., who encouraged me to work in materials and pavements at the beginning of my professional career. Thanks to my friend Mr. Paul Krugler for having the privilege of working together side by side on several projects for the Texas Department of Transportation (TxDOT). I would also like to thank Dr. William Stockton and Mr. Joe Button for the TTI support and personal encouragement to open new doors for conducting research beyond the U.S. borders. Last but not least, my heartfelt thanks to Mr. Tom Freeman from whom I have learned to see life from a different perspective, and to my family for supporting me in this effort.

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CHAPTER I

INTRODUCTION

One of the major challenges in pavement management is to provide the desired performance of available assets while investing the minimum funds. Pavement management systems have been used to assist agencies in this challenge since the mid 1960s. Pavement management systems use database management techniques, pavement condition assessment, performance models to estimate future condition, scenario analyses, and reporting tools to communicate the results.

Over the last forty years different tools have been developed for pavement management systems as technology has evolved in different disciplines. Although several tools are currently available to assist pavement management practitioners, the challenge of getting the most from available assets still persists due to the complexity of pavement performance and management practices. Pavement management practices require more than tools to be effective regardless of the degree of sophistication of the tools currently available.

Pavement management is a decision making process that must be applied to different management levels. To succeed in getting the most performance from available assets, pavement management practices require interaction among several management levels.

The format of this dissertation follows the style of the *Transportation Research Record.*

At the strategic management level, goals and objectives are set for the entire pavement network as well as other types of infrastructure. At the network management level, decisions are made regarding pavement preservation and rehabilitation programs for the overall network. At the project selection management level, a subset of pavement sections from the network is selected based on treatment needs, funds available for the program, and various constraints affecting selection options. At the project level, focus is on specific pavement sections and detailed technical information is needed to identify and design the best preventive or rehabilitation treatment to apply to individual pavement sections of the network.

In setting goals and objectives at the strategic management level, multiple objectives, that sometimes represent conflicting goals, are established (explicitly or implicitly) by agencies for the entire pavement network or for sub-groups of the pavement network. These decisions at the strategic management level impact the pavement network condition, pavement network value, and future budget needs. Objectives in terms of pavement condition, percentage of the pavement network in good condition, percentage of the pavement in poor condition, and life extension are some examples of target objectives.

The type and amount of data available to the agency are key factors that affect pavement management decision support tools available to address agency needs. Although pavement management systems are not as constrained by technical limitations as a few years ago, the system must consider the resources available in local agencies and the level of expertise of those practitioners. Local agencies often feel the impact of changes in budget constraints more than state agencies. This is due to fewer technical and human resources available to sustain pavement management practices along with frequent changes in political units that establish funding levels and objectives. In local agencies, pavement management practices must be effective but at the same time simple enough to be understood and carried out by practitioners in the agency.

The critical nature of strategic decisions in pavement management practices demands a rational approach to address agencies' multiple objectives with available resources. This problem is even more difficult to address in local agencies due to limited technical expertise and budget constraints.

The development of a multi-objective strategic management approach to assist in managing a local agency pavement network is addressed in this research. This first chapter provides an introduction of the overall dissertation explaining the nature of the research problem, research objectives, research methodology, and organization of the dissertation.

1.1 RESEARCH PROBLEM STATEMENT

The problem of developing a multi-objective strategic management approach to provide decision support for pavement management practices to achieve local agency objectives for pavement preservation and rehabilitation is addressed in this research.

The research problem can be generally stated as:

Because funds available for maintenance, repair, and reconstruction of pavement assets in local agencies are almost always less than those needed to address all funding needs immediately, the agencies must allocate available funds based on multiple agency objectives. A method to estimate the minimum funds needed to achieve multiple objectives over a planning horizon is needed to ensure the agency minimizes funds requested to those needed, can support fund requests, and allocates available funds effectively.

The specific research needs are summarized as follows:

- A rational management approach consistent with local agency objectives is needed to support strategic investment decisions for pavement network assets.
- Local agencies require a sound and effective approach to enhance multiple target objectives established by policy makers for the pavement network or sub-groups of the pavement network within budget constraints.
- The use of a multi-objective strategic management approach to support decisions for funding allocation is desired to facilitate communication among management levels.
- A method to determine needed funds to achieve multiple objectives, or set of pavement network conditions, over the planning horizon is desired to improve current pavement management systems used by a local agency.

1.2 RESEARCH HYPOTHESIS AND OBJECTIVES

The research objectives are based in a research hypothesis that is described prior to setting the objectives of the research.

1.2.1 Hypothesis of the Research

The hypothesis of the research is that the use of a multi-objective strategic pavement management approach leads to identifying better investment strategies and pavement management practices for achieving a pavement network state desired by a local agency.

The hypothesis can be considered as alternate hypothesis. To test this hypothesis, alternative methods to estimate the level of investments needed to achieve multiple objectives set by a local agency for its pavement network are compared. Therefore, the null hypothesis is “no difference” is obtained from using different funding allocation methods to estimate needed funds to achieve multiple objectives. A case study is used to test which hypothesis (alternate or null) should be accepted.

1.2.2 Research Objectives

The development of a multi-objective strategic management approach to improve investment decisions for pavement management practices in local agencies is the main objective of this research. The aim in developing this new approach is to better assist local agencies in achieving pavement performance objectives for their local pavement network.

In addition to the main objective, sub-objectives of this research include:

- Selecting key pavement performance parameters for characterizing pavement network states over the planning horizon that can be also used for setting target objectives that can be monitored over time.
- Proposing new methods to tie agency’s objectives to network pavement performance parameters for better justifying investments in pavement assets.
- Suggesting recommendations for an overall framework that integrates decision support tools to assist strategic management for better supporting pavement management practices.

- Identifying effective methods that can be used in pavement management to assist local agencies in estimating needed funds to achieve multiple objectives, or a set of pavement network conditions, over the planning horizon.
- Using a case study to compare results obtained with different methods developed during the research for estimating needed funds to achieve multiple objectives.
- Recommending a method that can be understood and effectively used by local agency personnel for estimating needed funds to achieve multiple objectives.
- Suggesting recommendations to sustain the multi-objective strategic pavement management approach over time with the aim of improving existing pavement management practices.

1.3 RESEARCH METHODOLOGY

The research is focused on the development of a multi-objective strategic management approach oriented to improve decisions for pavement management practices in a local agency. The following research tasks were used to fulfill the objectives of this research:

- Presenting a brief overview of current methods used to model decisions.
- Reviewing the concepts and purpose of decision support systems for pavement management practices.
- Discussing the strengths and weaknesses of decision support systems from a pavement management perspective.
- Providing an overview of target objectives and constraints for managing a local

agency pavement network.

- Presenting the criterion developed in this research for setting pavement network objectives.
- Performing investment analyses by setting multiple objectives and constraints for the following pavement network parameters:
  - Pavement condition for the entire pavement network or sub-groups of the pavement network
  - Percent of pavement in the entire network or sub-groups of the network in good condition
  - Percent of pavement in the entire network or sub-groups of the network in poor condition
  - Life extension in terms of remaining life
- Discussing how a multi-objective strategic management approach can assist a local agency in managing its pavement network and accomplish its goals.
- Using a case study to explore the applicability of the multi-objective strategic management approach in a local agency. The one hundred section database (100-DB), which is used for testing the pavement management system supported by the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area, was used for the case study.

1.4 ORGANIZATION OF THE DISSERTATION

This dissertation is composed of six chapters: Chapter I – Introduction, Chapter II – Decision Analysis and Strategic Management, Chapter III – Decision Support Systems for Pavement Management Practices, Chapter IV – A Multi-Objective Strategic Pavement Management Approach for Local Agencies, Chapter V – Case Study: Application, Interpretation, and Discussion, and Chapter VI - Conclusions and Recommendations.

Chapter I provides an introduction of the overall research. It addresses the nature of the research problem, and objectives. It describes the methodologies used in the research and the organization of this dissertation.

Chapter II explains the decision making process. It describes a rational approach for making decisions along with models and tools available for decision modeling. It also presents the concept of strategic management as an on-going process and discusses the process of making strategic decisions under risk.

Chapter III describes decision support systems for pavement management practices. It presents a historical overview of pavement management and its fundamental concepts. It explains the purpose, applications and benefits of pavement management systems, asset management systems, geographic information systems, and knowledge management systems. A holistic model for integrating these systems into an overall framework that takes advantage of modern technologies as well as lessons learned from previous experiences is proposed for better supporting strategic management and pavement management practices.

Chapter IV describes the multi-objective strategic management approach for pavement management. The elements, methods, and tools for the multi-objective strategic pavement management approach are described. Two alternative methods for determining needed funds to achieve multiple objectives are presented. The first method is the dynamic bubble up technique (DBU) which is based on the sequential year ranking method. The second method is a multi-objective optimization model that uses integer programming techniques to estimate investment needs required to meet the targets. Both methods are based on principles used by the pavement management system developed for the Metropolitan Transportation Commission in the San Francisco Bay Area (MTC). The chapter also explains how the multi-objective strategic management approach can be adopted into pavement management practices in a local agency to accomplish target objectives for the entire network or sub-groups of the pavement network.

Chapter V includes a case study. The case study shows how a multi-objective pavement management approach can assist an agency in developing an investment strategy to reach its target objectives. The alternative methods developed in chapter IV for determining needed funds to achieve multiple target objectives are used and compared for the pavement management system supported by the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area. Interpretation and discussion of the findings from the case study are included.

Chapter VI presents the conclusions and recommendations from the research. It also includes a list of activities suggested for future research followed by a list of references cited in this dissertation.

CHAPTER II

DECISION ANALYSIS AND STRATEGIC MANAGEMENT

Success in any organization largely depends on making sound strategic decisions. Strategic decisions are inherent in the entire management process and impact all management and functional areas across the organization. Decisions are made during the formulation of strategic plans as a response to key management questions. Management questions regarding what objectives the organization wants to achieve, how to allocate resources among competing needs, how to respond to changing funding scenarios, and how to improve the quality of service to the users, are just some of the questions that arise during the management process. Addressing these questions properly involves making sound strategic decisions with the aim of achieving the organization's target objectives.

Multiple objectives are usually set as targets by policy makers. Setting feasible objectives and using effective techniques to assess the impact of alternative scenarios is vital for the strategic decision making process. Strategic management is complex in nature, and the use of decision analysis principles and modern techniques to assist decision makers in this process is required.

This chapter describes a rational approach for decision analysis. The decision making process is reviewed, models and tools available for decision analysis are presented, and the application of principles and techniques for strategic management is discussed.

2.1 THE DECISION MAKING PROCESS

A decision is "the act or process of choosing one course of action among several alternatives" *(1)*. Decisions may be the result of a rational thinking process, subjective judgment, or a combination of both. In the management field, decisions are intended to lead an organization to achieving its goals and objectives *(2)*.

Some decisions have a short term impact, while others have a long term impact. Decisions that involve strategy or policy changes usually have a long term impact in the organization. Due to the long term impact of strategic decisions, the decision making process deserves careful thought.

Decision analysis techniques and tools have been developed to assist decision makers in making decisions. Although the use of these techniques can not assure success, their use can minimize the risk of making unwise decisions. Decision analysis techniques provide a systematic methodology to address problem solving. These techniques are designed to help decision makers understand the nature of the problem, develop alternatives to address the problem, and study the impact of selecting alternative course of actions. Indeed, the decision making process forces decision makers to exercise all their abilities and knowledge with the aim of making sound decisions *(2)*.

There are usually several alternatives to address a problem, and a process with steps to follow during the decision making process has been developed *(2)*. A flow chart to illustrate a rational process for decision analysis is shown in Figure 1.

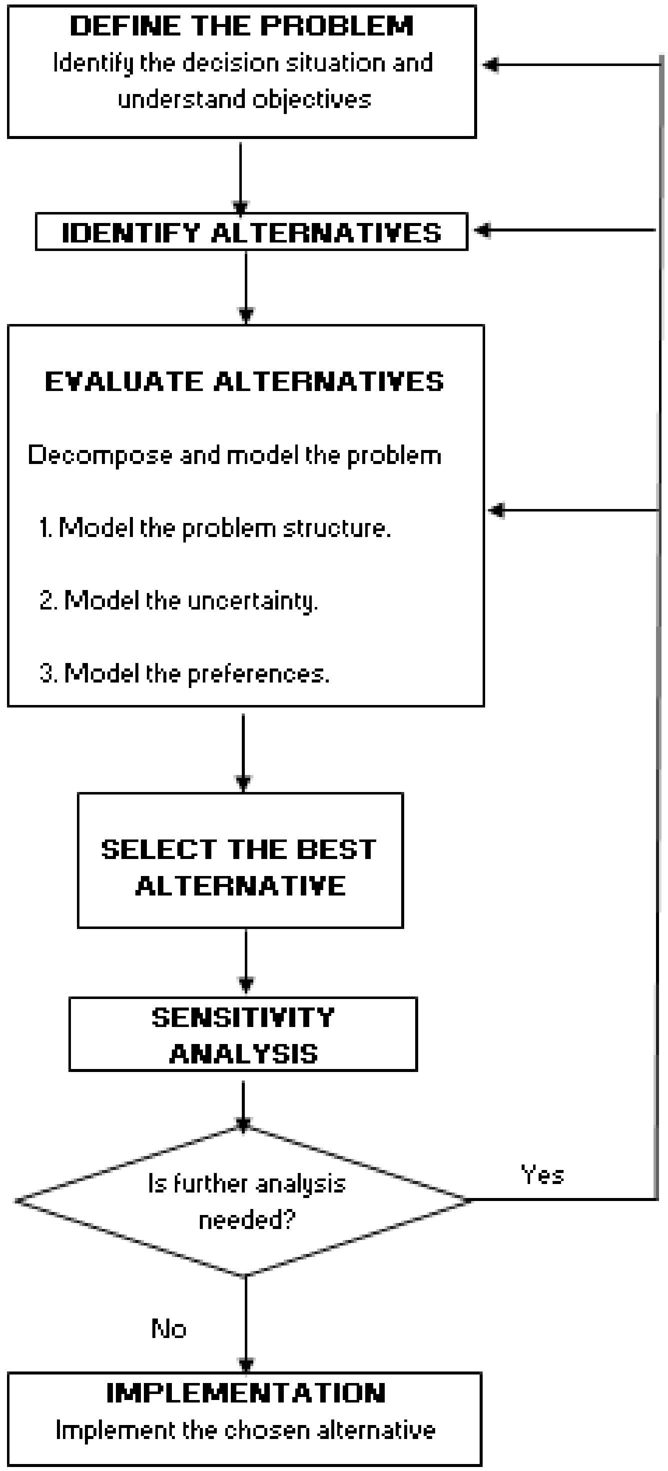

FIGURE 1 Decision analysis process flow chart *(after reference 2)*.

The decision making process involves six steps: define the problem, identify alternatives, evaluate the alternatives, select the best alternative, conduct sensitivity analysis, and implement the chosen alternative *(2)*.

2.1.1 Define the Problem

In this step the context of the decision situation is identified and the objectives are described. Key questions about the main objectives of the organization and the kind of outcomes expected by decision makers help to define the problem.

Decision makers must think about desirable results and set objectives that should lead to achieving these results. Objectives can be classified as fundamental and means objectives. Fundamental objectives are the core objectives that decision makers want to accomplish, while means objectives are the ones that help to accomplish fundamental objectives. This difference is important to be understood in order to ensure that key issues relevant to the problem are clearly identified *(2)*.

2.1.2 Identify Alternatives

Alternative courses of actions to address the problem are formulated by decision makers. The experience and knowledge of decision makers is challenged in this step. The proposed alternatives must be aligned with the organization's objectives and key issues relevant to the problem to ensure they are feasible. This second step ends up with a list of feasible alternative courses of action *(2)*.

2.1.3 Evaluate the Alternatives

Strengths and weaknesses of each alternative are analyzed in a systematic manner. Decision makers use models to analyze the alternatives to develop insights that may not be obvious at first identification. A model is an abstraction, or representation of the real world. Modeling involves understanding the relationships among objectives and the factors present in the decision situation. Elements of uncertainty for the different facets of the problem are addressed by a model of uncertainty. Decision maker preferences or perspectives are expressed through a model of preferences. If the model is too complex, the problem is structured and decomposed into smaller and more manageable units. Economic techniques are usually applied to compare alternatives, expected outcomes are pondered, and the impact of each alternative is assessed *(2)*.

2.1.4 Select the Best Alternative

The best alternative is selected based on findings from evaluating the alternatives. The definition of best alternative depends on the objectives set by the decision makers at the beginning of the analysis. In this sense, the best alternative is the option that better fits decision makers' objectives and follows a course of action that should lead to the accomplishing of the desired outcomes. A lot of subjective judgment is involved in the selection of the best alternative, but if the problem is clearly defined at early stages, a rational approach can be followed to select the best alternative *(2)*.

2.1.5 Conduct Sensitivity Analysis

To assess how sensitive the expected outcome is to changes in the input parameters that feed the model, a sensitivity analysis for the selected alternative is performed. This analysis answers "what if" questions, providing more insights about the selected alternative. The sensitivity analysis allows decision makers to identify the parameters that most influence the outcomes. By knowing the critical parameters, decision makers can maximize their efforts and focus on refining their estimates for the parameters that matter most. Results from the sensitivity analysis may also cause a re-evaluation of decisions or even reformulation of objectives. In practice, the decision making process follows an iterative cycle to refine the solution and to ensure that all the factors that affect the outcomes are considered by decision makers in the analysis. Therefore, a decision-analysis cycle loop continues until a satisfactory solution is found *(2)*.

2.1.6 Implement the Chosen Alternative

The course of action chosen by the organization's decision makers is carried out. Although this is the last step of the decision making process, the implementation phase could bring new problems in planning, organizing, or controlling. These new problems require careful thought, and the decision analysis process may need to be reviewed to ensure that unexpected events are handled properly *(2)*.

2.2 MODELING DECISIONS

Decisions are difficult to model with several factors contributing to this difficulty. The factors vary from personal preferences and perspectives to information technology issues. Major sources of difficulty in these include: complexity of the problem, uncertainty of the situation, objectives set by decision makers, and decision makers' perspectives. All of which should be taken into account when developing models *(2)*.

Complexity arises from the nature of the problem itself. Most models address many issues that need to be decomposed for analysis. For example, the selection of a rehabilitation pavement treatment may require considering not only technical aspects, but also environmental, social, and economic impacts. Each of these areas deserves attention in the analysis, and the interrelations among them should be also considered in the model *(2)*.

Uncertainty occurs with any decision. The level of uncertainty depends on the situation *(2)*. For example, if a new revolutionary pavement rehabilitation treatment is under consideration, the effectiveness of the treatment and environmental impact in the long-term is uncertain, but if a conventional pavement rehabilitation treatment is chosen the level of uncertainty regarding its effectiveness and impact is much less due to historical performance information.

Objectives set by decision makers influence the analysis and the models. When multiple objectives are pursued, there may be conflicts. Trade-offs must be considered in the analysis since benefits in one area might cause negative impacts in another. The model should be able to handle these situations *(2)*.

The background and previous experiences of decision makers play an important role in the decision making process. Each team member participating in the decision analysis process brings a unique perspective to handle the problem. Different perspectives may lead to different conclusions. The definition of the problem and identification of clear objectives at the beginning of the process is vital to overcome these differences in order to provide a common ground for solving the problem *(2)*.

2.2.1 Types of Models

In terms of requirements, the objective is to develop a model that addresses factors essential for solving the problem which is called a requisite model. “A model can be considered requisite only when no new intuitions emerge about the problem” *(3)*. This implies that a model is called a requisite model when the decision makers’ thoughts, beliefs, and preferences have been considered in the model formulation.

Models currently used in decision analysis can be divided in two major groups: deterministic and probabilistic models, both of which are used in practice *(4)*. The selection of a particular model type depends on the nature of the problem and the availability of information. The factors that affect decisions need to be considered in selecting a model.

Deterministic models are used when the outcomes are determined by certain rules that do not change. They are considered static models since the rules that govern the relationships among model parameters remain stable over the analysis horizon *(4)*. Probabilistic models are largely based on the application of statistics for probability assessment and follow statistical principles. The application of these principles involves risk assessment techniques. The strength of probabilistic models is that they can consider not only uncertainty, but also decision makers' preferences, or past experiences; and they encourage decision makers to think about all the factors that affect outcomes, both objective and subjective factors. The weakness of probabilistic models comes from the availability and accuracy of information needed to develop the probability distributions to run the model. *(4)*.

2.2.2 Tools for Modeling Decisions

Modeling decisions involves the development of a framework that enhances all the elements of the decision situation. Two tools are commonly used to assist in developing this framework: influence diagrams and decision trees.

Influence Diagrams

An influence diagram is a graphical representation of a decision situation. The purpose of an influence diagram is to show the relevance and relations among the decision elements. The elements involved in the decision situation are represented by certain shapes. Decisions are represented by rectangles, chance events by ovals, and final consequences by diamonds. Relationships among elements can be expressed by arcs in influence diagrams. Sequential decisions are shown by arrows. Relevant events are highlighted by an arrow pointing to a node, which means that the predecessor is relevant for the outcomes associated to that event *(2*).

Figure 2 shows an example of an influence diagram for an investment decision. The decision of investment is represented by a rectangle. The alternative choices for the decision which are to invest in a recreational project, a transportation project, or a water systems project, are shown by rounded rectangles. Since there are factors that may affect the final outcome and cause the project to succeed or to fail, an oval is included in the diagram to represent this influence. The final consequence or payoff of the decision, which is public satisfaction, is expressed by a diamond.

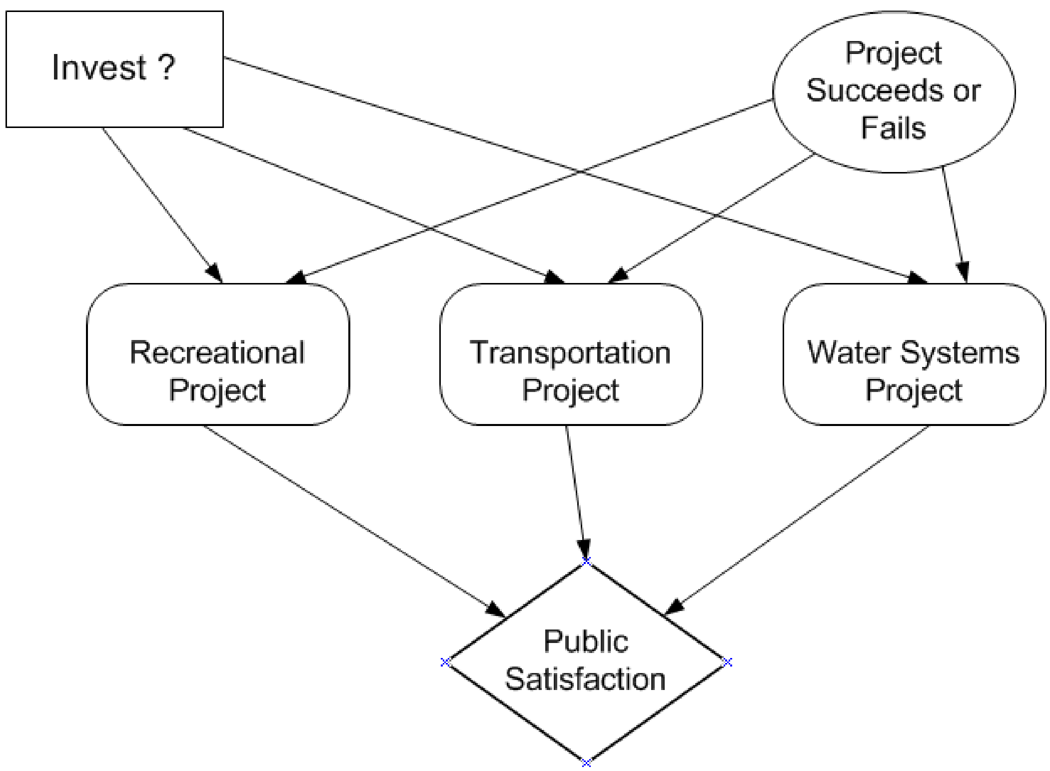

FIGURE 2 Influence diagram for an investment decision.

Decision Trees

Decision trees show alternatives or potential courses of actions graphically. Each course of action is a branch of the tree. Branches start at nodes which represent a chance event or a decision. Chance event nodes are distinguished from decision nodes by using a different shape. Chance event nodes are represented by circles and decision nodes by squares. The branches emanating from a chance event node represent the possible outcomes of that event, and the branches from a decision node correspond to the alternative choices available to the decision maker *(2)*.

There are rules generally applied when building a decision tree. The first rule is that the alternatives choices available to the decision maker, which are expressed by branches that emanate from a decision node, must be exclusive. This means that only one alternative can be chosen by the decision maker. The second rule is that the outcomes from a chance event, expressed by branches that emanate from a chance node, must be mutually exclusive and collectively exhaustive. This means that only one outcome can occur (mutually exclusive), and that no other possibilities exist (collectively exclusive). The third rule is that the decision tree must represent all the possible courses of actions that the event might follow through time. The fourth rule is that nodes must follow a time sequence from left to right. Nodes located at the left represent decisions or chance events that occur first *(2)*.

Figure 3 shows an example of a decision tree for an investment decision. Three branches emanate from the decision node representing the investor’s options. The alternative choices are to invest in a recreational project, a transportation project, or a water systems project. In each case, there is a chance for success or failure. These chance events are represented by a circle node. The final outcome or payoff is the public satisfaction or dissatisfaction.

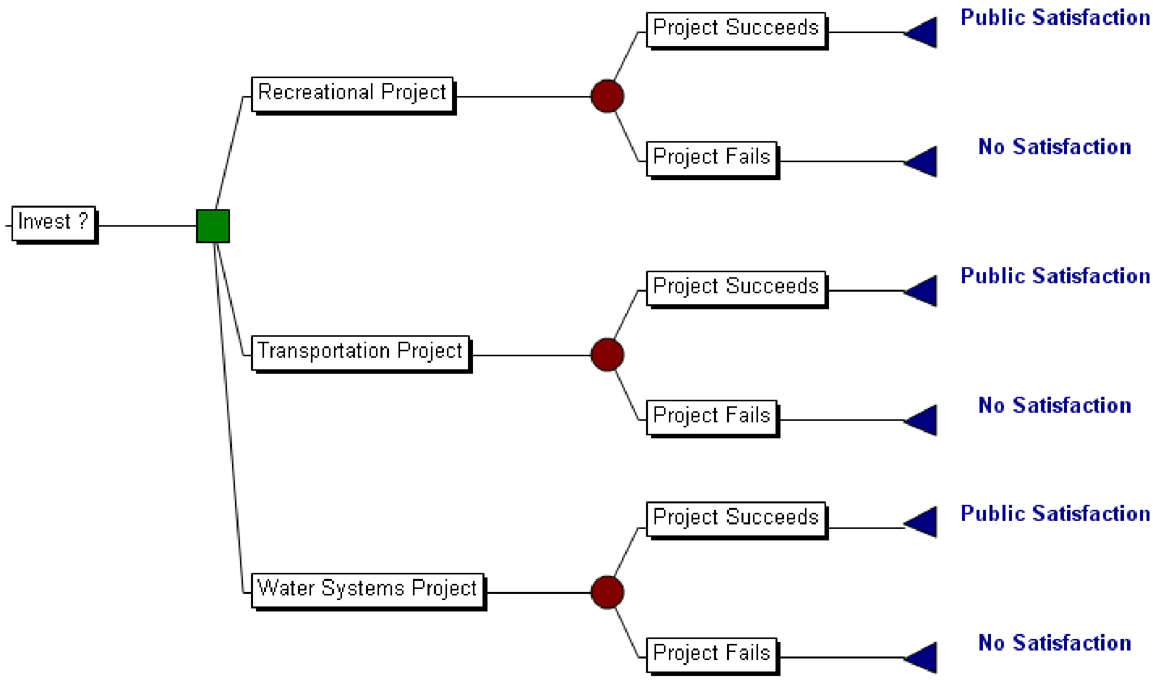

FIGURE 3 Example of a decision tree for an investment decision.

The example shown in Figure 3 illustrates the concept of decision trees. In a real investment decision situation, there are more sources of uncertainty and chance events which mean that the number of paths is considerably larger. However, decisions are made within the boundaries of a decision context or a setting scenario in which the events occur. This setting scenario shapes the level of complexity of the decision tree. Defining the boundaries of a decision context and ensuring that all the essential elements for solving a problem are represented in the decision tree is not an easy task. This task becomes even more complex when risk factors are considered in the process *(4)*.

2.3 STRATEGIC MANAGEMENT AS AN ON-GOING PROCESS

Strategy in business terminology is defined as “a blueprint for which alternative entrepreneurial, competitive, and functional area approaches will be pursued in positioning the organization to achieve sustained success” *(5)*.

Two major tasks are involved in strategic management: formulating the strategic plan, and implementing and executing the strategic plan. Formulating the strategic plan implies knowing the organization’s mission, goals and objectives. Implementing and executing the strategic plan means knowing the methods and actions needed to achieve the goals and objectives to fulfill the organization’s mission. Performance targets must be established in the formulation of the strategic plan to be measured during its implementation in order to take on-going corrective actions as needed *(5)*.

Strategic management is an on-going process that involves several phases. The first phase is determining the business purpose and establishing the mission of the organization; the second phase is setting strategies and performance targets that can be measured over time; the third phase is formulating the strategy; the fourth phase is implementing and executing the strategic plan; and the fifth phase is evaluating performance. Figure 4 shows the different phases of the strategic management process *(5)*.

The sequence from phase 1 to phase 5 does not have to follow a unique pattern. Phases can be performed in different sequences. However, no matter the sequence, objectives must be consistent with the mission, and appropriate parameters need to be selected to monitor the organization's performance targets and then make incremental adjustments during the management process *(5)*.

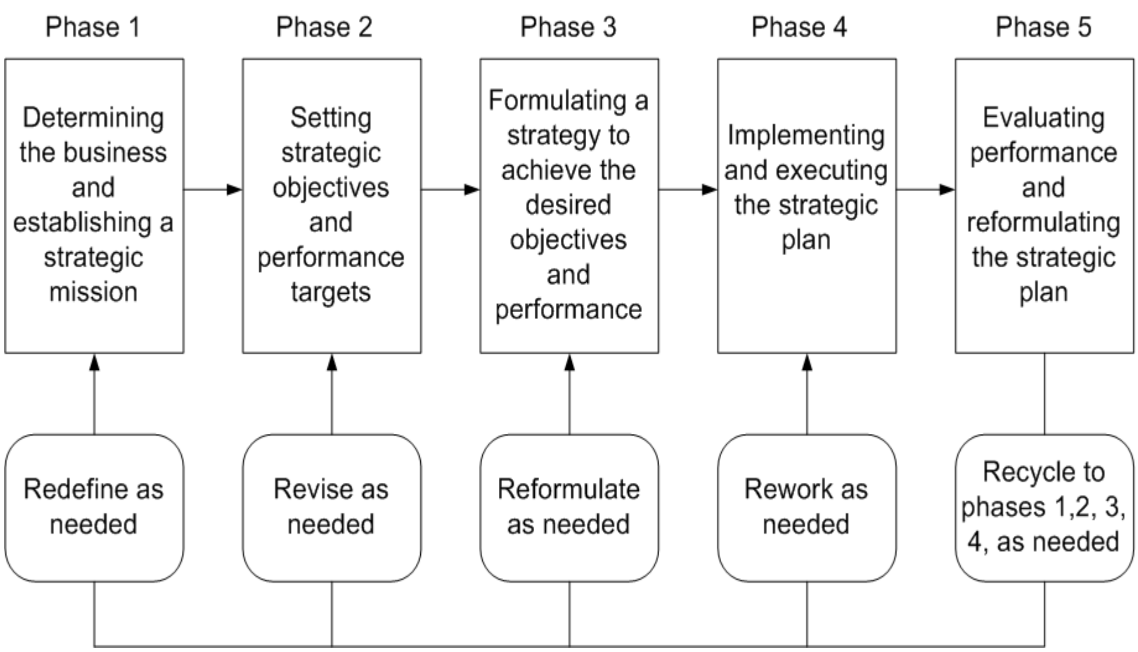

FIGURE 4 Phases in the process of strategic management *(5).*

Some questions asked during the strategic management process are *(5)*:

- What are the organization's goals?
- What parameters can be used to assess if the organization's strategic target objectives are being accomplished?
- What is the gap between the current scenario and the target scenario?
- Are there any conflicts among strategic objectives?
- What level of investment is needed to achieve the organization's target objectives?
- What resources are available to deploy a strategy to meet the organization's target objectives?
- How can an organization sustain organizational growth and foster better strategic management practices?

These questions illustrate the complexity of the strategic management process. This complexity makes it difficult to define the problem, to identify alternatives, and to forecast the potential payoffs for each alternative. Furthermore, the dynamics of strategic management as an on-going process make it difficult to predict all potential courses of actions for the alternatives under consideration, introducing a risk component which is inherent in the decision making process.

2.4 MAKING STRATEGIC DECISIONS UNDER RISK

Strategic decisions are generally made under some level of risk. Risk is defined as an uncertainty event for which the probability distribution is known *(1)*. To make uncertainty explicit, it is assumed that outcomes follow a probability distribution. An outcome is defined as the final resolution of an uncertain event, and risk assessment techniques are used to deal with the uncertainty of unknown events.

2.4.1 Risk Assessment and Knowledge

Risk assessment is a study conducted to determine the potential outcomes along with their probabilities. The level of risk depends on the level of knowledge of the problem and factors that affect the outcomes. Knowledge is required to define the problem properly, to gather the right information, to distinguish relevant information in the problem, to incorporate lessons learned from the past into the decision model, to choose the appropriate probability function for risk assessment analysis, and at last to make a decision *(4)*.

As the level of knowledge increases, the level of risk decreases. Depending on the level of knowledge, the decision context falls under one of these three scenarios *(4)*:

a. Decisions made under pure uncertainty

b. Decisions made under risk

c. Decisions made under complete knowledge

Figure 5 shows three decision context scenarios and their relationship with knowledge.

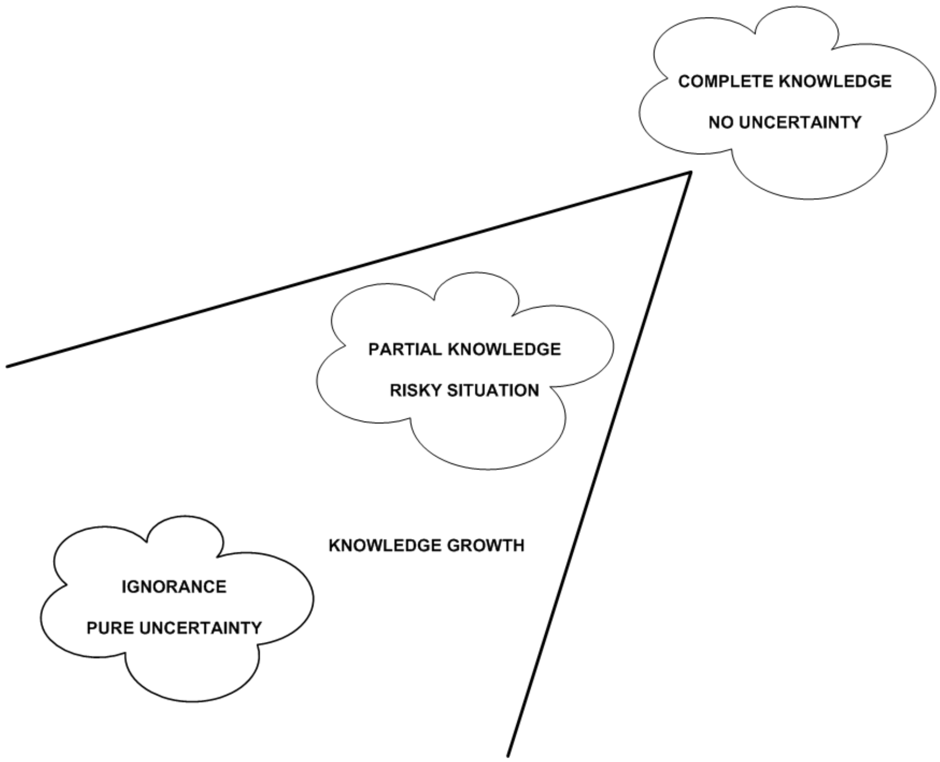

FIGURE 5 Knowledge growth and level of risk in decision context scenarios *(after reference 4)*.

At the strategic management level, risk assessment becomes more challenging since multiple objectives are involved in the decision context. Measurements are essential to track the work progress toward the objective. A measurement scale called the objective's attribute scale can be developed for this purpose *(2)*.

Table 1 shows examples of objectives with natural attribute scales. These attributes are used to measure the level of achievement. The most common attribute is money. For example, money is a natural attribute for objectives that involve maximizing revenues, or minimizing costs. Percentage is a natural attribute for maximizing the rate of return of an investment. Indices are used to measure whether objectives are being achieved or not. These indices are selected based on the attribute-objective relationship. For example, to measure the level of riding comfort on a pavement, a serviceability index is used. According to AASHTO, “the serviceability of a pavement is defined as its ability to serve the type of traffic”. The serviceability index varies from 0 to 5, where 5 represents the highest level of serviceability *(6)*.

TABLE 1 Example of Objectives and Natural Attributes ***(after reference 2)***

Objective	Attribute
Maximize revenue	Money
Minimize cost	Money
Maximize rate of return	Percentage
Maximize riding comfort	Serviceability Index

When natural attributes are not available, a scale can be built by decision makers for measuring the level of achievement for the objective. For example, if the level of public satisfaction measures the success or failure of an investment decision, an attribute scale representing public response can be developed. Table 2 shows a constructed attribute scale to assess the public’s response. The scale has three ranks: best, neutral, and worst. A description for each rank is provided. There could be more than three ranks. More details are needed as more ranks are included in the scale. Numerical values can be associated with the rank scale. If the scale has three ranks, values may vary from 0 to 2, or -1 to 1.

Converting descriptive scales to numerical values are especially helpful when more than one objective is being considered and there is a need for a weighted index to compare alternatives *(2)*.

TABLE 2 Example of an Attribute Scale for Public Response ***(after reference 2)***

Rank	**Description**
Best	Public support of the investment decision
Neutral	Public is indifferent or uninterested in the investment decision
Worst	Public strong action-oriented opposition to the investment decision

2.4.2 Comparison of Alternatives under Risk

A common index used to compare risky alternatives is the expected value (EV). Expected values are based on the attribute scale. The alternative with the highest expected value is recommended. If money is involved in the process, the expected monetary value (EMV) is calculated. The procedure to calculate the EMV is called "folding back the tree" *(2)*. The procedure starts at the far right-hand side of the decision tree and moves to the left. If a chance node is found, the expected value is calculated for each branch. The highest expected value is selected when a decision node is encountered.

Figure 6 illustrates the use of the EMV for selecting an alternative. The decision investment tree is used as an example. Assuming that there is US $ 100,000 available for investment, the decision maker has to choose among investing in a recreational project, a transportation project, or a water systems project.

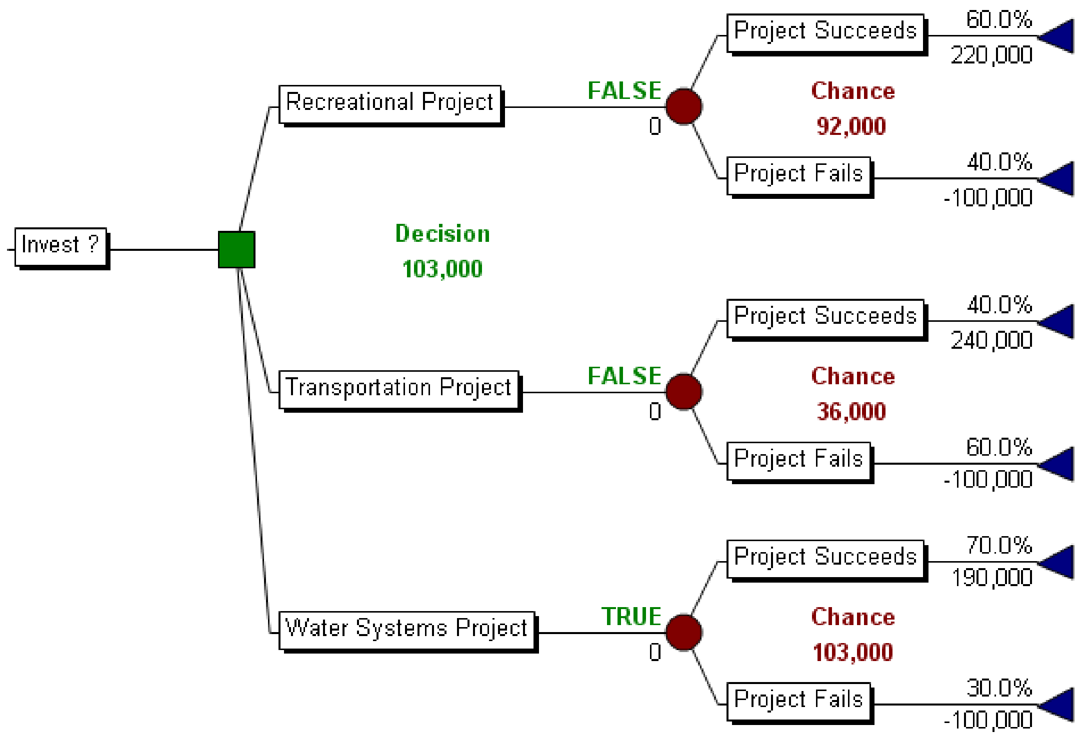

FIGURE 6 EMV calculated for an investment decision tree.

Each investment alternative generates different revenues over the analysis period. Estimates show that the recreational project will generate US$ 220,000 in revenues, the transportation project will generate US$ 240,000, and the water systems project will generate US$ 190,000. It is assumed in this example that the probability of success is different for each investment alternative: the recreational project offers a probability of success of sixty percent, the transportation project forty percent, and the water systems project seventy percent.

The expected monetary value for each alternative is calculated for each alternative. The EMV is calculated by multiplying the probability of each branch by the expected outcome which is expressed in monetary terms, and then adding partial results.

The EMV for each alternative is calculated as follows:

EMV for Recreational Facilities : 0.6 x $220,000 + 0.4 x -$100,000 = $ 92,000

EMV for Transportation Assets : 0.4 x $240,000 + 0.6 x -$100,000 = $ 32,000

EMV for Water Systems : 0.7 x $190,000 + 0.3 x -$100,000 = $103,000

The investment on the water systems project offers the highest EMV. Therefore, the recommendation is that the decision maker should invest the US $ 100,000 in the water systems project.

It seems that making decisions based on this methodology is quite simple. The difficulty does not reside in following the mechanics of the method but in forecasting all the courses of actions and corresponding probabilities for each alternative. In a real situation, it may happen that the decision maker needs to decide how to distribute the US$ 100,000 among several projects on recreational facilities, transportation assets, and water systems instead of selecting just one project for investment. This is the type of situation faced during the strategic management process which demands the use of decision support systems to assist in identifying the best investment strategy.

CHAPTER III

DECISION SUPPORT SYSTEMS FOR PAVEMENT MANAGEMENT PRACTICES

Decision support systems are developed to assist agencies in managing their assets effectively. The level of complexity included in a decision support system depends on the agency's objectives and the resources available for the development and maintenance of the system. The aim in using a decision support system is to assist agencies in making sound decisions regarding what to do, when to do it, how much money to invest, and how to prioritize investments when funds are constrained.

Pavement management practices involve all the activities for managing pavement assets. Management practices implemented by an agency can be very simple and informal or very complex and systematized. The level of complexity in pavement management practices depends on the goals and objectives established by the agency, the type of information required to make decisions, and the resources available at the agency.

This chapter presents a historical overview of pavement management practices and describes its fundamental concepts. It also explains the purpose, applications, and benefits of pavement management systems. In a broader perspective it introduces asset management systems, geographic information systems, and knowledge management systems as decision support tools that can be used in or with pavement management practices. Each of these systems is described in an independent section, and an integrated approach to better support the strategic management process is presented at the end of this chapter.

3.1 HISTORICAL OVERVIEW OF PAVEMENT MANAGEMENT PRACTICES

The use of pavement management practices and systems engineering as a systematic approach to manage pavement assets is not new. The concept of pavement management systems started as an effort to integrate engineering, economic, and systems principles.

At the beginning, in the mid 1960s, management methods and system engineering principles were applied to pavement design to select the most effective treatment for a specific pavement section. By the end of the1960s, the concepts had been expanded to the network management level and were used to identify maintenance and rehabilitation pavement needs and budget. During the 1970s, several research projects developed methods to prioritize fund allocation *(7)*.

New techniques for data collection, data management, model performance, economic analysis, and optimization techniques were integrated into pavement management systems as research advanced in different disciplines during the 1980s. In 1989, the Federal Highway Administration (FHWA) defined pavement management systems as "a set of tools or methods that (can) assist decision makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition" *(8)*.

The need for the implementation of pavement management systems to assist decision makers to develop effective maintenance and rehabilitation strategies was more crucial during the 1990s. In 1991, the United States (U.S.) Congress approved the Intermodal Surface Transportation Act (ISTEA) to provide Federal financial support to highway investments. ISTEA recognized that investment decisions should be based on systematic cost-benefit analysis to maximize the return on investment *(9)*. ISTEA authorized the allocation of $ 155 billion over six years (1992-1997) *(10)*. On May 22, 1998, the U.S. Congress passed the Transportation Equity Act for the 21st Century (TEA-21). A total of $ 215 billion for highway, transit, research, and motor carrier programs over six years (1998-2003) was authorized by TEA-21. TEA-21 provided states and local governments greater flexibility than ISTEA by allowing states and metropolitan planning organizations to meet programmatic budget needs by transfer of up to fifty percent from all highway program categories to any other highway category *(11)*. On August 10, 2005, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) was signed. SAFETEA-LU constitutes the largest surface transportation investment in U.S. history with a total of $244.1 billion over five years (2005-2009) for highways, highway safety, and public transportation *(12)*. These legislative initiatives encouraged the diffusion and deployment of pavement management systems at different management levels. As a result, pavement management systems advanced in terms of applied technology.

With more mature methods for analysis, a variety of tools available, and lessons learned from previous experience, the next stage in the evolution of pavement management practices was the integration of business concepts through an asset management approach. Even though asset management is a term that began to appear in the early 1990s (7), it was at the end of the 1990s that this approach really emerged as a systematic process for managing physical assets in the public sector *(13)*.

An asset management approach goes beyond the application of engineering and economic principles and incorporates business practices to improve the decision making process. In this approach, there is a need to monitor and record changes in an agency's capital assets. On June 15, 1999, the Governmental Accounting Standards Board (GASB) released statement 34 (GASB 34), "Basic Financial Statements for State and Local Governments," which requires agencies to capitalize their assets in financial statements. Following accounting principles, GASB 34 requires agencies to determine the cost associated with their infrastructure assets including initial construction costs and subsequent costs for capital improvements or any associated expense for using the assets *(14).*

The effective integration of business management concepts, accounting procedures, and engineering and economic principles with emerging technologies and computer science tools is the key for the evolution of pavement management practices. Knowledge is essential to integrate concepts and methodologies available in each area of expertise. Areas of improvement for pavement management are listed in Table 3. These areas of improvement are grouped in institutional, economic, and technical categories.

TABLE 3 Areas for Improvement for Pavement Management *(after reference 7)*

Area of Improvement	Degree of Risk	Payoff
A. Institutional		
1. Dealing with the effects of different organizational structures and rapid turnover of key personnel.	Medium	Long term
2. Establishing appropriate systems for different local area, provincial/state and federal needs.	Low	Intermediate
3. Integrating Pavement Management Systems with other management systems and/or with total asset management (including overall, objectively based prioritization).	High	Long term
4. Adapting Pavement Management Systems to privatization.	Medium	Short term
5. Breaking down institutional barriers.	Low	Short term
B. Economic		
1. Quantification of Pavement Management System benefits.	Low	Short term
2. Quantifying benefits of technology.	Low	Long term
3. Development of incentive programs (public and private sector) for better materials, maintenance and constructions.	Low	Long term
C. Technical		
1. Better interfacing between network and project levels of Pavement Management Systems.	Low	Short term
2. Automation technologies in construction, maintenance and surveillance.	Low	Long term
3. Better performance models.	Low	Long term
4. Longer lasting pavements (better Quality Control/Quality Assurance, construction, maintenance, etc.).	Low	Long term
5. Better technical capabilities (private and public sector).	Low	Short term
6. Development of objectively based long terms performance specifications.	Medium	Long term
7. Implementation and improvement of Strategic Highway Research Program (SHRP) products.	Medium	Long term

3.2 PAVEMENT MANAGEMENT LEVELS

Pavement management is traditionally divided in two management levels: network and project level *(15)*. The purpose of the decision and the quantity of the pavement network considered in the process are the main differences between these two management levels. An overview of the entire pavement management process will distinguish two additional management levels: an upper management level called the strategic management level which is on top of the network level, and a project selection management level which is the link between the network and project level *(16)*. The four management levels involved in pavement management practices are shown in Figure 7.

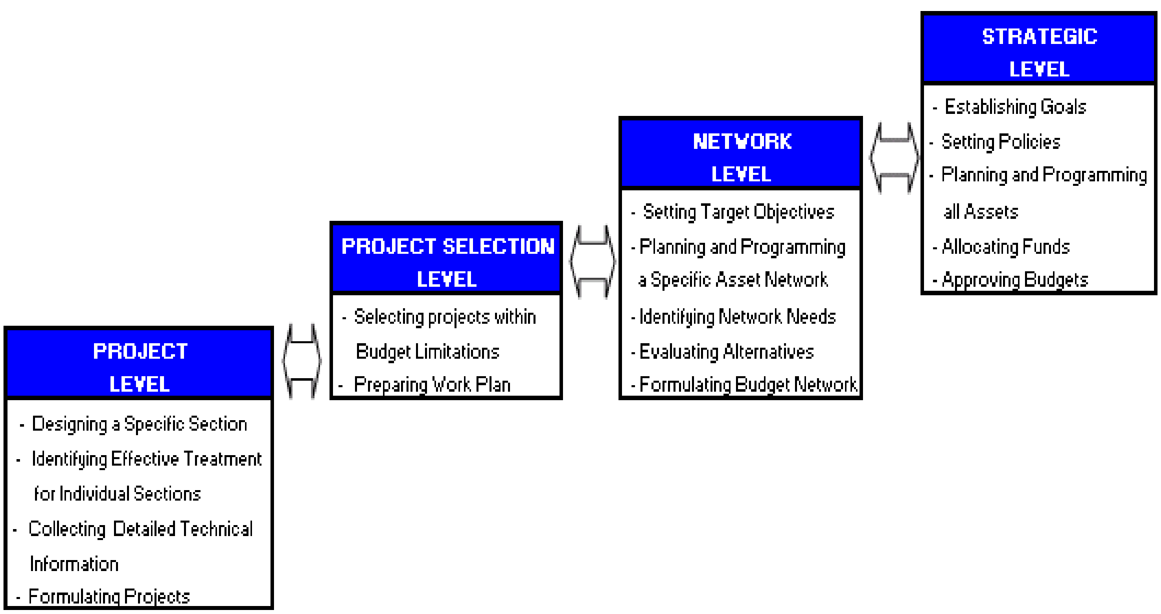

FIGURE 7 Management levels involved in pavement management practices.

At the strategic management level policies and goals are established. These policies and goals set the basis for formulating agency target objectives. Policies given at the strategic level influence the funding allocation process among agency's assets. Decisions at this level affect the entire organization *(16)*.

At the network management level, target objectives to achieve agency goals and objectives are set. The purpose of activities at this level is to identify which pavement sections need treatment, when preventive maintenance and rehabilitation treatments should be applied, how much money is required to achieve the target objectives, and a prioritized listing of required work. The product of this process is a formulated budget that is submitted for the approval of funding authorities *(16)*.

At the project selection management level a subset of pavement sections from the entire network are selected based on treatment needs, available funds, and other constraints. The purpose of the project selection level is to finalize a list of pavement sections that will be selected for repair or maintenance in the work program and better quantify the expected cost of the work for each selected pavement section *(16)*.

At the project management level, the purpose is to identify and design the best maintenance or rehabilitation treatment for individual pavement sections of the network that were selected at the project selection level. Detailed technical information for each individual pavement section is required to determine the most cost-effective treatment and finalize the cost estimate to complete the work.

The type of data, amount of data, level of complexity of the engineering and economical models used to analyze the data, and content of the reports depends on the specific needs of each management level. Technical, economical, and financial information must be integrated at the strategic and network management levels to support funding decisions for the entire pavement network. On the other hand, at the project level detailed data is required to establish the final treatment and funding needs for individual pavement sections *(16)*.

Strategic decisions about pavement investments are made by senior managers and funding authorities at the strategic management level. The budget prepared at the network level is revised and approved at this upper management level. The strategic management level is responsible not only for managing pavement assets but also for managing the other infrastructure assets under the agency's jurisdiction. The main purpose of the strategic management level is to ensure that coherent decisions are being made toward the accomplishment of the agency's goals and objectives for all types of infrastructure. A common platform serving as an interface to facilitate the flow of information among management levels is essential to accomplish this purpose. The integration of isolated individual management systems into an integrated overall asset management system is the key to achieving this need.

3.3 PAVEMENT MANAGEMENT SYSTEMS

A pavement management system is defined as "a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time" *(6)*. AASHTO states that the purpose of a pavement management system is "to improve the efficiency of decision making, expand its scope, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization" *(6).*

Although the purpose of a pavement management system is clear, there are different approaches currently in practice. The methods and tools also vary depending on the approach adopted by the agency. Moreover, the level of sophistication of a pavement management system is related to the decision support required by the agency, and the level of knowledge among the personnel that will use it.

Some of the essential requirements for pavement management systems are *(17)*:

- Capability of retrieving and presenting the information stored in the database quickly and effectively
- Capability of basing decisions on rational procedures with quantified attributes, criteria, and constraints
- Capability of providing information about current and future network condition
- Capability of considering alternative pavement maintenance and rehabilitation treatments in the analysis
- Capability of using feedback information regarding the consequences of decisions in current practice
- Capability of easily being updated or modified as new information and better models become available

3.3.1 Components of a Pavement Management System

A central database, performance models, analysis techniques, and reporting tools are the basic components of a network level pavement management system *(18)*. Figure 8 shows these components.

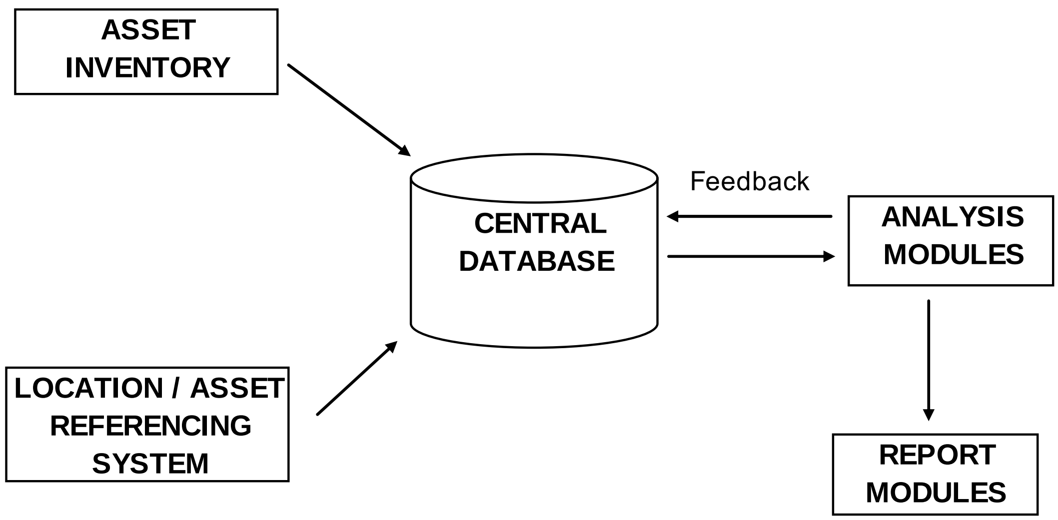

FIGURE 8 Components of a pavement management system *(18).*

These components perform several functions in the system including:

- Storing inventory and condition data of the pavement sections
- Predicting future condition
- Identifying pavement sections needing treatment
- Determining the budget required to fulfill treatment needs

- Assisting in the prioritization of projects needing treatment when funds are constrained
- Reporting analysis results

A description of the functionalities and level of sophistication of each pavement management component follows.

Central Database

The central database contains the pavement network inventory and stores data required by the system. In most pavement management systems, the pavement network is divided into management sections which are classified by surface type and functional class. Information including the length and width of the individual sections, the date of construction, maintenance and rehabilitation history, current pavement condition, treatment costs, and traffic level is stored in the central database *(18)*.

Performance Models

Performance models are primarily used to forecast pavement condition. They can be classified as mechanistic, mechanistic-empirical, empirical, probabilistic, or bayesian models.

Table 4 presents a brief summary of the strengths and weaknesses for each of the prediction models described in this section.

TABLE 4 Comparison of Prediction Models: Strengths and Weaknesses *(after reference 16)*

Prediction Model	Strengths	Weaknesses
Mechanistic	Predicting future changes in mechanistic response such as stress, strain, or deflection	Requiring detail information Not all the information can be described by mechanistic terms
Empirical Regression Analysis	Using historical data and statistical methods to develop the model	Limiting the conditions of pavement sections used to develop the model Unknown factors may influence the precision of the model because most of them are based on data monitored from in-service segments
Empirical Fuzzy Set	Considering uncertainty and randomness in the formulation of the model Incorporating past experience and personal opinion in the model	Modeling fuzziness is difficult due to complex interactions among factors Depending on the quality of the data used to develop the model as well as knowledge of the experts that interpret the results
Empirical Artificial Neural	Learning from past experiences Recognizing incomplete or partially incorrect data and modifying by itself	Requiring a large amount of good quality data Using complex relations to link the data Being difficult to trace back what the model does and how it works
Probabilistic Markov Models	Depending each condition state on previous states	Involving large transition matrix operations and related complications Time intervals are fixed
Probabilistic Semi-Markov	Allowing random time intervals in the model Simplifying Markov model by reducing the size of the problem	Demanding adequate data to develop the probability distributions of time intervals between consecutive stages
Probabilistic Survivor Curves	Being easy to implement and use	Depending on availability of historical data
Probabilistic Bayesian	Combining observed data with expert experience Using field data to adjust models	Demanding expert opinion and well documented previous experiences from in-service segments

Mechanistic models predict future changes in strain, stress, or deflection as a function of known factors. These models usually demand a great level of detail in the input data that is not available at the network level, so they are more suitable for pavement analysis and design at the project level than for predicting pavement performance at the network level *(19)*.

Empirical models are based on historical data and relate changes in pavement condition to pavement aging, or to traffic loads applied to the pavement. Regression analysis is normally used to develop empirical equations to predict pavement condition. In addition to regression analysis, new methods have been proposed to develop empirical models such as fuzzy sets and artificial neural network. Fuzzy sets are models that consider the randomness and uncertainty of the input variables in their formulation *(20)*. Artificial Neural Network models are based on back-propagation techniques that act on historical data to fill any incomplete data by modifying themselves through an iterative process *(21)*. Empirical models are limited by the quantity and quality of the data used to develop the model.

Probabilistic models are used to predict a range of values for a dependent variable. They can be used to assess the variability observed in pavement condition. Markov models and semi-Markov models are the most common probabilistic models used in pavement management systems *(19)*. The probability that a known pavement condition state at a known time changes to another condition state in the next period of time is represented in Markov models by transition matrices. Markov models use identical time intervals, while semi-Markov models allow random time intervals between consecutive states *(22)*. Another probabilistic model to predict pavement life involves the use of survivor curves. The number of pavement sections that remain in service at selected ages is represented by a survivor curve. Survivor curves can be used in pavement management systems to predict the probability that a pavement section remains in service at some given time in the future *(16)*.

Bayesian models use statistical techniques to combine expert opinion and field data. Statistical techniques involve regression analysis where regression parameters are considered random variables. The user can generate a probability density function with regression coefficients to compare them in a single plot *(16)*.

Analysis Techniques

Analysis techniques are used to identify pavement sections in need of treatment. Trigger values are set up by agencies to establish a specific condition or performance level at which a certain type of treatment category is required. Condition indices are often considered as a measure of condition and are used to define trigger values *(19)*. Based on these trigger values, pavement sections in need of work are identified and the treatment and budget needs over the funding period are forecasted *(16)*.

Additional analysis techniques are required to choose among pavement sections in need of treatment when funds are constrained. Analysis techniques vary from ranking approaches to optimization techniques to select pavement sections for funding *(16)*.

Ranking approaches are used in many pavement management systems to prioritize funding allocation among pavement sections in need of treatment. Ranking approaches are based on damage measures, performance functions, usage weighted performance functions, composite criteria, first cost, least life cycle cost, benefit-cost ratio, or cost effectiveness. The agency's criterion could be to repair sections in worst condition first, or to invest in sections with greater benefit-cost ratio first, or to treat sections with poor roughness first, or maybe a composite criterion. Based on the ranking criterion, a list of candidate sections ranked from the highest to the lowest priority is prepared. Funds are allocated to pavement sections starting from the top to the bottom of the ranked list. Non-funded pavement sections are moved for consideration into the next fiscal year *(16)*. A description of the different ranking approaches used in pavement management systems is presented in Table 5.

In a single year prioritization approach, the selection process is repeated over the years of the analysis period based on the initial list of ranked pavement sections. Another alternative is to follow a multi-year prioritization approach. In a multi-year prioritization approach, the condition of non-funded pavement sections, as well as funded pavement sections, is projected to the next year of analysis, and a new list of candidate sections is produced each year *(16)*.

Optimization techniques are an alternate methodology to select projects. Optimization techniques applied in pavement management systems vary from linear programming techniques to non-linear programming, integer programming, dynamic programming, and heuristic methods. A description of these optimization techniques with comments is presented in Table 6.

TABLE 5 Ranking Approaches Used in Pavement Management Systems *(after reference 16)*

Ranking Approach	Description	Comment
Damage Measures	Ranks sections with the greatest quantity of damage first	Ignores benefits of funds invested
Performance Function	Uses performance functions such as serviceability, roughness, or a composite index to rank sections from worst to best	Ignores benefits of funds invested
Usage Weighted Performance Function	Weights performance functions for usage. Each section is related to a weighted performance index. Sections with the lowest value have priority	Ignores benefits of funds invested
Composite	Develops a priority score by combining condition indices with performance indices, or other functional indices Sections with highest usage levels have priority	Difficult to interpret Skews the allocation of funds to sections with the highest usage criteria considered by the method
First Cost	Ranks sections with the lowest first treatment cost first Normalizes costs by the size of the segment	Ignores impact on future condition Neglects costs or benefits to the user
Life-Cycle Cost	Ranks sections with the lowest life-cycle treatment cost first	Considers initial construction cost, future maintenance costs, future rehabilitation costs, salvage value, and user costs Considers impact on future condition
Benefit Cost Ratio	Ranks sections with the greatest benefit cost ratio in monetary terms first	Considers benefits and costs over the analysis period
Cost-Effectiveness	Ranks sections with the greatest cost-effectiveness ratio first	Uses a surrogate ratio instead of monetary benefits Expresses effectiveness as a function of condition improvement over time

TABLE 6 Optimization Techniques Used in Pavement Management Systems *(after reference 16)*

Optimization Technique	Description	Comment
Linear Programming	Solves simultaneous equations with certain constraints to satisfy an objective function which is expressed as a linear equation	Demands an extensive analysis to insure that the optimum is the true optimum
Non Linear Programming	Expresses simultaneous equations and the objective function by non linear equations	Demands an extensive analysis to ensure that the optimum is the true optimum
Integer Programming	Sets an objective function and constraint equations in terms of decision variables Allows only a value of 0 or 1 is allowed for decision variables	Demands powerful computer resources to process the information. Requires staff members with a strong background in mathematics, statistics,and operations research. More realistic since decisions are either to apply a treatment, expressed by a value of 1, or not to apply a treatment, expressed by a value of 0
Dynamic Programming	Considers decisions in a logical interrelated sequence Finds a solution by starting at the final condition and working backwards to meet the objective	Demands powerful computer resources to process the information Requires staff members with a strong background in mathematics, statistics,and operations research. Difficult to trace back to verify the results due to the size of the problem.
Heuristic Method	Uses problem solving techniques that utilize self-learning techniques to find the optimum. An alternative to true optimization methods	Combines heuristic techniques with other optimization techniques such as dynamic programming

In these methodologies, systems analysis concepts and operations research techniques are used to find the optimum strategy to minimize cost or maximize benefits. Since the solution space is large, there may be more than one combination of projects that fits with the optimum solution or is close to it, so that the interpretation of the results from applying optimization techniques becomes critical. The level of expertise needed to interpret the answers provided by optimization techniques may be beyond the level of training of local agencies' personnel *(18)*.

Optimization techniques are often perceived as too complex, and answers provided by these methodologies are not well understood by local agencies. The major criticism is that the optimum solution can not be carried out without changes due to technical, economical, social, and political issues that influence investment decisions in the project selection level over the planning horizon. The optimal solution may require periodical adjustments to reflect future situations. For example, technological advances in data collection may require adjustments in the condition assessment criteria used for treatment selection; funding policies may affect budget constraints initially considered in the optimization model; and social conditions may influence political decisions and predetermine investments toward certain pavement sections *(16)*.

On the other hand, limitations in data available for applying optimization techniques to select the best solution make it difficult to accept the optimum solution as the true optimum. Data collected for pavement management systems used by local agencies at the network management level may not be sufficient to provide better solutions using optimization techniques rather than ranking. Finally, pavement sections identified for treatment and corresponding budget estimates provided by optimization or ranking are not final at the network level and will be refined at the project selection level. The additional effort spent in optimization may not be translated to a better solution compared to that determined by ranking. Due to these considerations the applicability of optimization techniques in pavement management practices for local agencies level is limited. However, in spite of their limitations, it is recognized that optimization techniques can provide valuable insights to decision makers when they are properly used *(16)*.

Reporting Tools

Reporting tools should provide adequate information to support cost-effective decision making. Adequate information is required to convey the treatment needs and effects of pavement management preventive and rehabilitation strategies across the agency. User oriented reports are the key to address this aim *(16)*.

Since each management level in the organization requires different types of information, the reporting tools should be flexible enough to provide a variety of reports. Not only the type of information but also the level of detail provided by the report is important. At the project management level, detailed technical information is required. More emphasis on the economic impact of pavement management preservation and rehabilitation strategies should be given at the network and strategic management levels. The content and form of the report must be conceived to satisfy the requirements of each management level *(16)*.

Reports can be classified according to the type of information that they provide to the user. Network inventory, condition assessment, needs analysis, and impact analysis reports are commonly used in pavement management *(16)*.

Inventory network reports include information related to the pavement network inventory. Location, description of individual pavement sections, length and width of the section, functional class and surface type of the pavement section, and the year of construction are some of the typical information presented in inventory network reports.

Condition assessment reports include information about the current and future pavement condition of the management sections and the entire pavement network. Distress information from inspection surveys is normally used to assess current pavement condition and to adjust performance models for projecting future pavement condition.

Needs analysis reports provide information about the pavement sections in need of treatment. Information about where and when a maintenance or rehabilitation treatment should be applied as well as treatment costs are reported.

Impact analysis reports provide information regarding the results from the impact analysis conducted for the levels of investment or allocation alternatives under consideration. These reports include information about the condition of individual management sections and the overall network condition for both constrained and unconstrained funding scenarios, pavement sections in need of treatment, pavement sections selected for treatment, pavement sections not selected for treatment, stop-gap costs, and backlogged sections due to deferred funds.

The availability of these types of reports is essential in pavement management practices. With the information provided in these reports, a communication bridge across the strategic, network, project selection, and project management levels can be built.

3.3.2 Benefits of Implementing a Pavement Management System

The implementation of a pavement management system offers the agency a powerful tool to assist their personnel in managing the pavement network with the aim of making better informed investment decisions. Some other benefits that result from implementing a pavement management system are *(16)*:

- Improving the accuracy and accessibility to pavement section records
- Monitoring the performance of treatments applied in the past
- Providing data regarding pavement treatment costs
- Improving pavement network condition and extending remaining life
- Generating reports on completed activities and costs incurred
- Improving the overall decision making process
- Facilitating coordination of the work across the agency

An approach for quantifying the benefits of implementing a pavement management system is to monitor historical data to compare trends through selected indicators used to measure the level of success. Pavement maintenance and rehabilitation programs can be evaluated using statistical analysis to verify whether the implementation of a pavement management system has had a positive influence or not *(23)*.

Performance indicators can be used to track changes in pavement condition and pavement life. Some studies have shown that there is a positive influence in terms of pavement life due to the implementation of a pavement management system. A study conducted in Arizona concluded that the implementation of a pavement management system contributed to extending the life of the pavement network by about fourteen percent. Translating these benefits into monetary terms, the study estimates that there is a benefit-cost ratio of thirty dollars in savings for each dollar spent in the development of the pavement management system *(23)*.

3.4 ASSET MANAGEMENT SYSTEMS

Asset management emerged as an effort to integrate finance, planning, engineering, personnel, and information management to assist agencies in managing its assets cost-effectively *(24)*. In its broadest sense, asset management is defined as "a systematic process of maintaining, upgrading, and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public's expectations" *(25)*.

The main objective of an asset management approach is to improve decision making processes for allocating funds among an agency's assets so that the best return on investments is obtained. To achieve this objective, asset management embraces all of the processes, tools, and data required to manage the assets effectively *(26)*. For this reason asset management is also defined as "a process of resource allocation and utilization" *(27)*. The framework needed to carry out this process effectively encompasses an agency's policy goals and objectives, performance measurements, planning and programming, program delivery, and system monitoring and performance results as shown in Figure 9.

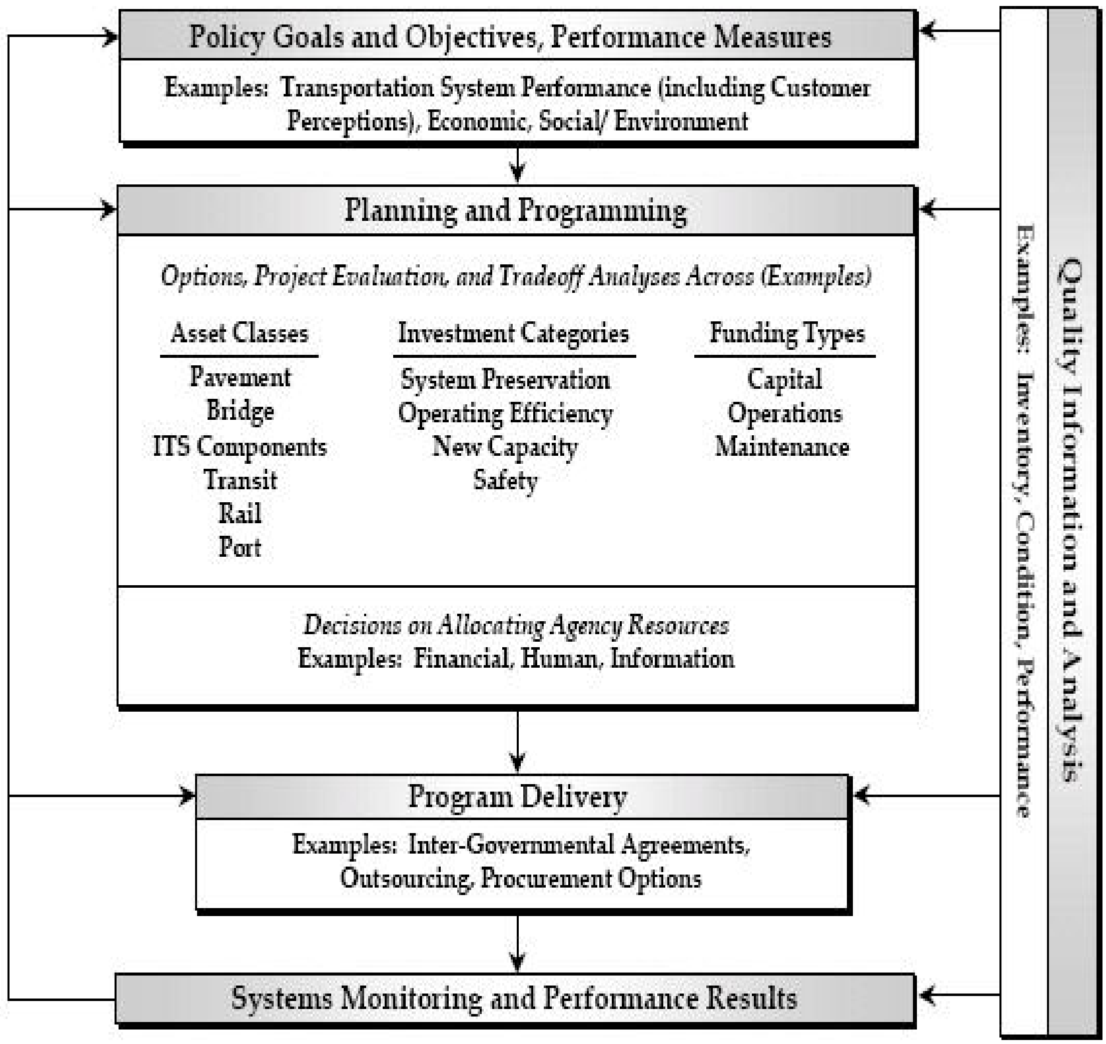

FIGURE 9 Resource allocation and utilization process in asset management *(27).*

Asset management decisions are based on policy goals and objectives. Policy goals and objectives are established by the agency to reflect the desired system condition and target level of service. Performance measures are selected to express the desired system condition and target level of service in an objective manner, and to allow tracking of progress toward desired goals.

Planning and programming is a complex process since many agencies manage several types of physical infrastructure facilities such as those illustrated in Figure 10. A structured asset management system should provide information about the effects of investing different levels of funding in each of these various types of facilities and the effects of investing more in one type while investing less in another *(28)*.

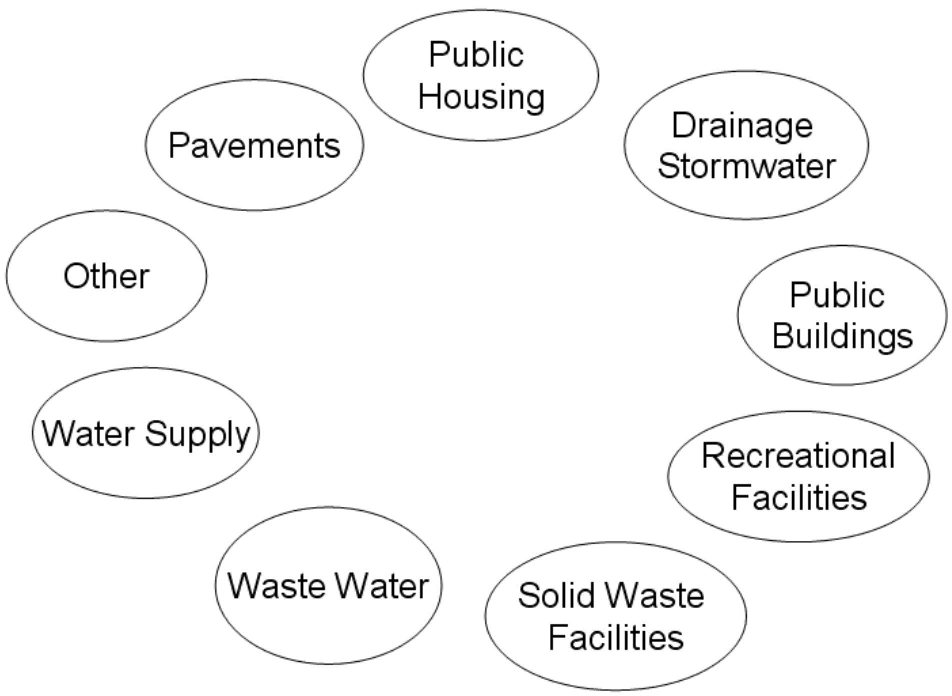

FIGURE 10. Example types of physical assets.

The agency also decides how to allocate available resources among different types of activities involved with each type of physical asset. Example activities are illustrated in Figure 11. *(28)*.

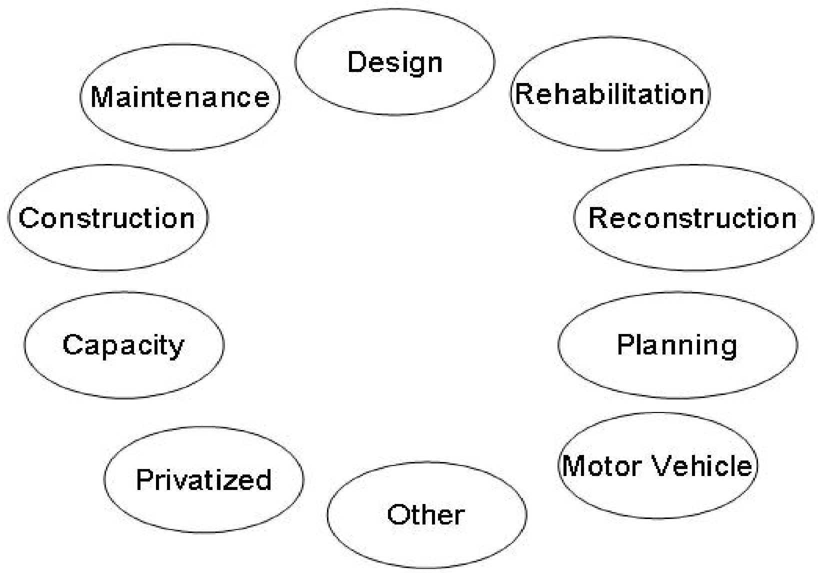

FIGURE 11. Example types of activities *(28).*

A structured asset management system must provide information about both the short-term and long-term impacts of allocating different amounts of resources among different activities. Additionally, an agency manages many different types of resources, such as those shown in Figure 12; and the structured asset management system should show the impact of limitations on the different amounts of the various types of resources. These impacts should be expressed in terms of performance measures *(28)*.

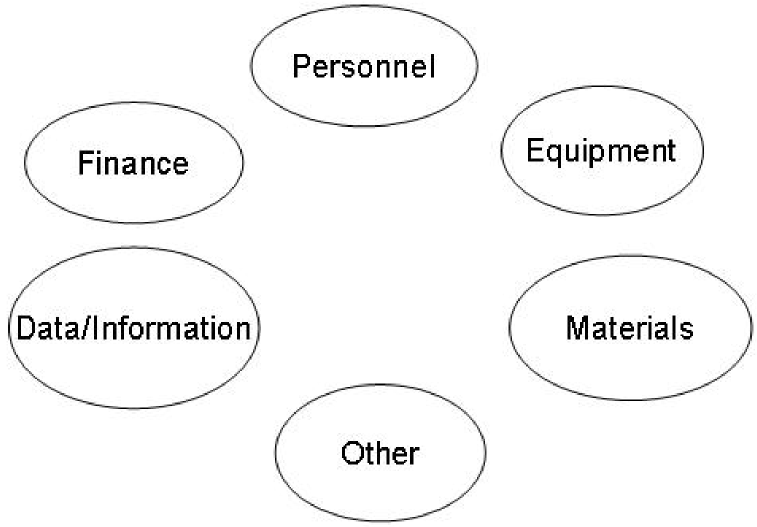

FIGURE 12. Example types of resources *(28).*

Work programs developed during the planning stage are delivered and periodically evaluated by the agency. Results from program delivery are monitored using performance measures to quantify the asset management program's effectiveness and to allow timely corrective actions as needed *(28)*.

3.4.1 Components of an Asset Management System

Asset management systems provide decision makers with tools for evaluating probable effects of alternative decisions. These decision support tools are based on quantitative data regarding the organization's resources, condition of physical assets, and estimations of their value.

According to the FHWA, to effectively support the asset management process, an asset management system should include *(29)*:

- Strategic goals
- Inventory of assets
- Valuation of assets
- Quantitative condition and performance measures
- Measures of how well strategic goals are being met
- Usage information
- Performance-prediction capabilities
- Relational databases to integrate individual management systems
- Consideration of qualitative issues
- Links to the budget process
- Engineering and economic analysis tools
- Useful outputs, effectively presented
- Continuous feedback procedures

These asset management elements can be grouped into five major building blocks: basic information, performance measures, needs analysis, program analysis, and program delivery. Figure 13 shows in detail the individual components of each building block providing a comprehensive view of an asset management system.

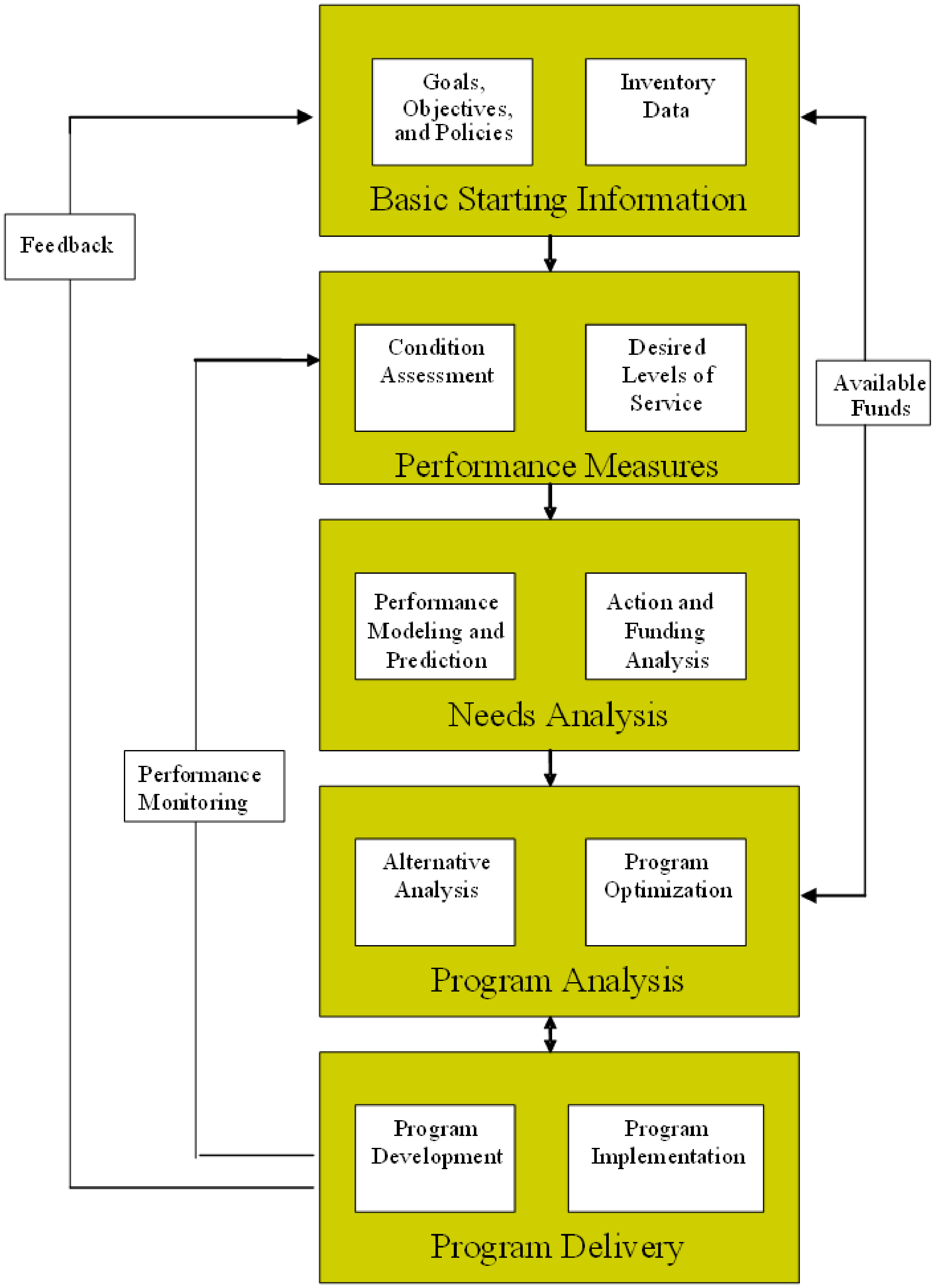

FIGURE 13 Components of an asset management system *(30)*.

Goals, objectives, and policies as well as inventory data are considered in the basic information block. Condition assessment and desired levels of service are components of the performance measures block. Performance modeling and prediction along with action and funding analysis constitute the needs analysis block. Alternative analysis and program organization are included in the program analysis block. Program development and program implementation belongs to the program delivery block. Finally, performance monitoring and feedback completes the cycle of the asset management process.

Goals, Objectives, and Policies

Asset management is a goal-driven management process. To manage assets effectively, the decision making process must be aligned with the agency's goals, objectives, and policies. Goals are expressed in terms of objectives to be met over the planning horizon. Policies are developed to provide the necessary framework to support achieving target objectives. Policies regarding engineering standards, economic development, community interaction, political issues, administration rules, and the agency's organizational structure influence asset management components *(29)*.

Inventory Data

The asset inventory contains information about physical location, characteristics, usage, work history, work planned, costs, resources, and any other information considered relevant by the agency. Additional information provided by asset management systems may include financial reports about the agency's assets showing both the current economic value and future asset value estimates. Decisions regarding the type and amount of data to be collected are made based on the agency's needs for decision support and available resources *(29)*.

Condition Assessment

Knowledge of current condition is needed to assess the asset network current scenario. Condition assessment is expressed in terms of performance measures selected by the agency. These performance measures should be the ones used by the agency to establish its objectives. Condition indices, percentage of the network system rated in good condition, and remaining life of the asset network are some examples of performance measures used for physical assets *(29)*.

Desired Levels of Service

Performance measures are also used to establish the desired levels of service for the asset network. Establishing level of service goals for the planning horizon allows the development of strategies to achieve those goals. Periodical condition assessment conducted by the agency allows agencies to assess if the desired levels of service are met or not in order to take corrective measures and adjust strategies as needed *(29)*.

Performance Modeling and Prediction

Performance models are used to predict future scenarios for the asset network. Projecting the asset network condition over the planning horizon helps to identify future funding needs. Appropriate selection of performance models is essential to effective asset management. The selection of performance models is based on the types of assets being managed and data available in the data inventory to support the models. Performance models are used to predict future condition and identify treatment needs over the funding period. Prioritization for funding allocation among assets in need of investment can be supported by analytical methods based upon performance models. Optimization techniques, if preferred by the agency, require well calibrated performance models.

Action and Funding Analysis

Funding analysis involves forecasting the impact of investment strategies on the asset network condition and future funding needs. Scenario analysis can be conducted to assess this impact due to different funding strategies. The challenge of funding analysis is to assess the impact of allocating funds among the assets owned by the agency. Trade off analysis to estimate how an investment strategy affects the future performance and funding needs of the assets is challenging because each asset component performs differently. Funding analysis relies on condition assessment and performance modeling. Assessing the impact of an investment strategy on the asset network condition implies monitoring changes in performance measures over time.

Alternative Analysis

Program analysis implies studying different alternatives that may be feasible for implementation. Analytical tools are developed to assist agencies in evaluating the implications of different investment scenarios and work plan strategies. A "What if analysis" is usually performed to assess the impact of alternative management decisions. This type of analysis is difficult, if not impossible, without the assistance of analytical tools. Analytical tools to assist evaluating alternative decisions may involve database query, life-cycle costing, benefit/cost analysis, optimization, simulation, risk analysis, and other methodologies. Decision-support tools to assist an agency's personnel in identifying needs and comparing investment alternatives are essential in the asset management process *(29)*.

Program Optimization

The available budget is allocated among a subset of projects requiring funds. Decisions are made on how to allocate limited funds to new construction, rehabilitation, maintenance, and rehabilitation projects. The aim is to optimize the use of funds invested by selecting the best overall group of projects from among all of these funding categories *(29)*.

Program Development

Project selection criteria should be established to choose the best group of projects. Having criteria for project selection implies having methods of identifying both short and long term affects expected from projects. Methods to prioritize work activities and select projects are based on economic techniques, but social and political factors should also be considered in the criteria. A final list of projects is developed for the asset management program. The asset management program not only lists selected projects but also needs to lay out the strategy in detail which involves knowledge on how the agency's resources will be used, what actions will be taken, and when they should be taken *(29)*.

Program Implementation

Program implementation involves implementing the work program developed by the agency. A detailed analysis for each individual project included in the work program is needed. Technical details to complete the design and develop plans are required for each project including specific location, the type of action to be undertaken, and cost. Timing for scheduling the projects becomes more important to avoid conflicts and make effective use of allocated funds and resources.

Performance Monitoring

Monitoring the asset performance over the planning horizon serves to assess whether the desired level of service is being accomplished or not. Performance monitoring requires tracking performance over time which allows the agency to detect changes in the asset condition and to take timely corrective actions if needed. The desired level of service targeted by the agency may also be adjusted based on results from implementation.

Feedback

Feedback is an essential activity to maximize the agency's benefits from an asset management system. The asset management system should be capable of incorporating lessons learned from monitoring the on-going process. Goals, objectives, and the agency's policies may be adjusted based on feedback from implementation. However, care should be taken before modifying core components of the system. Frequent modifications can damage its credibility. Major modifications to the system; including changes in database requirements, prediction models, economic analysis techniques, and reporting tools; deserve careful evaluation since they will affect cost estimates. Minor changes that simplify the flow of information in the process are preferred. Particularly preferred are those changes that provide better means of accomplishing the agency's objectives without disturbing on-going activities.

3.4.2 Benefits of Implementing Asset Management Systems

There are several benefits of implementing an asset management system. Some of the agency's functional areas benefited by an asset management system include communications, asset inventory, network performance, management tools, budget process, and staff development *(25)*.

In the communication area, benefits are reflected in having better channels for communicating agency's goals and objectives and encouraging the implementation of asset management procedures across different management levels. Since the decision support tools used by asset management systems are data driven, the agency's personnel can more easily access quality information to make better informed decisions *(25)*.

In the data inventory area, an asset management system usually improves the quality, consistency, and robustness of the inventory database. Due to advances in technology, extended capabilities in data collection, storage, management, analysis, and reporting can be added to existing systems improving the flow of information in the agency.

More quantitative information will be available to decision makers to make better informed decisions *(25)*.

In the network performance area, benefits derive from having better means to relate performance measures to the agency's goals and objectives. This benefit should be reflected in the use of more comprehensive quantitative reports that provide information to the agency's personnel on how well the investment strategy is serving to accomplish the agency's target objectives *(25)*.

In the management tools area, an asset management system provides up-to-date accurate information about the assets owned by the agency, and it enables the implementation of tools that facilitate the analysis of investment alternatives, contributing toward a better link between the agency's target objectives and funding needs. It also facilitates the agency comparing the effect of different funding scenarios, and allows the prioritization of investments based on engineering practices and business management principles *(25)*.

In the budget area, benefits are expected by improving the efficiency of the funding allocation process. Asset management systems enable the use of accounting concepts and provide more quantitative information to decision makers. Another benefit comes from having business-oriented reports that help not only to make better informed decisions but also to communicate the budget needs to financing authorities *(25)*.

Although several benefits due to the implementation of an asset management system are clearly recognized, at present a formal methodology to quantify these benefits has not been developed. The major difficulty in measuring these benefits comes from the involvement of multi-disciplinary fields in the asset management process. Trade-offs among asset categories are hard to compare by the agencies. The development of metrics for asset management practices is an area of research that deserves attention in the near future *(25)*.

3.5 GEOGRAPHIC INFORMATION SYSTEMS

Data integration is a key element in improving asset management systems by making the most effective use of available resources and providing reliable information on the physical, financial, equipment, materials, and personnel assets managed by an agency. The process of integrating data in a decision support system requires a solid foundation built upon reliable asset records. These asset records should be easily accessed by the users of the asset management system *(29)*.

A Geographic Information System (GIS) is a powerful tool to manage and analyze data referenced to a geographic location. GIS can be used to integrate geographic and tabular data, and to retrieve relevant information in a rapid and effective manner. Information about pavement network sections and other infrastructure assets can be stored in textual databases linked by location and attribute in geographic maps. Due to these capabilities, GIS can serve as a common platform for an integrated asset management system in order to interconnect individual management systems used by the agency *(31)*. Figure 14 shows the concept of an integrated asset management system using GIS as a common platform.

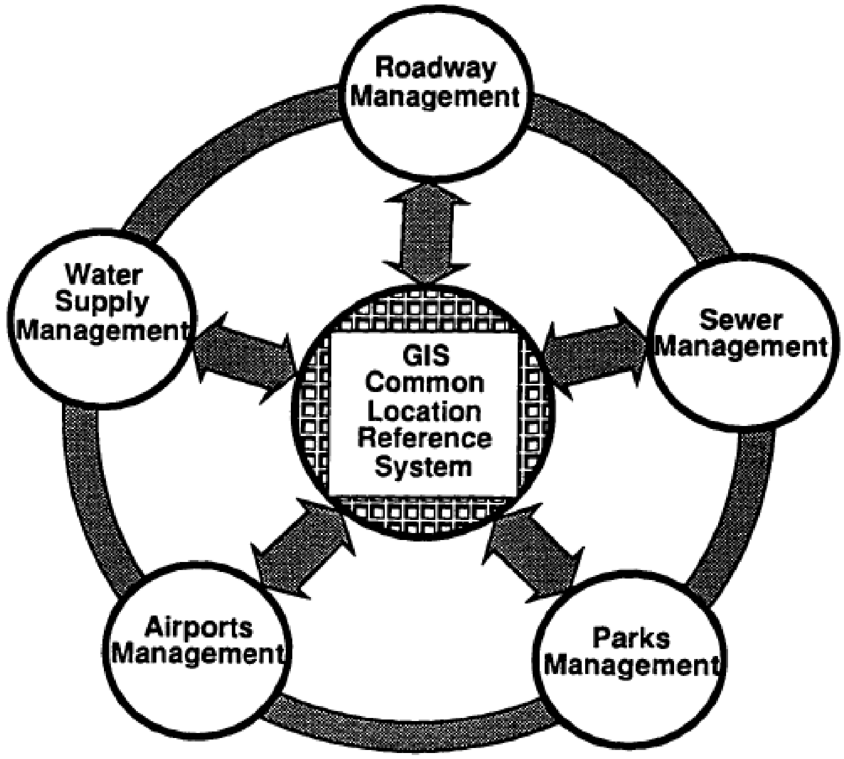

FIGURE 14 Integrated asset management system using GIS *(31)*.

3.5.1 Components of a Geographic Information System

A Geographic Information System (GIS) is defined as "a system of computer hardware, software, personnel, organization, and business processes designed to support the capture, management, manipulation, analysis, and display of spatially referenced data for solving complex planning and management problems" *(32)*.

GIS should be considered a tool to integrate spatial data into an asset management system. Three basic GIS components are identified as *(31)*:

- Database management system (DBMS)

- Conceptual models to integrate spatial analysis functions
- Visual interface to display maps, reports, and plans

Database Management System (DBMS)

The database management system (DBMS) enhances a set of programs that manipulate the database attributes and geometric objects. The database is the central component of the system, and the DBMS uses geo-references for indexing information and manipulating spatial relationships among features stored in the database. DBMS preserves data integrity to ensure consistency and correctness of data by coordinating data accessing and updating. DBMS also supports data validation to check that data values input into the database match the types and formats of corresponding data fields defined in the database architecture. Finally, DBMS should protect the database from unauthorized intrusion and accidental or malicious alteration of data stored in the database *(31)*.

Conceptual Models to Integrate Spatial Analysis Functions

Spatial analysis functions in data groups or layers used to visually analyze relationships between spatial entities become powerful tools in GIS. These tools differentiate GIS from computer assisted mapping tools. Relationships among spatial entities are handled by conceptual models *(33).* Since assets owned by the agency are geographically related to each other, GIS can support proximity analysis. Proximity analysis helps the agency to coordinate and schedule work activities among infrastructure assets in a more efficient manner by analyzing spatial relationships. Spatial models used in GIS applications provide the generic framework for conducting the analysis and are flexible enough to incorporate local conditions into the process without changing the structure of the model *(31)*.

Visual Interface

The visual interface allows display of theme maps with the results of computational analysis or queries conducted by the user. Complex relationships that may not be obvious in tabular form may be visualized in theme maps *(31)*.

The GIS components can not be considered as independent components from an asset management system. In fact, when GIS is integrated with an asset management system, the term Visual Asset Management System (VAMS) becomes more appropriate. A VAMS handles a wide variety of data and information visually, analyzes data spatially, and presents the results of the analysis graphically (*31*). Figure 15 shows the major functional components of a VAMS.

Compared to a non visual asset management system, a VAMS contains a geographical database to store spatial and descriptive data in addition to tabular data. This georelational database is organized in such a manner that facilitates storage and retrieval of physical geographic elements. The geographical database is supported by an attribute database. The attribute database stores and retrieves tabular data. This dataset of attributes can be in the geographic dataset or in a separate component which functions as a relational database. Spatial analysis functions used for performing computations are integrated into the model base component. A multimedia server can be also integrated into the VAMS to combine static media with dynamic media resources giving the system another dimension for data display *(31)*.

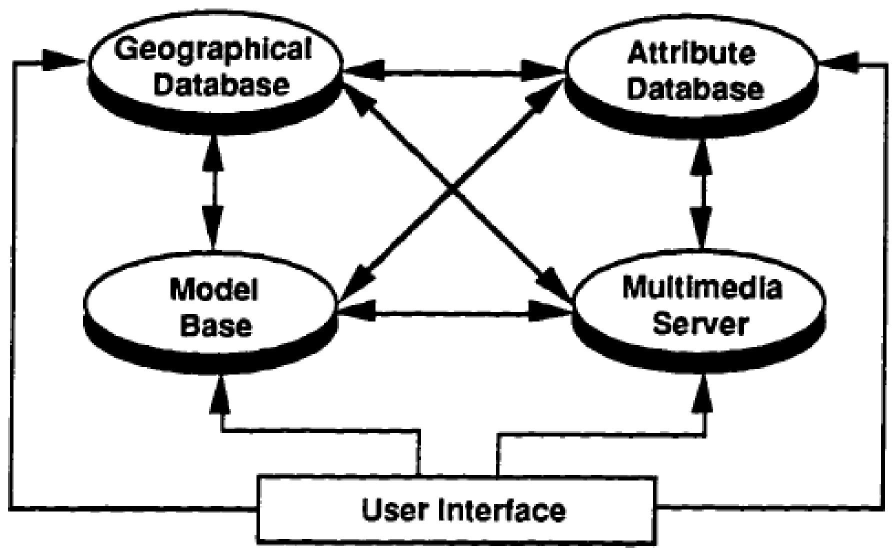

FIGURE 15 Major functional components of a visual asset management system (*31*).

3.5.2 Benefits of Implementing a Geographic Information System

There are several benefits of implementing a Geographic Information System (GIS) in an infrastructure management system. From an overall perspective, the major benefit of implementing a GIS is providing a common platform for data integration. "Data integration is the process of combining or linking two or more data sets from different sources to facilitate data sharing, promote effective data gathering and analysis, and support overall information management activities in an organization" *(32)*. If data are not integrated, the objectives and benefits of an asset management approach are not fully achieved.

From a manager's perspective, the integration of individual infrastructure management systems into an overall asset management system using GIS as a common platform brings several benefits. This data integration will allow agency personnel from different divisions to share information about their projects and avoid potential conflicts. Data integration requires the implementation of virtual time interface response and functional standards of user interfaces *(34, 35)*.

From a practitioner's perspective, the major benefit of a GIS is to serve as an analytical tool to perform queries and to visualize the results on theme maps. Theme maps are generated by the system to display information already stored in the database or to visualize query results. Technology advances in User Interface Management Systems (UIMS), User Interface Development Systems (UIDS), and User Inter-face Toolkit methodologies open new frontiers for asset management system from which agencies can benefit *(36)*.

In pavement management practices, GIS provides decision makers with better tools to manipulate data and to visualize the information. The capability of a GIS for generating theme maps to visualize information provides great flexibility and versatility to the system. "What if" theme maps can be generated to visualize the results from impact analysis. These theme maps are useful to evaluate the effects of alternative investment strategies on selected pavement network parameters. Theme maps facilitate agencies in communicating their funding needs and supporting budget requests for pavement maintenance and reconstruction programs.

3.6 KNOWLEDGE MANAGEMENT SYSTEMS

Pavement management practices are intended to assist agencies in the decision making process of allocating funds among pavement assets. Lessons learned from decisions made in the past are vital to improve existing pavement management practices. Gathering knowledge is certainly not a one-time task, and demands a constant effort. To sustain this effort a comprehensive approach based on knowledge elements is needed.

Knowledge is required at different phases of the pavement management process. Knowledge is needed for but not limited to interpreting data, predicting pavement performance, estimating funding needs over the planning horizon, selecting effective pavement treatments, prioritizing investments in pavement sections when funds are constrained, evaluating pavement maintenance and rehabilitation strategies, and managing political and social influence on investment decisions.

Knowledge management systems are defined as the integration of technologies and mechanisms to support knowledge management processes that help in discovering, capturing, sharing, and applying knowledge. In simple terms, knowledge management can be defined "as doing what is needed to get the most out of knowledge resources" *(37)*.

To be more explicit about what knowledge management involves, the following explanation applies: "knowledge management includes all the methods, instruments and tools that contribute to the promotion of integrated core knowledge process – with the following four core activities as a minimum to generate knowledge, to store knowledge, to distribute knowledge and to apply knowledge – in all areas and levels of the organization in order to enhance organizational performance by focusing on the value creating business processes" *(38)*.

3.6.1 The Nature of Knowledge

The complexity of knowledge management is compounded because optimal mechanisms for acquiring knowledge are related to the nature of knowledge. Tacit and explicit knowledge are the two primary categories of knowledge, as identified and supported by Polanyi in 1967 *(39)*, Nonaka in 1991 *(40)*, Koulopoulos and Frappaolo in 1999 *(41)*, Tiwana in 2000 *(42)*, and Gamble and Blackwell in 2001 *(43)*.

Tacit and explicit knowledge are different in nature, and only by understanding their nature, components, and differences is it possible to select or develop the right tools to capture and transfer knowledge efficiently *(39)*.

Tacit Knowledge

Tacit knowledge resides in the minds of people. The acquisition of tacit knowledge is usually developed through a process of trial and error during practical experience. This is the reason why tacit knowledge is so difficult to articulate, formalize, and encode. If knowledge gained from practice remains only in the minds of people who had the experiences, then this knowledge is lost when the experienced employees retire or change employment. To turn personal knowledge into corporate knowledge, subjective tacit knowledge must be externalized to an explicit form of representation. Once the knowledge is externalized, it is easier to move across communication networks *(39)*.

Knowledge that comes from experiences accumulated by a field engineer over the years is an example of tacit knowledge. The lessons learned by this engineer are not written in any book or manual and will be usually transferred to other engineers by mentoring.

Explicit Knowledge

Explicit knowledge is formal knowledge or information. The acquisition of explicit knowledge is usually achieved by formal study through some type of educational process. Since explicit knowledge can be articulated in formal language, it is much easier to convey and capture than tacit knowledge. An example of explicit knowledge is knowledge that is found in manuals, books, articles, and any other written documents *(39)*.

3.6.2 Background of Knowledge Management

The growing importance of managing organizational or corporate knowledge was emphasized in Massachusetts Institute of Technology (MIT) and Carnegie Mellon research in the 1970s. However, these efforts were oriented toward the development of automated machine processes and artificial intelligence rather than toward integrating human resources as a unifying corporate goal. In the 1990s, the idea of better utilizing human resource knowledge began to be considered as a new organizational approach. Only now, in the 2000s, has the ability to deploy and exploit knowledge been recognized as being crucial to corporate survival *(44)*.

What is defined as knowledge management today has emerged from diverse disciplines over at least three decades. Some of the disciplines having the most profound effect on the development of knowledge management concepts are organizational science and human resource management, computer science and management information systems, management science, psychology, and sociology. This diverse legacy has resulted in various approaches to knowledge management, but there is no unique, universally accepted method of implementing knowledge management. The historical development of knowledge management from isolated data applications before the 1970s through the late-1990s is shown in Figure 16 *(44)*.

Before the 1970s, at the beginning of information technology (IT) development, no special attention was given to data management. The first step in the historical development of knowledge management started with technical integration of isolated data with the implementation of database management systems (DBMS) in the mid-1970s. The second stage, in the mid-1980s, involved conceptual data integration, data modeling, and data handling. The need for enterprise-wide horizontal integration led to very large database systems (DBS) in the late 1980s. This step is considered the third stage in the historical development of knowledge management. In the 1990s, information was considered as a production factor and object oriented database management systems (OODBMS) were implemented for data warehousing, data mining, and document management. This advance is considered the fourth stage in the evolution. Finally, knowledge management emerged as a business approach in the late-1990s with new technological tools including information and communication technology (ICT), knowledge management systems (KMS), customer relation management (CRM), web portals supported by "intelligent technologies," and a new model to structure data called extensible markup language (XML) *(44)*.

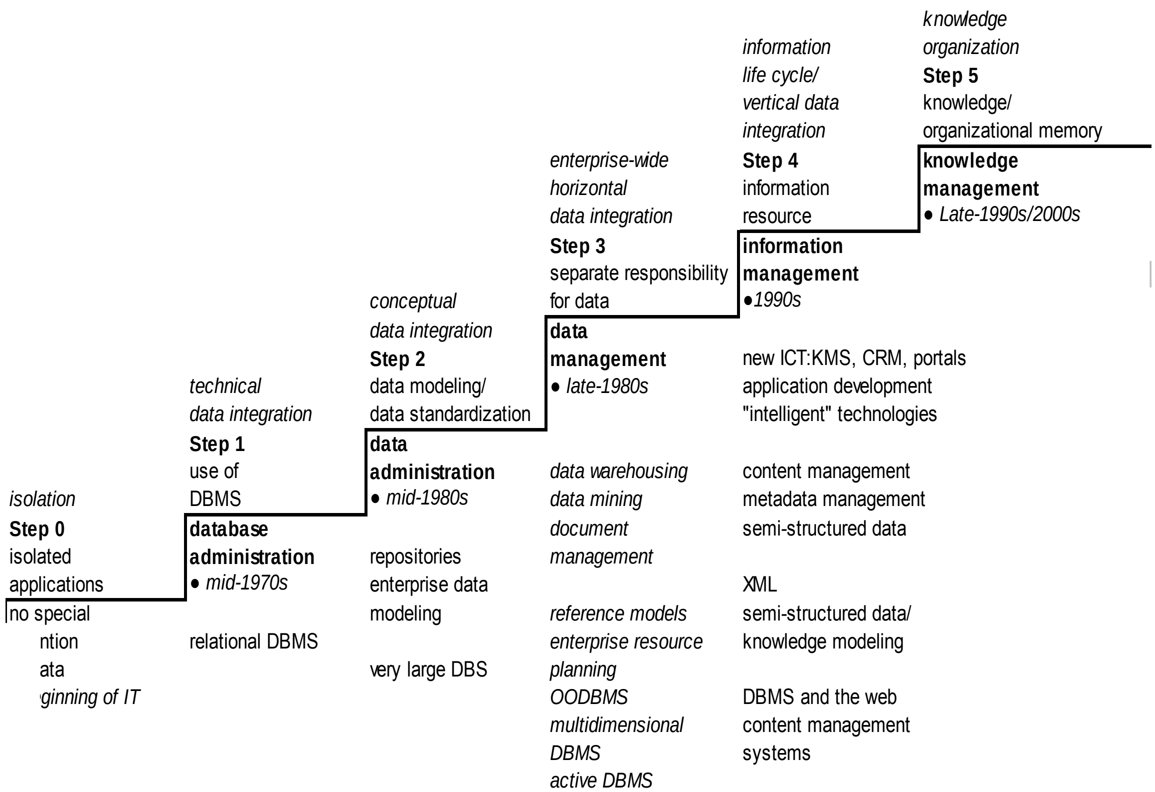

FIGURE 16 Historical development of knowledge management *(after reference 44).*

3.6.3. Recent Knowledge Management Approaches

In the 2000s there are three approaches that can be considered the state of the art in knowledge management. They are the “Promote Methodology” developed by Hinkelman *(45)*, the “Business Process-Oriented Knowledge Management Method” developed by the Fraunhofer Institute for Production Systems and Design Technology *(38)*, and the “Ten-Step Knowledge Management Roadmap” developed by Amrit Tiwana *(42)*. A description of these three knowledge management approaches follows.

PROMOTE Methodology

Hinkelman et al. proposed in 2002 a method and a software tool to model business and knowledge processes *(45)*. This approach distinguishes five phases for the introduction of knowledge management: becoming aware of enterprise knowledge, discovering knowledge processes, modeling knowledge processes and organizational modeling, making knowledge processes and organizational modeling operational, and evaluating enterprise knowledge. The objective of this approach is to identify the kind of knowledge and knowledge flow during the business processes. As a result, knowledge-intensive tasks within the business processes are clearly identified.

Business Process-Oriented Knowledge Management Model Method

This approach was proposed by the Fraunhofer Institute for Production Systems and Design Technology in 2002. Their aim was to integrate the activities of the people involved in the processes with supporting information tools *(38)*. The method consists of a knowledge management implementation model, a knowledge management audit, a knowledge management analysis of the business process, and knowledge management best practices organized in building blocks.

To analyze the business process, this approach considers a knowledge supply cycle. The knowledge supply cycle consists of four phases: generate, store, distribute, and apply knowledge. This cycle is used in businesses activities to create awareness of the knowledge inherent in daily tasks and processes *(38)*. An overall vision of the knowledge supply cycle is presented in Figure 17.

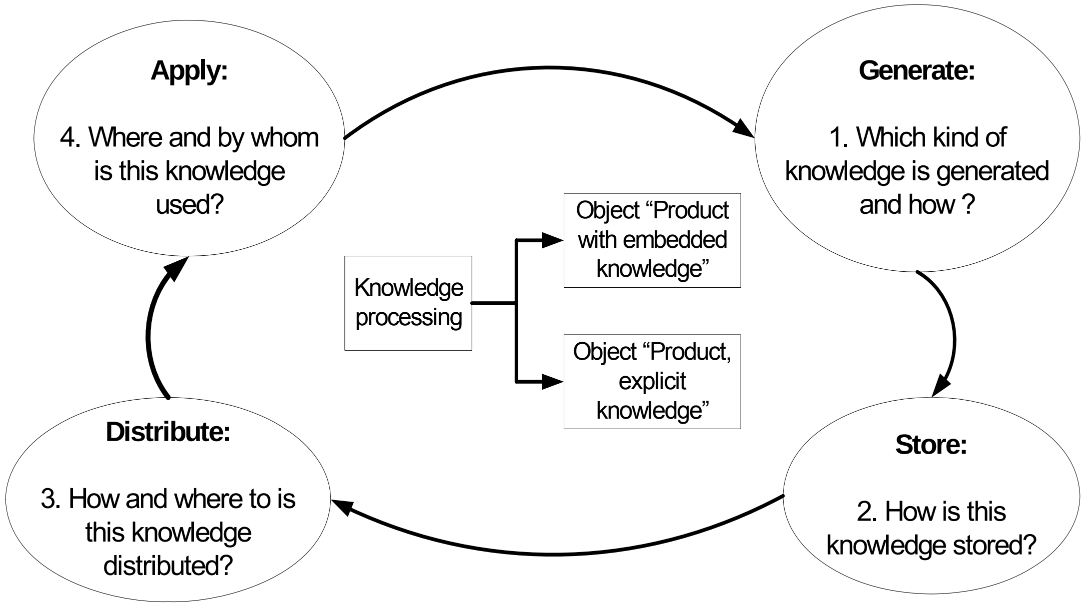

FIGURE 17 Knowledge management supply cycle *(38).*

The method of Integrated Enterprise Modeling (IEM) is used by this approach to describe, analyze, and design the knowledge management process. IEM considers three object classes: order, product, and resource. A generic activity model is built by combining these three objects *(38)*. The IEM generic knowledge management model is shown in Figure 18.

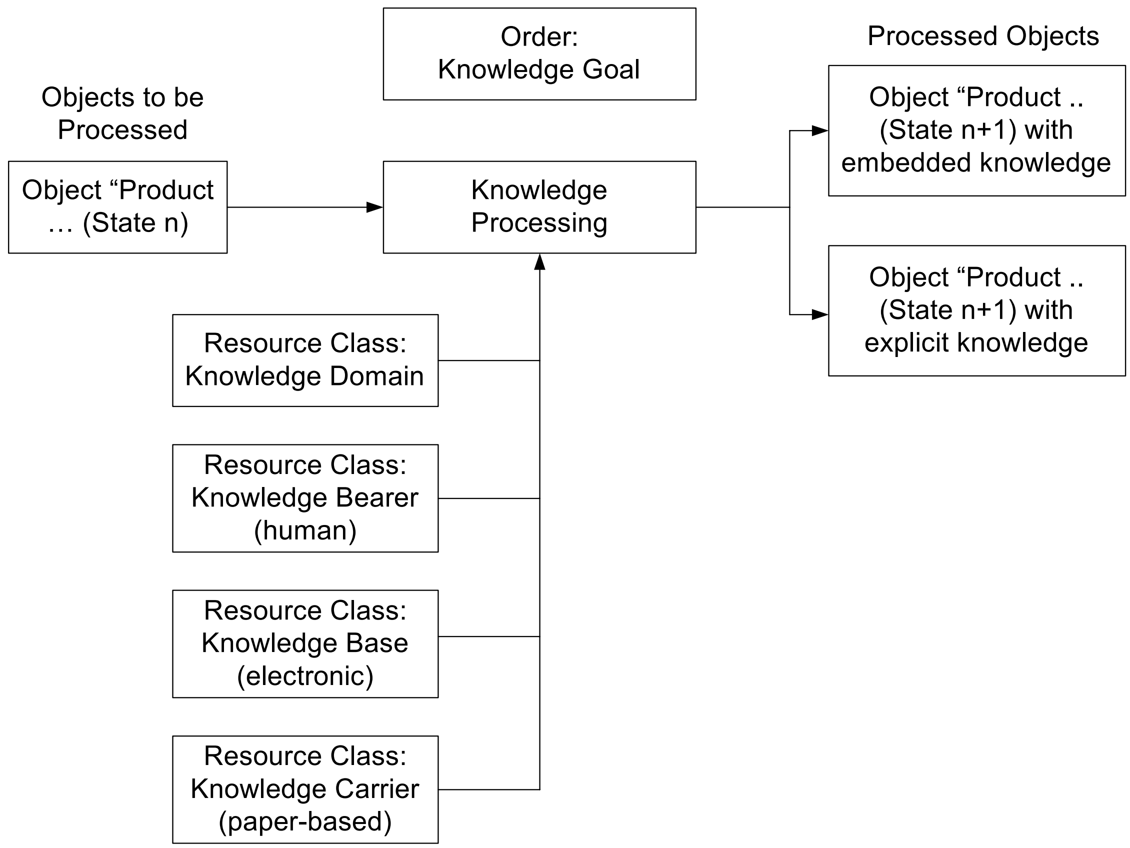

FIGURE 18 IEM generic activity model for knowledge management *(38).*

The knowledge goal set by the agency represents the order object; the objects to be processed and processed objects represent the product objects; and the resource objects are composed of the knowledge domain, knowledge bearer, knowledge base, and knowledge carrier.

Ten-Step Knowledge Management Roadmap

In 2000, Amrit Tiwana presented a methodology to develop a knowledge management strategy and a companion knowledge management system to support this approach. The ten steps are organized in four phases *(42)*. The first phase corresponds to an infrastructural evaluation. The second phase of knowledge management implementation involves analysis, design, and development of the system. The third phase involves the deployment. Finally, the fourth phase is the implementation of methods to measure the business value of knowledge management. Figure 19 shows the ten-step roadmap and phases proposed by Tiwana.

The first phase, infrastructural evaluation, is composed of two steps. First, an analysis of the existing infrastructure is conducted. The purpose of this first step is to identify critical gaps to correct them and to be able to build on what already exists. Second, knowledge management is aligned to the business strategy by connecting the knowledge management system platform to strategic plans *(42)*.

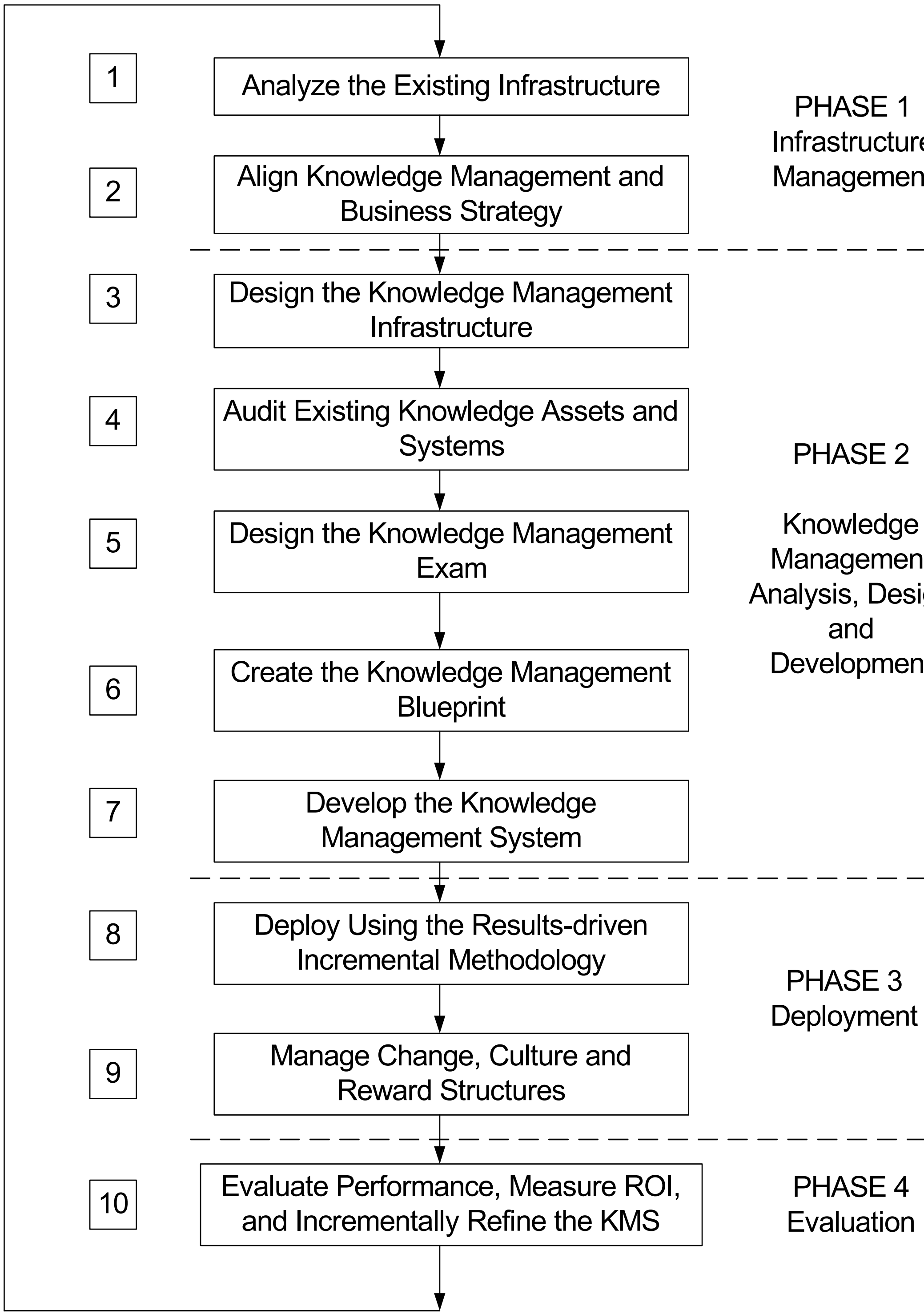

FIGURE 19 Knowledge management roadmap *(42).*

The second phase, knowledge management implementation, is composed of five steps. First, the knowledge management architecture design and component design is selected. Second, a knowledge audit analysis is conducted to identify strengths and weaknesses. Third, the knowledge management team that will design, build, implement, and deploy the system is formed. Fourth, the knowledge management team develops the blueprint that provides a plan for building and improving the knowledge management system. Fifth, the working management system is developed *(42)*.

The third phase, deployment, is composed of two steps. The first step is testing and deployment using a results-driven incremental technique. The second step involves leadership and the implementation of a reward structure to encourage employees to use the system *(42)*.

The fourth phase, metrics for evaluation, is a one-step phase that involves the selection of a set of metrics to monitor the knowledge management process *(42)*.

3.6.4 Components of a Knowledge Management System

Due to the combination of factors and extent of the approach, it is hard to list the components of a knowledge management system explicitly. However, the components can be identified by the knowledge process that they support. Some components may share a common mechanism or technology *(37)*.

The entire knowledge management system can be visualized as being composed of four primary components which are integrated under one common framework. The four components are: knowledge discovery, knowledge capture, knowledge sharing, and knowledge application. These components are shown in Figure 20 *(37)*.

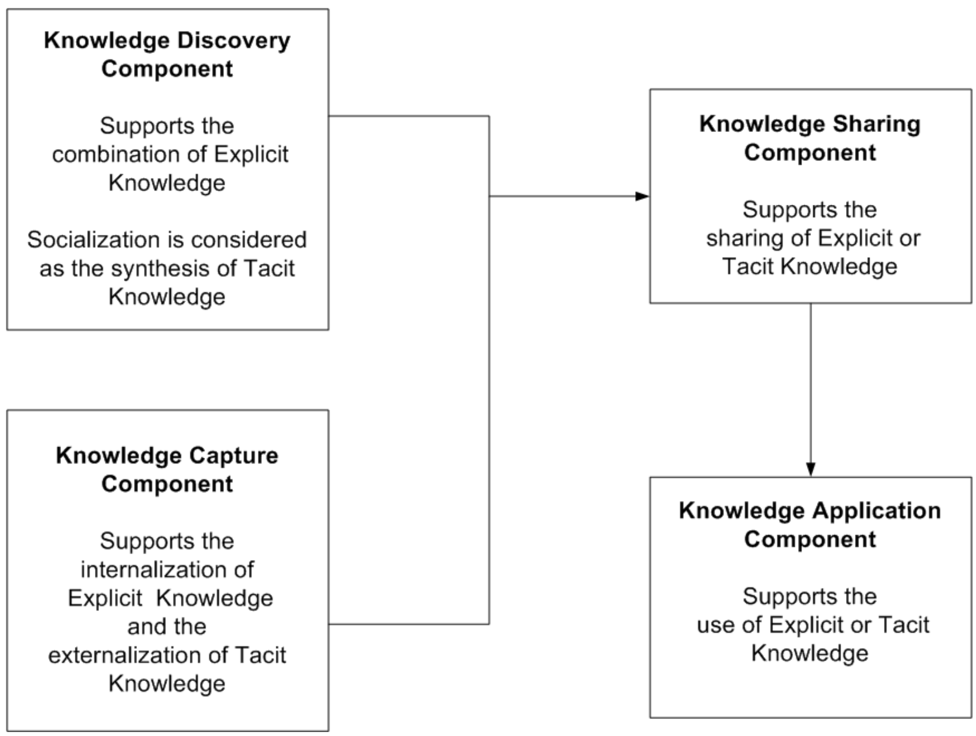

FIGURE 20 Knowledge management system components *(after reference 37).*

Some knowledge management systems are focused on only one knowledge process, even though the four knowledge processes should be addressed in some manner to fully implement a knowledge management system *(37)*.

Knowledge discovery supports knowledge creation by combining existing sources of explicit knowledge or by enabling the formation of new tacit knowledge through socialization. Mechanisms used to foster knowledge creation include meetings, conference calls, telephone conversations, cooperative team work, and employee rotation. Among the technologies available for knowledge discovery are web access to knowledge databases, electronic mail communication, peer network, and video conference *(37)*.

Knowledge capture supports knowledge retrieval from people or from organizational entities. Lessons learned records, mentoring programs, face to face meetings, and computer-based models are some of the mechanisms used to capture knowledge. Knowledge technologies for capturing knowledge involve chat groups, best practices and lessons learned databases, expert based systems, computer-based simulations, and artificial intelligence *(37)*.

Knowledge sharing assists in communicating knowledge. Sharing knowledge implies that the receiver understands the knowledge well enough to apply it and solve problems. Mechanisms to support knowledge sharing are similar to the other systems. Technologies are well-developed in this area with emphasis in the use of web-based systems to gain access to best practice databases, lessons learned records, and expertise locator systems *(37)*.

Knowledge application assists individuals in utilizing knowledge. Some of the mechanisms used to support knowledge application are organizational policies, standards, work practices, and support centers. Technologies vary from expert systems, case-based reasoning systems, and decision support systems to simple directions or instructions or a webpage containing frequently asked questions with appropriate answers *(37)*.

3.6.5 Benefits of Implementing a Knowledge Management System (KMS)

The stronger the relationship between an agency's goals and a knowledge management system is, the greater the benefits. According to previous experiences, benefits can be achieved in improving employee performance and increasing level of satisfaction which leads to an overall improvement of the agency's performance both directly and indirectly *(37, 42)*. Table 7 summarizes the benefits due to the relationship between agency's goals and the implementation of a knowledge management system.

Direct benefits in revenues or costs are expected and translated into a higher return for the investments made. Indirect benefits from implementing a knowledge management system come from strengthening of existing communities of practice, improving access to corporate information, and facilitating the discover and capture of new knowledge. Competitive advantage is also mentioned as an indirect benefit. To achieve these benefits, knowledge management systems should support organizational growth through on-going improvement of existing organizational processes in three major areas: effectiveness, efficiency, and degree of innovation. *(37)*.

TABLE 7 Relationship between Agency's Goals and Benefits for Implementing a Knowledge Management System *(after reference 46)*

Agency's Goal	Benefits of Implementing a Knowledge Management System (KMS)
Strengthened Community of Practice	KMS encourages the community to function as a team when unique challenges occur
	KMS increases recognition of the community of practice as a functioning team
	KMS facilitates improved communications among team members and throughout agency
	KMS offers improved procedure for review of draft documents
	KMS facilitates locating technical expertise
	KMS promotes mentoring by senior members
	KMS expedites learning of junior members
Improved Information Accessibility	KMS facilitate precise information retrieval
	Specific location provided for any agency employee to seek highly technical assistance
	Ready access to best tools
	Ready access to best information resources available
	KMS facilitates locating technical expertise
On-Going Capture of New Knowledge and Resources	Specific locations provided for new knowledge capture and unique experience documentation
	User evaluation of information is basis for retaining it within the KMS
	Specific locations provided for supporting active teams
	Periodic review and update of materials maintain information currency
	Plan for annual interview selections for on-going capture of tacit knowledge

3.7 DECISION SUPPORT TOOLS AS MAJOR COMPONENTS OF AN INTEGRATED SYSTEM TO SUPPORT STRATEGIC MANAGEMENT

Pavement management systems, asset management systems, geographic information systems, and knowledge management systems are decision support tools used to assist decision makers in making better informed decisions. Agencies may use these systems as stand alone decision support tools and benefit from their usage, but to get the most benefit from these tools they should be used in an orchestrated manner functioning as major components of an integrated overall decision support system.

Pavement management systems deal with only one of many infrastructure assets managed by an agency. In a local agency, infrastructure assets may include, but are not limited to, pavements, water supply, waste water, solid waste facilities, public buildings, public housing, and recreational facilities. At the strategic management level, investment decisions are made with the target of obtaining the best return from funds allocated among infrastructure assets. To achieve this target, decision makers need to manage infrastructure components in an orchestrated manner requiring the assistance of asset management systems to support asset management processes *(27)*.

"Good asset management implies a systematic, integrated approach to project selection, analysis of tradeoffs, and program and budget decisions. It also implies that the right information be available to the right levels of management at the right times" *(27)*. To provide the right information to the right level of management at the right time, methods for data integration are crucial *(47)*.

Data integration is defined as "the process of combining or linking two or more data sets from different sources to facilitate data sharing, promote effective data gathering and analysis, and support overall information management activities in an organization" *(47).* Many transportation agencies have developed databases for managing their assets, but they are not necessarily working in a common framework. Reference systems are used by database management systems to relate information stored in separate locations *(47).*

A Geographic Information System (GIS) can provide the physical framework required to connect independent databases based on a common location reference system. "The location reference system allows not only the integration of spatially referenced data but also the mapping and analysis of information using geographic information systems (GIS) software" *(47).* "Geographic Information Systems (GIS), which uses a coordinate system to define the location of features in a network, has proven to be the most effective computerized common location reference system. In fact, many transportation and public works agencies have already adopted GIS as their location reference systems" *(31).* The use of GIS as a major component of an integrated overall decision support system allows decision makers access and use of information from a number of databases through a visual interface. Querying and reporting tools provided by GIS combined with spatial analysis techniques facilitate data interpretation by decision makers *(47).*

Information provided by decision support systems is meaningless to decision makers without interpretation within the context of the decision situation. Knowledge is required to interpret data and make effective use of available information provided by decision support systems. There is a sequence necessary for data to become knowledge. Dr. Hossein Arsham from the University of Baltimore states that "the sequence from data to knowledge is: from

Data to Information, from Information to Facts, and finally, from Facts to Knowledge" *(4)*. "Data becomes information, when it becomes relevant to your decision problem. Information becomes a fact, when data can support it. Facts are what data reveals" *(4)*. "Fact becomes knowledge, when it is used in the successful completion of a decision process" *(4)*.

The need for applying knowledge through the decision making process involves interpreting information provided by decision support systems using personal or organization insights and experience *(48)*. As the level of experience and expertise increases, the chances of making sound decisions due to the effective use of knowledge also increase. The complexity and interdisciplinary nature of management along with the speed of technological advances makes it almost infeasible for one person to possess all the knowledge required to ponder and interpret available information, thus the assistance of decision support tools developed for managing knowledge is required *(37)*.

Knowledge management systems are developed to face the challenge of making efficient use of resources available to the agency. Getting the most of these resources by turning knowledge into effective actions is the goal of knowledge management systems. Knowledge management systems can play a key role in the integration, application, and management of knowledge *(42)*.

The integration of knowledge management systems with traditional decision support tools involves a change in the agency's culture which should start at the strategic management level. The key to success in developing a system that takes advantages of the strengths of individual decision support tools resides in the ability to align strategies with the agency knowledge culture (*49*). Figure 21 shows this strategy-knowledge link.

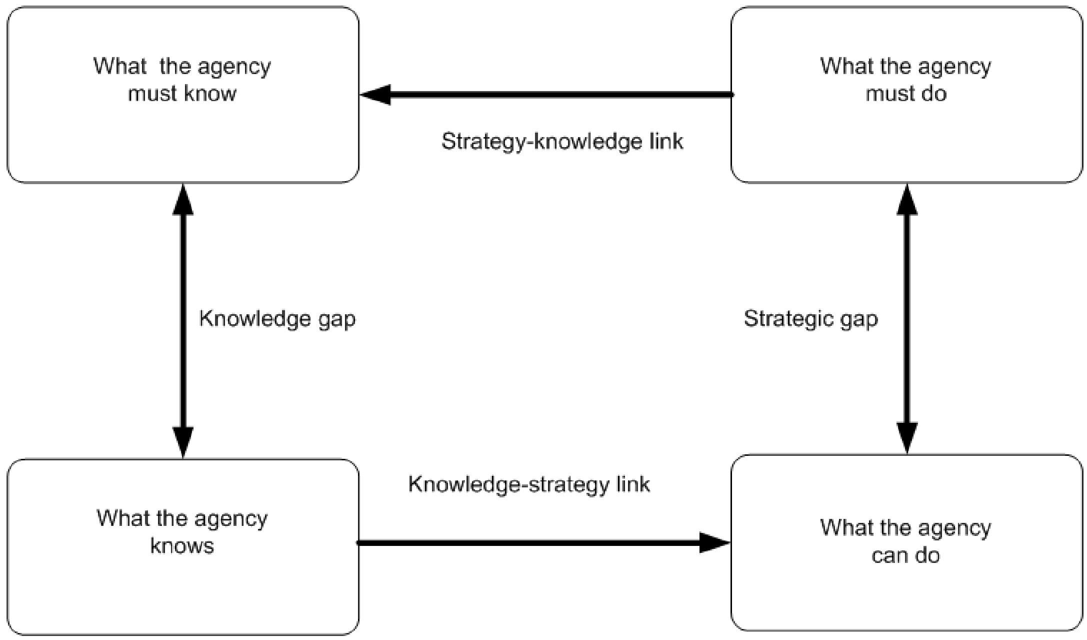

FIGURE 21 Agency's strategy-knowledge link *(after reference 49).*

Many times strategic goals involve the agency's desire for achieving multiple objectives. While managing infrastructure assets, the agency deals with complex issues due to the particular characteristics and performance behavior of each individual infrastructure component. There may be a gap between "what the agency must do" and "what the agency can do" to achieve its target objectives. To assess what an agency can do there is a need for a knowledge-strategy link based on "what your agency knows". However, there may also be a gap between "what the agency knows" and "what the agency must know" to meet its target objectives. Therefore, there must be a strategy-knowledge link between "what the agency must do" and "what the agency must know" *(49)*. This reasoning leads to consideration of the integration of knowledge management systems with traditional decision support tools that have been typically used in infrastructure management. Figure 22 shows my vision of an overall framework for an integrated system to support strategic management.

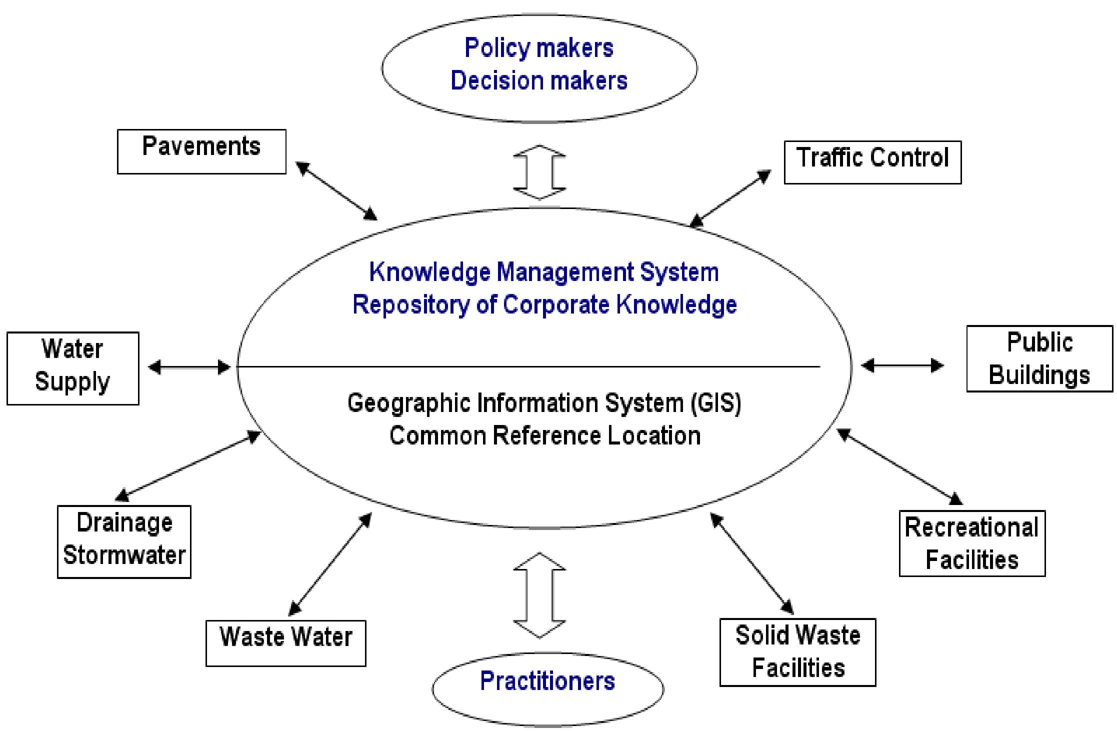

FIGURE 22 Overall framework for an integrated system to support strategic management.

The knowledge management system can serve as a repository of corporate knowledge about the infrastructure assets owned by the agency. Policy makers and decision makers may act as "moderators" of the knowledge stored in the knowledge database, while practitioners can interact through the integrated system and share knowledge.

An integrated system that incorporates knowledge management tools to better support strategic management may be seen as a holistic model which is difficult to visualize. Knowledge is embedded in the management process itself. The model described here for an integrated system must be customized for each particular agency. The development of a customized system requires specific knowledge about the agency size, management objectives, resources available, and types of assets being managed. Developing the integrated system for large organizations such as a state department of transportation or a regional transportation planning agency will differ from an integrated system for local agencies where resources are more limited.

Most agencies, including local agencies, have adopted pavement management systems and integrated GIS to serve as a common location reference system *(47)*. Many agencies have implemented asset management principles for managing their assets. Standards such as the Governmental Accounting Standards Board (GASB) Statement 34 (GASB 34), which was promulgated on June 15, 1999, "calls for state, local, and municipal governments to calculate the original cost of infrastructure constructed or improved during the 20-year period prior to the Statement's issuance date in their annual financial reports" *(14)*. The aim of GASB 34 is to improve the way financial information on infrastructure assets is reported by the state and local governments to facilitate funding requests and also to keep the public better informed about infrastructure issues of concern to them *(50)*.

GASB 34 distinguishes large, medium, and small size governments by their annual revenues. Governments with annual revenues above US$ 100 million are classified as large size governments and were required to begin reporting all major infrastructure acquired, renovated, or improved after June 30, 1990, for years following June 15, 2005. Governments with annual revenues from $ 10 million up to $ 100 million are classified as medium size governments, and they had until 2006 to satisfy reporting requirements. For small size governments, with annual revenues below $ 10 million, reporting requirements are optional *(14)*.

The use of knowledge management systems has occurred in diverse areas of expertise. The use of formal knowledge management systems in transportation agencies is relatively new. Prototype projects for the development and adoption of knowledge management systems have been developed in the last five years by transportation agencies. Pioneers in this area have been the Pennsylvania Department of Transportation (PennDOT), the Virginia Department of Transportation (VDOT), and most recently the Texas Department of Transportation (TxDOT) *(50)*.

PennDOT developed "Fleet Ideas Exchange and Information Technology (FIXIT)" with the objective to extend a communication bridge between equipment managers and technicians. The aim is to create value by transferring best practices, innovations, tips and techniques, policies, and procedures. The FIXIT process uses an Internet-based system to locate, store, and disseminate centralized data through a user-friendly interface *(51)*.

VDOT has implemented a knowledge management office that "collects, organizes, preserves and shares the expertise and institutional knowledge of the agency and its employees to benefit current and future projects" *(52)*. The purpose of this VDOT office is to create and foster internal networks of experts "to promote efficiency and to ensure consistency of best practices throughout the agency" *(52)*.

TxDOT has developed a knowledge management system for managing knowledge about flexible and rigid pavement forensic methods in Texas. Legacy knowledge from experts was captured through an interviewing process. Forensics reports, pavement related-website addresses, books, power point presentations, and other documents related to the topic were also gathered during the research. The knowledge content is stored in the TxDOT intranet system, and it is available to TxDOT's personnel through a friendly portal which has additional features for sharing knowledge such us virtual team rooms and bulletin boards *(53)*.

The Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area, created in 1970 by state legislature, is the transportation planning, coordinating, and financing agency for the nine-county San Francisco Bay Area in California. MTC supports a pavement management program that has been continuously evolving since 1982 *(54)*. MTC's pavement management program encourages the use of StreetSaver® which is a computer-assisted decision-making process designed to help cities and counties address pavement problems *(55)*. A knowledge base is supported by the pavement management program through the implementation of a web-based bulletin board where users can exchange information on different categories within the domain of the software application such as software installation, section description, inspection units, needs and scenarios calculation, project selection, maintenance treatments, and reports *(56)*. In addition to the bulletin board, training sessions on pavement distress field evaluation, software use, program development along with technology transfer seminars, newsletters, and user meetings to exchange information are scheduled on a regular basis *(55)*.

The use of knowledge management tools in transportation agencies has typically focused on specific areas. A holistic model for an integrated system would emphasize the need for systematic use of knowledge to improve existing pavement management practices.

CHAPTER IV

A MULTI-OBJECTIVE STRATEGIC PAVEMENT MANAGEMENT APPROACH FOR LOCAL AGENCIES

An agency's goals for their pavement network may be expressed in terms of target objectives. Generally an agency will have multiple objectives, and typically more than one investment strategy is available to pursue the agency's target objectives. However, most goals focus on achieving the target objectives at the minimum cost. Most approaches used by the agency for allocating funds among pavement assets should identify an investment strategy capable of achieving the agency's multiple target objectives at the minimum cost.

Approaches used by agencies should not be limited to an analytical method to mathematically solve the funding allocation problem. Methods to ensure system sustainability over time and efficiency of the investment strategy should also be considered in the approach. These methods should facilitate the timely flow of knowledge among management levels and should provide the means to provide feedback from practitioners to support adjustments to the strategy along the planning horizon.

This chapter describes a multi-objective strategic pavement management approach for managing a pavement network by a local agency, including the methodology for allocating funds among pavement sections when multiple objectives are set by the agency.

4.1 OVERVIEW OF A MULTI-OBJECTIVE STRATEGIC PAVEMENT MANAGEMENT APPROACH (MOSPMA)

The multi-objective strategic pavement management approach (MOSPMA) is an approach that ties an agency's objectives to pavement performance parameters through the entire management cycle. The management cycle starts by setting objectives aligned with an agency's goals and policies. The pavement network stage is assessed by network performance parameters to determine the level of investments needed to achieve targets. Engineering and economic techniques are used as analysis tools for identifying the best group of candidate sections to maximize treatment effectiveness for funds spent on the network. Future pavement network stages are forecasted using pavement performance models. The network performance parameters are also used to monitor the agency's progress toward achievement of target objectives over time.

Decisions made at any phase of the management cycle affect future network stages and investment needs required to achieve targets. Feedback obtained from monitoring changes in the pavement network parameters allows adjustments in the strategy. By monitoring pavement network performance over time and comparing these results to target objectives, agencies can learn from previous experience and improve existing practices. Figure 23 shows my proposed general overview of the multi-objective strategic pavement management approach through the management cycle.

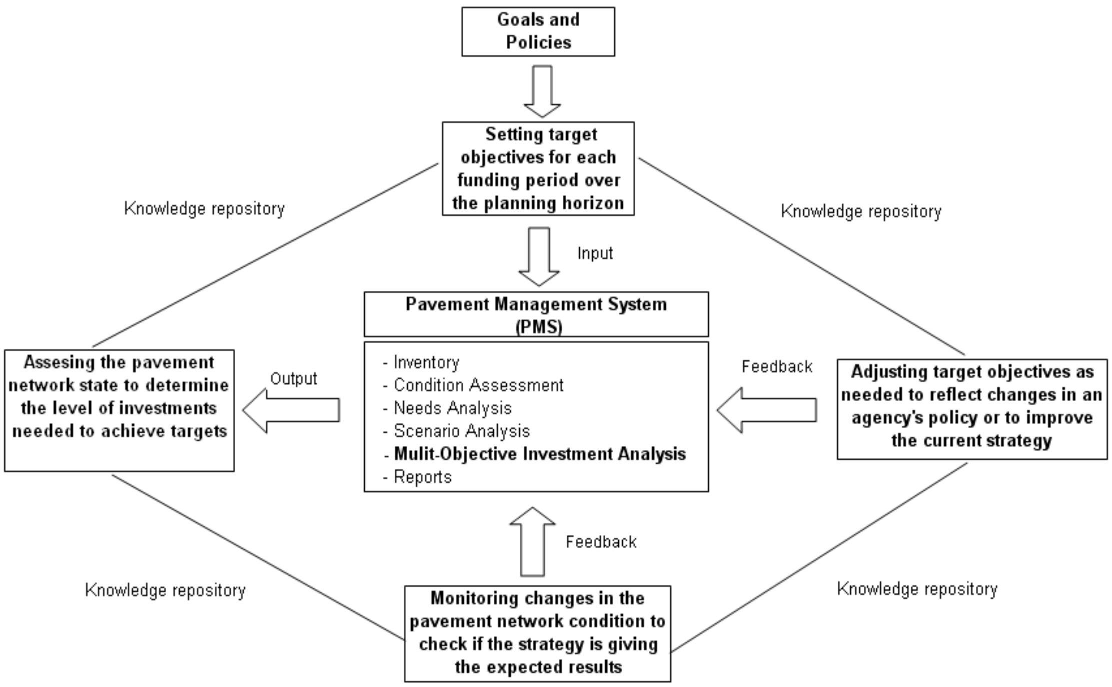

FIGURE 23 General overview of the multi-objective strategic pavement management approach.

Although the management cycle shown in Figure 23 for MOSPMA resembles a traditional pavement management usage cycle, the main differences reside in the emphasis given in MOSPMA to tie target objectives to performance parameters and in determination of the level of investments required to meet multiple target objectives. Typically, traditional pavement management systems are used to assess the impact on the pavement network for an investment strategy in which available funds for maintenance and rehabilitation are given *(57)*. In MOSPMA, the desired pavement network condition over the planning horizon, or target objectives, are established first and then investments required for achieving the targets are calculated. The need for developing a multi-objective strategic management approach for local agencies was suggested by Dr. Shameem Ahmed Dewan in his doctoral dissertation published in December 2002 *(58)*. Dr. Dewan states in his recommendations for future research that "research is needed to include a method in the existing pavement management system that would enable the system to estimate the needed funds for the network for a fixed condition (or set of conditions)" *(58)*.

Another difference between MOSPMA and a traditional pavement management approach is that the use of knowledge management tools through the entire management cycle is encouraged in MOSPMA. The integration of knowledge system components with traditional pavement management system components is considered important for supporting MOSPM and improving current management practices.

4.2 COMPONENTS OF A PAVEMENT MANAGEMENT SYSTEM TO SUPPORT A MULTI-OBJECTIVE STRATEGIC PAVEMENT MANAGEMENT APPROACH (MOSPMA)

The components of a pavement management system that I propose to support a multi-objective strategic pavement management approach (MOSPMA) combines pavement management systems components supported by a geographic information system (GIS) with knowledge management system components. Figure 24 shows the components of a pavement management system conceived to support the multi-objective strategic pavement management approach.

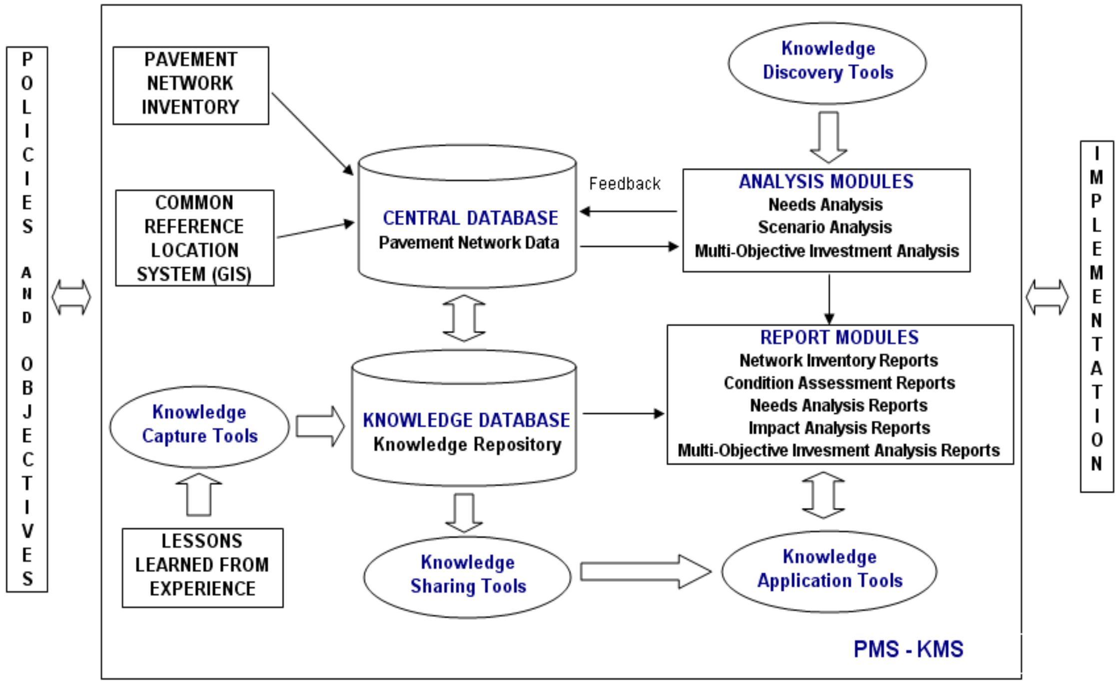

FIGURE 24 Components of a pavement management system designed to support a multi-objective strategic management approach.

Pavement management components include a central database that stores a pavement network inventory and pavement network data such as pavement conditions and treatment history among others. Data stored in the central database is linked by a common reference location system based on GIS. Analysis modules include needs analysis, scenario analysis, and multi-objective investment analysis. Reports for network inventory, condition assessment, needs analysis, impact analysis, and investments analysis are provided by the system. These components of a pavement management system are empowered by knowledge management system components for discovering, capturing, sharing, and applying knowledge through the management cycle. A knowledge database connected to the central pavement network database serves as a knowledge repository for lessons learned from experience that were captured by knowledge capture tools. Knowledge sharing tools facilitate diffusion of knowledge stored in the knowledge database for its application with the support of knowledge application tools. Analysis modules in the pavement management system are combined with knowledge discovery tools to facilitate the interpretation of the information provided by the system.

The pavement management system that supports the multi-objective strategic pavement management approach is not isolated from other infrastructure decision support systems. To better support decision makers making strategic decisions, the pavement management system should be integrated with other infrastructure decision support systems. The vision of a holistic model for an integrated system to support strategic management was described in Chapter IV. Although it is recognized that this vision may be beyond application by local agencies, a transportation planning agency that supports local agencies could act as a “change agent” for moving current management practices toward a knowledge oriented organization that takes advantage of modern technologies as well as lessons learned from previous experiences.

In practice the current focus of MOSPMA is determination of the level of investments required for achieving an agency’s target objectives over its planning horizon, and without a method for this purpose, the overall conceptual approach is meaningless.

4.3 METHOD FOR DETERMINING INVESTMENT NEEDS TO MEET MULTIPLE OBJECTIVES IN A LOCAL AGENCY

The method for determining investment needs to meet multiple objectives is built upon principles used by the pavement management system developed for the Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area. MTC functions as both the regional transportation planning agency for federal purposes and as the region's metropolitan planning organization *(54)*.

4.3.1 MTC Pavement Management System

The pavement management system (MTC–PMS) sponsored by the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area has been successfully used by local agencies for more than twenty years. The implementation program began with six local jurisdictions in the 1980s *(54)*. Currently, MTC has more than one hundred users of the MTC-PMS within the Bay Area. The success of its implementation resides in the support provided by MTC which includes training, on-site assistance to address special cases, assistance in the budgeting process, and continuous feedback *(55)*.

The MTC-PMS decision support tools consider five surface types: asphalt concrete (AC), portland concrete cement (PCC), asphalt concrete over asphalt concrete (AC/AC), asphalt concrete over portland concrete cement (AC/PCC), and surface treatment (ST) *(50)*. In the MTC-PMS pavement sections are grouped in four functional classes: arterial (A), collector (C), residential/local (R/L), and other (O). Functional classification is based on the volume of traffic, type of traffic, and priority for maintenance. Arterial roads provide the highest level of mobility and the least interrupted flow of traffic. Collector roads provide a lower level of mobility at lower speeds and are usually shorter distances than arterial roads. These facilities normally connect local roads with arterial roads. Local roads provide a high level of access to abutting land but limited mobility. Sections classified as other (O) may correspond to industrial areas or a particular type of road that does not match one of the other three functional classes *(57)*.

Pavement condition in MTC-PMS is expressed in terms of the Pavement Condition Index (PCI), which ranges from 0 to 100, and is based on a walking distress survey. One hundred in this scale represents a pavement section in excellent condition *(57)*.

From the PCI of individual sections, the network average PCI is calculated using the following equation:

$$PCI_n = \frac{\sum_{i=1}^{n} a_i \times PCI_i}{\sum_{i=1}^{n} a_i} \qquad \text{(Eq.1)}$$

where

PCI_n	=	average PCI for network
PCI_i	=	PCI value for section *i*
a_i	=	area in square yards of section *i*.
n	=	total number of sections

All the sections are included in this calculation.

Five condition categories are defined in MTC-PMS. PCI trigger values are used to define the boundaries of each condition category. Typical trigger values used by Bay Area agencies are shown in Figure 25.

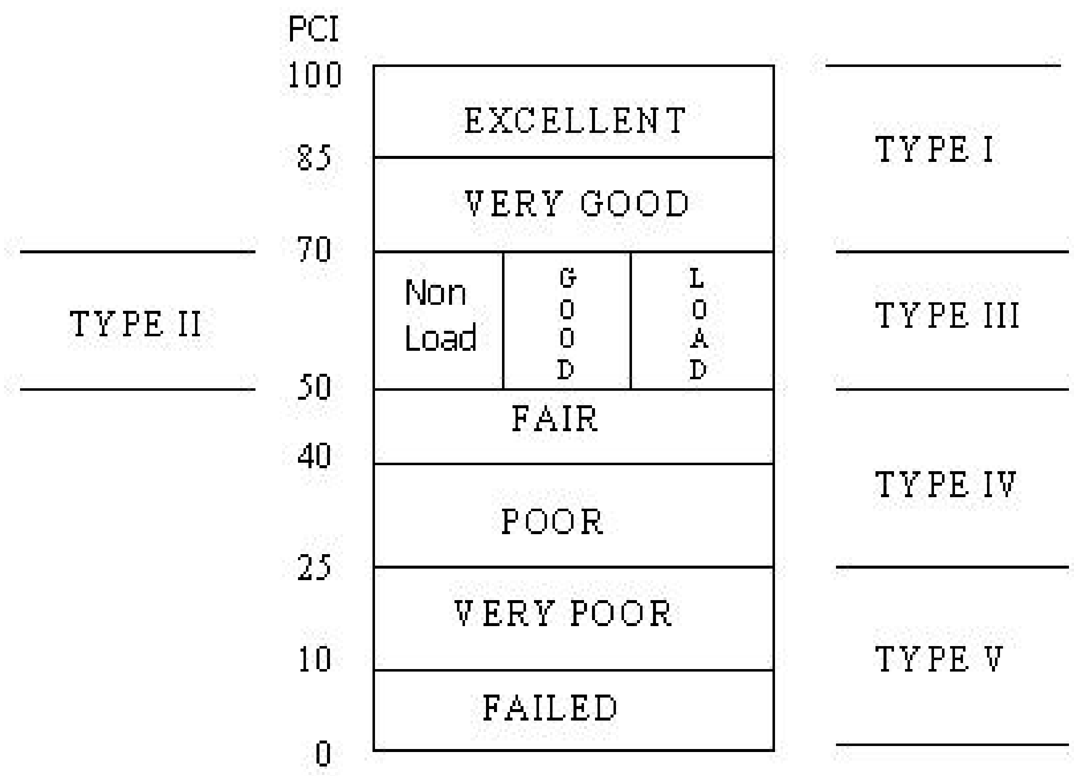

FIGURE 25 A typical definition of pavement condition categories based on PCI *(57)*.

Normally, the condition categories are defined as follows *(57)*.

- Type I pavements are those which have little or no distress with a PCI value between 100 and 70. A pavement in this category may be described as excellent or very good.
- Type II pavements are those which have a significant level of distress which is predominantly non load-related; such as block cracking at low or medium severity level, longitudinal and transverse cracking at low or medium severity level, or weathering and raveling at any severity level *(51)*; with a PCI value between 70 and 50. A pavement in this category may be described as good or fair.
- Type III pavements are those which have a significant level of distress which is predominantly load-related; such as alligator cracking at any severity level, block cracking at high severity level, longitudinal and transverse cracking at high severity level, or rutting at any severity level *(51)*; with a PCI value between 70 and 50. A pavement in this category may be described as good or fair.
- Type IV pavements are those with a PCI value between 50 and 25. A pavement in this category may be described as fair or poor.
- Type V pavements are those with extensive amounts of distress with a PCI value between 25 and 0. A pavement in this category may be described as very poor or failed.

The MTC-PMS performance model uses pavement performance family curves which relate performance to age for specific groups of pavements. The Pavement Condition

Index (PCI) is used by the model to express pavement performance. Figure 26 illustrates an example of a pavement performance family curve.

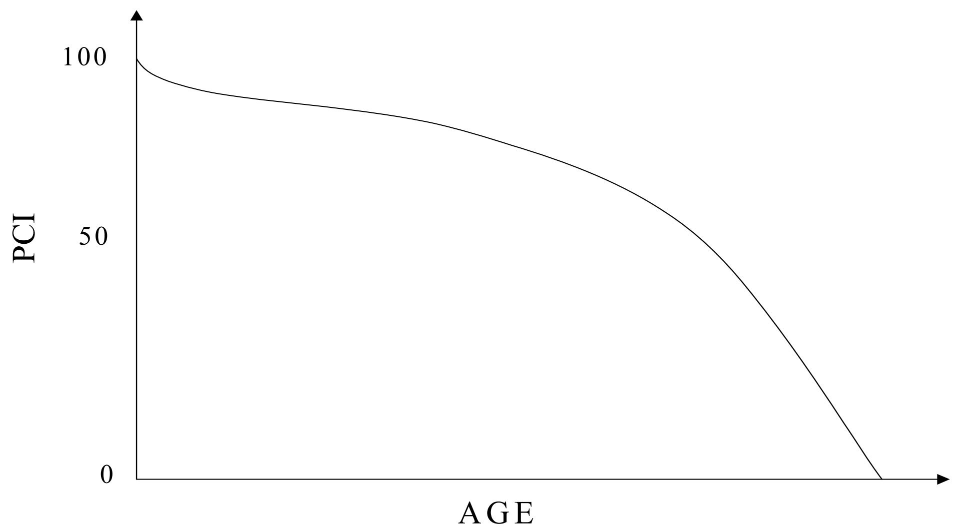

FIGURE 26 Pavement performance family curve.

Pavement performance family curves are defined for each combination of functional class and pavement surface type: arterial-asphalt concrete, arterial-portland cement concrete, arterial-asphalt concrete over asphalt concrete, arterial-asphalt concrete over portland-cement concrete, arterial-surface treatment, collector-asphalt concrete, collector-portland cement concrete, collector-asphalt concrete over asphalt concrete, collector-asphalt concrete over portland-cement concrete, collector-surface treatment, residential/local-asphalt concrete, residential/local-portland cement concrete, residential/local-asphalt concrete over asphalt concrete, residential/local-asphalt concrete over portland-cement concrete, residential/local-surface treatment, other-asphalt concrete, other-portland cement concrete, other-asphalt concrete over asphalt concrete, other-asphalt concrete over portland-cement concrete, and other-surface treatment *(57)*.

A decision tree based on PCI trigger values, functional class and surface types, is used to identify maintenance and rehabilitation treatment needs for each pavement management section. A network level maintenance or rehabilitation treatment is established for each pavement condition category for each combination of functional pavement network class (arterial, collector, residential/local, and other) and pavement surface types (asphalt concrete, asphalt concrete over asphalt concrete, asphalt concrete over portland cement concrete, portland cement concrete, and surface treatment). Figure 27 shows a decision tree to identify treatment needs for pavement condition categories. Trigger values can differ for each group *(57)*.

A cost-effectiveness ranking method is used for prioritizing investments to select pavement management sections for treatment when funds are constrained. The method is based on the concept of treatment effectiveness over time. Effectiveness is defined as the area under the PCI time curve above the minimum acceptable condition level which is usually identified as 25 *(57)*. Figure 28 illustrates the concept of effectiveness for a pavement treatment.

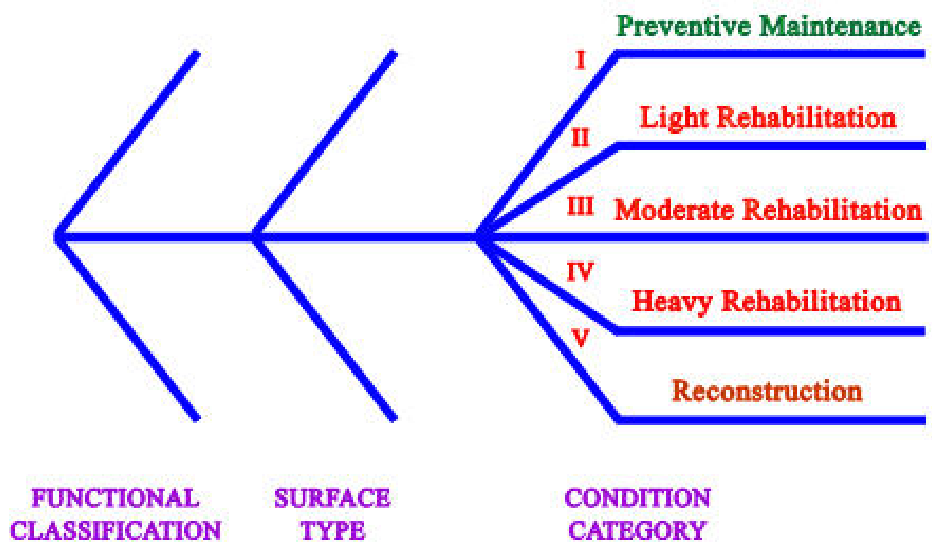

FIGURE 27 Decision tree to identify treatment needs based on pavement condition category *(after 57)*.

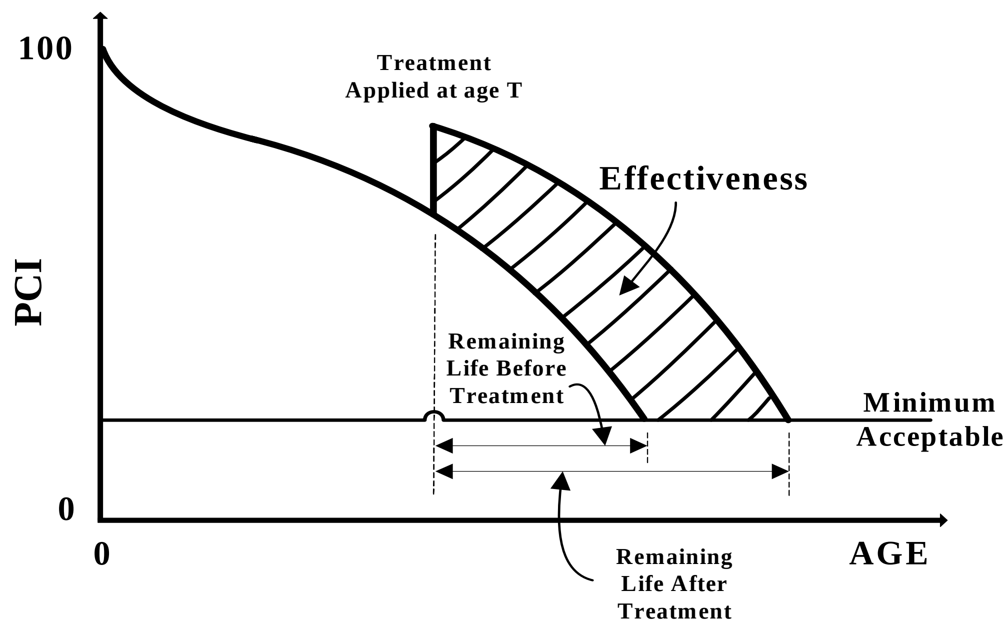

FIGURE 28 Effectiveness of a pavement treatment *(after 57)*.

The annualized effectiveness is calculated by dividing the area under the curve due to treatment by the remaining life after treatment. This annualized effectiveness is multiplied by a weighting factor (WF) to consider the usage or importance of the pavement section. The Weighted Effectiveness Ratio (WER) is obtained by dividing this product by the equivalent uniform annual cost (EUAC) per unit area (UA). Equation 2 shows the formula to calculate WER *(57)*.

$$WER = \frac{(Annualized\ Effectiveness)(WF)}{EUAC/UA}\ X\ 1000 \qquad \text{(Eq.2)}$$

When funds are constrained, pavement management sections are ranked from the highest to the lowest Weighted Effectiveness Ratio (WER), and sections are selected for funding starting at the top of the list until funds are depleted. The current version of MTC-PMS can forecast the pavement network condition and recommend pavement treatments for a given stream of investments allocated over the planning horizon. However, MTC-PMS can not directly estimate the level of investment required to achieve a desirable pavement network condition that could be established by an agency as a target. *(57, 59)*.

4.3.2 Problem Formulation

The problem is how to achieve multiple objectives established by an agency at the minimum cost, and at the same time to identify the best combination of candidate projects over the planning horizon to maximize the effectiveness of treatments. This second objective can be translated as selecting the group of projects that maximizes the overall WER having the minimum costs required to meet the objectives as a constraint.

To establish target objectives, the following parameters used by MTC-PMS have been selected:

- Network Average Pavement Condition Index (PCI) for the entire pavement network or sub-groups of the pavement network
- Network Average Remaining life for the entire pavement network or sub-groups of the pavement network
- Percent of the entire pavement network or sub-groups of the network in good condition
- Percent of the entire pavement network or sub-groups of the network in poor condition

These four network parameters are used to characterize the current pavement network state and to establish targets over the planning horizon. Defining pavement network targets in terms of these parameters implies setting certain conditions that should be met at a certain time. The problem is reduced to meet these targets by investing the minimum amount of funds while maximizing the overall effectiveness for the group of projects selected for funding. The problem can be mathematically formulated as follows:

$$\text{Minimize } Z: \quad \sum_{i=1}^{N} C_i \, X_i \qquad \text{(Eq.3)}$$

Maximize W: $$\sum_{i=1}^{N} WER_i \; X_i$$ (Eq.4)

subject to:

$$\sum_{i=1}^{N} a_i \; x \; (PCI_i + \Delta PCI_i \; X_i) \; / \sum_{i=1}^{N} a_i \geq b_1$$ (Eq.5)

$$\sum_{i=1}^{N} a_i \; x \; (RL_i + \Delta RL_i \; X_i) \; / \sum_{i=1}^{N} a_i \geq b_2$$ (Eq.6)

$$\sum_{i=1}^{N} (a_{i1} + p_{i1} \; X_i) \; / \sum_{i=1}^{N} a_i \geq b_3$$ (Eq.7)

$$\sum_{i=1}^{N} (a_{i4} - q_{i4} \; X_i + a_{i5} - r_{i5} \; X_i) \; / \sum_{i=1}^{N} a_i \leq b_4$$ (Eq. 8)

where

Z = objective function for minimizing treatment costs

W = objective function for maximizing WER

X_i = 1 if section "i" is selected for a treatment; 0 otherwise

N = total number of sections ("i" from 1 to N)

C_i = cost associated with the treatment given to section "i"

PCI_i = PCI associated to section "i"

ΔPCI_i = PCI increment for section "i" due to treatment

RL_i = remaining life associated to section "i"

ΔRL_i = remaining life increment for section "i" due to treatment

a_i = area of section "i"

a_{i1} = area of section "i" which is in very good condition (PCI above 70, condition category I)

p_{i1} = area of section "i" which is moved to good condition due to treatment

a_{i4} = area of section "i" which condition is in poor condition (PCI below 50, condition category IV)

q_{i4} = area of section "i" which is recovered from poor condition due to treatment

a_{i5} = area of section "i" which condition is in very poor condition (PCI below 25, condition category V)

r_{i4} = area of section "i" which is recovered from very poor condition due to treatment

b_1 = minimum average PCI for the entire pavement network

b_2 = minimum average remaining life for the entire pavement network

b_3 = minimum percent of network in very good condition(PCI above 70)

b_4 = maximum percentage of network in poor (PCI below 50) and very poor condition (PCI below 25)

In addition to the conditions set for the entire pavement network, the agency may set conditions for each sub-group of the pavement network. Each functional class such as arterial, collector, residential/local, and other could have their own set of conditions for a given year. Sixteen additional conditions can be added to the mathematical formulation.

For arterials:

$$\sum_{j=1}^{A} a_j \times (PCI_j + \Delta PCI_j) X_j / \sum_{j=1}^{A} a_j \geq b_5 \qquad \text{(Eq.9)}$$

$$\sum_{j=1}^{A} a_j \times (RL_j + \Delta RL_j X_j) / \sum_{j=1}^{A} a_j \geq b_6 \qquad \text{(Eq.10)}$$

$$\sum_{j=1}^{A} (a_{j1} + p_{j1} X_j) / \sum_{i=1}^{N} a_i \geq b_7 \qquad \text{(Eq.11)}$$

$$\sum_{j=1}^{A} (a_{j4} - q_{j4} X_j + a_{j5} - r_{j5} X_j) / \sum_{i=1}^{N} a_i \leq b_8 \qquad \text{(Eq. 12)}$$

where

A	=	total number of sections classified as arterials ("j" from 1 to A)
PCI_j	=	PCI associated to arterial section "j"
ΔPCI_j	=	PCI increment for arterial section "j" due to treatment
RL_j	=	remaining life associated to arterial section "j"
ΔRLj	=	remaining life increment for arterial section "j" due to treatment
a_j	=	area of arterial section "j"
a_{j1}	=	area of arterial section "j" which is in very good condition (PCI

above 70, condition category I)

p_{j1} = area of arterial section "j" which is moved to good condition due to treatment

a_{j4} = area of arterial section "j" which condition is in poor condition (PCI below 50, condition category IV)

q_{j4} = area of arterial section "j" which is recovered from poor condition due to treatment

a_{j5} = area of arterial section "j" which condition is in very poor condition (PCI below 25, condition category V)

r_{j4} = area of arterial section "j" which is recovered from very poor condition due to treatment

b_5 = minimum average PCI for the arterial sub-group

b_6 = minimum average remaining life for the arterial sub-group

b_7 = minimum percent of arterial network in very good condition (PCI above 70)

b_8 = maximum percent of arterial network in poor (PCI below 50) and very poor condition (PCI below 25)

For collectors:

$$\sum_{k=1}^{C} a_k \text{ x } (PCI_k + \Delta PCI_k \; X_k) / \sum_{k=1}^{C} a_k \geq b_9 \qquad \text{(Eq.13)}$$

$$\sum_{k=1}^{C} a_k \times (RL_k + \Delta RL_k X_k) / \sum_{k=1}^{C} a_k \geq b_{10} \quad \text{(Eq.14)}$$

$$\sum_{k=1}^{C} (a_{k1} + p_{k1} X_k) / \sum_{i=1}^{N} a_i \geq b_7 \quad \text{(Eq.15)}$$

$$\sum_{k=1}^{C} (a_{k4} - q_{k4} X_k + a_{k5} - r_{k5} X_k) / \sum_{i=1}^{N} a_i \leq b_8 \quad \text{(Eq. 16)}$$

where

C = total number of sections classified as collectors ("k" from 1 to C)

PCI_j = PCI associated to arterial section "j"

ΔPCI_j = PCI increment for arterial section "j" due to treatment

RL_j = remaining life associated to arterial section "j"

ΔRLj = remaining life increment for arterial section "j" due to treatment

a_k = area of collector section "k"

a_{k1} = area of collector section "k" which is in very good condition (PCI above 70, condition category I)

p_{k1} = area of collector section "k" which is moved to good condition due to treatment

a_{k4} = area of collector section "k" which condition is in poor condition (PCI below 50, condition category IV)

q_{k4} = area of collector section "k" which is recovered from poor condition due to treatment

a_{k5} = area of collector section "k" which condition is in very poor condition (PCI below 25, condition category V)

r_{k4} = area of collector section "k" which is recovered from very poor condition due to treatment

b_9 = minimum average PCI for the collector sub-group

b_{10} = minimum average remaining life for the collector sub-group

b_{11} = minimum percent of collector network in very good condition (PCI above 70)

b_{12} = maximum percent of collector network in poor (PCI below 50) and very poor condition (PCI below 25)

For residential/local:

$$\sum_{l=1}^{R} a_l \text{ x } (PCI_l + \Delta PCI_l X_l) / \sum_{l=1}^{R} a_l \geq b_{13} \qquad \text{(Eq.17)}$$

$$\sum_{l=1}^{R} a_l \text{ x } RL_i \ \Delta RL_l / \sum_{l=1}^{R} a_l \geq b_{14} \qquad \text{(Eq.18)}$$

$$\sum_{l=1}^{R} (a_{l1} + p_{l1} X_l) / \sum_{i=1}^{N} a_i \geq b_{15} \qquad \text{(Eq.19)}$$

$$\sum_{l=1}^{R} (a_{l4} - q_{l4} X_l + a_{l5} - r_{l5} X_l) / \sum_{i=1}^{N} a_i \leq b_{16} \qquad \text{(Eq. 20)}$$

where

R	=	total number of sections classified as residential ("l" from 1 to R)
PCI_j	=	PCI associated to arterial section "j"
ΔPCI_j	=	PCI increment for arterial section "j" due to treatment
RL_j	=	remaining life associated to arterial section "j"
ΔRLj	=	remaining life increment for arterial section "j" due to treatment
a_l	=	area of residential section "l"
a_{l1}	=	area of residential section "l" which is in very good condition (PCI above 70, condition category I)
p_{l1}	=	area of residential section "l" which is moved to good condition due to treatment
a_{l4}	=	area of residential section "l" which condition is in poor condition (PCI below 50, condition category IV)
q_{l4}	=	area of residential section "l" which is recovered from poor condition due to treatment
a_{l5}	=	area of residential section "l" which condition is in very poor condition (PCI below 25, condition category V)
r_{l4}	=	area of residential section "l" which is recovered from very poor condition due to treatment
b_{13}	=	minimum average PCI for the residential sub-group
b_{14}	=	minimum average remaining life for the residential sub-group
b_{15}	=	minimum percent of residential network in very good

condition (PCI above 70)

b_{16} = maximum percent of residential network in poor (PCI below 50) and very poor condition (PCI below 25)

For other:

$$\sum_{m=1}^{O} a_m \times (PCI_m + \Delta PCI_m X_m) \Big/ \sum_{m=1}^{O} a_m \geq b_{17} \qquad \text{(Eq.21)}$$

$$\sum_{m=1}^{O} a_m \times (RL_m + \Delta RL_m) \Big/ \sum_{m=1}^{O} a_m \geq b_{18} \qquad \text{(Eq.22)}$$

$$\sum_{m=1}^{O} (a_{m1} + p_{m1} X_k) \Big/ \sum_{i=1}^{N} a_i \geq b_{19} \qquad \text{(Eq.23)}$$

$$\sum_{m=1}^{O} (a_{m4} - q_{m4} X_k + a_{m5} - r_{m5} X_k) \Big/ \sum_{i=1}^{N} a_i \leq b_{20} \qquad \text{(Eq. 24)}$$

where

O = total number of sections classified as others (“m” from 1 to O)

PCI_m = PCI associated to other section “m”

ΔPCI_m = PCI increment for other section “m” due to treatment

RL_m = remaining life associated to arterial section “m”

ΔRL_m = remaining life increment for arterial section “m” due to treatment

a_m = area of other section “m”

a_{m1} = area of other section "m" which is in very good condition (PCI above 70, condition category I)

p_{m1} = area of other section "m" which is moved to good condition due to treatment

a_{m4} = area of other section "m" which condition is in poor condition (PCI below 50, condition category IV)

q_{m4} = area of other section "m" which is recovered from poor condition due to treatment

a_{m5} = area of other section "m" which condition is in very poor condition (PCI below 25, condition category V)

r_{m4} = area of other section "m" which is recovered from very poor condition due to treatment

b_{17} = minimum average PCI for the collector sub-group

b_{18} = minimum average remaining life for the other sub-group

b_{19} = minimum percent of other network in very good condition (PCI above 70)

b_{20} = maximum percent of other network in poor (PCI below 50) and very poor condition (PCI below 25)

Finally,

$$A + C + R + O = N \quad \text{(Eq.25)}$$

A set of target conditions is set for each year of the planning horizon. This set of conditions defines the target scenarios over the planning horizon. The set of target conditions for the pavement network can be also expressed in a matrix as shown in Table 8.

TABLE 8 Matrix to Define Targets for the Pavement Network for a Given Year

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life	Minimum Percent of the Pavement Network Group in Very Good Condition	Maximum Percent of the Pavement Network Group in Poor and Very Poor Condition
Entire Network	b_1	b_2	b_3	b_4
Arterial	b_5	b_6	b_7	b_8
Collector	b_9	b_{10}	b_{11}	b_{12}
Residential/Local	b_{13}	b_{14}	b_{15}	b_{16}
Other	b_{17}	b_{18}	b_{19}	b_{20}

A set of matrices is used to define targets for the pavement network over the planning horizon.

4.3.3 Analytical Procedure to Estimate Investment Needs to Meet Target Objectives

The analytical procedure to estimate investment needs to meet target objectives relies on concepts used by MTC-PMS *(57)*. Two methods are presented in this section: (1) a sequential year ranking method called "dynamic bubble up" technique and (2) a multi-objective optimization model coupled with an integer program solving technique.

Both methods are used in the case study presented in Chapter V. Discussion about the advantages and disadvantages of applying either the "dynamic bubble up" technique or the "optimization solving technique" is also presented in Chapter V when findings from the case study are analyzed.

Ranking with the Dynamic Bubble Up Procedure (DBU)

The dynamic bubble up procedure (DBU) is based on a sequential year ranking method in which each year of the planning horizon is independently considered as a one-year period for estimating investment needs to achieve the target objectives and for identifying candidate projects to allocate the funds. After each one-year period, the pavement section condition is deteriorated or upgraded as appropriate using pavement performance family curves.

The steps to estimate investment needs to meet target objectives using DBU are summarized as follow:

1. Conduct a diagnosis of the current pavement network state. Calculate the Pavement Condition Index (PCI) and remaining life for each section. Calculate the network average PCI, network average remaining life, percent of pavements in very good condition (PCI above 70), and percent of pavements in poor and very poor condition (PCI below 50) for the entire pavement network and each sub-group of the pavement network (arterial, collector, residential, other).
2. Set target objectives for the pavement network. Target objectives are expressed in terms of network average PCI, network average remaining life, percent of pavement

network in very good condition, and percent of pavement network in poor and very poor condition.

3. Identify treatment needs for each section of the pavement network for the given year of analysis.

4. Calculate WER for each pavement section identified as needing treatment.

5. Rank the pavement sections from highest to lowest WER. WER was selected as the criterion for ranking since this is the parameter currently used by MTC-PMS to prioritize funding allocation when funds are constrained. The aim is to select a group of sections that provides the highest overall WER for the investments.

   Other parameters for ranking sections can be considered such as the increment in PCI, a Cost/PCI ratio, and Cost/WER ratio. Funding needs estimated using DBU may vary depending on the criterion used for ranking.

6. Estimate the minimum amount of funds required to meet the target objectives set in step 2. For each pavement network target objective including the network average PCI, network average remaining life, percent of pavement network in very good condition, percent of pavement network in poor condition; the minimum amount of funds required to meet the target is calculated. DBU is used to estimate this amount. DBU consists of an iterative calculation that starts from the top of the list of sections identified for treatment and ranked in step 5. For this calculation the process assumes that k sections are being funded and N-k are not funded (k starts with 1, and N is the total number of sections in the dataset). If the value calculated for the pavement network parameter does not meet the target objective, the next section is

"bubbled up" (k increases) and the new value for this pavement network parameter is calculated until the target objective is met, or the last section in the dataset is reached (k = N).

7. Compare the minimum amount of funds required to meet each target objective, and ensure that sections in different objective groups are appropriately counted when calculating the minimum amount of funds needed to meet all the objectives.
8. Project the pavement network state for the next year.
9. Revise the strategy and adjust accordingly. Repeat steps 3 to 9 for the remaining years of the planning horizon.

Figure 29 shows a flow chart illustrating the steps for estimating the level of investment required to meet the target objectives using a ranking method and DBU. Figure 30 presents the flow chart for DBU explained in step 6. DBU is used to identify the group of candidate sections that will return the greatest overall WER for the entire network.

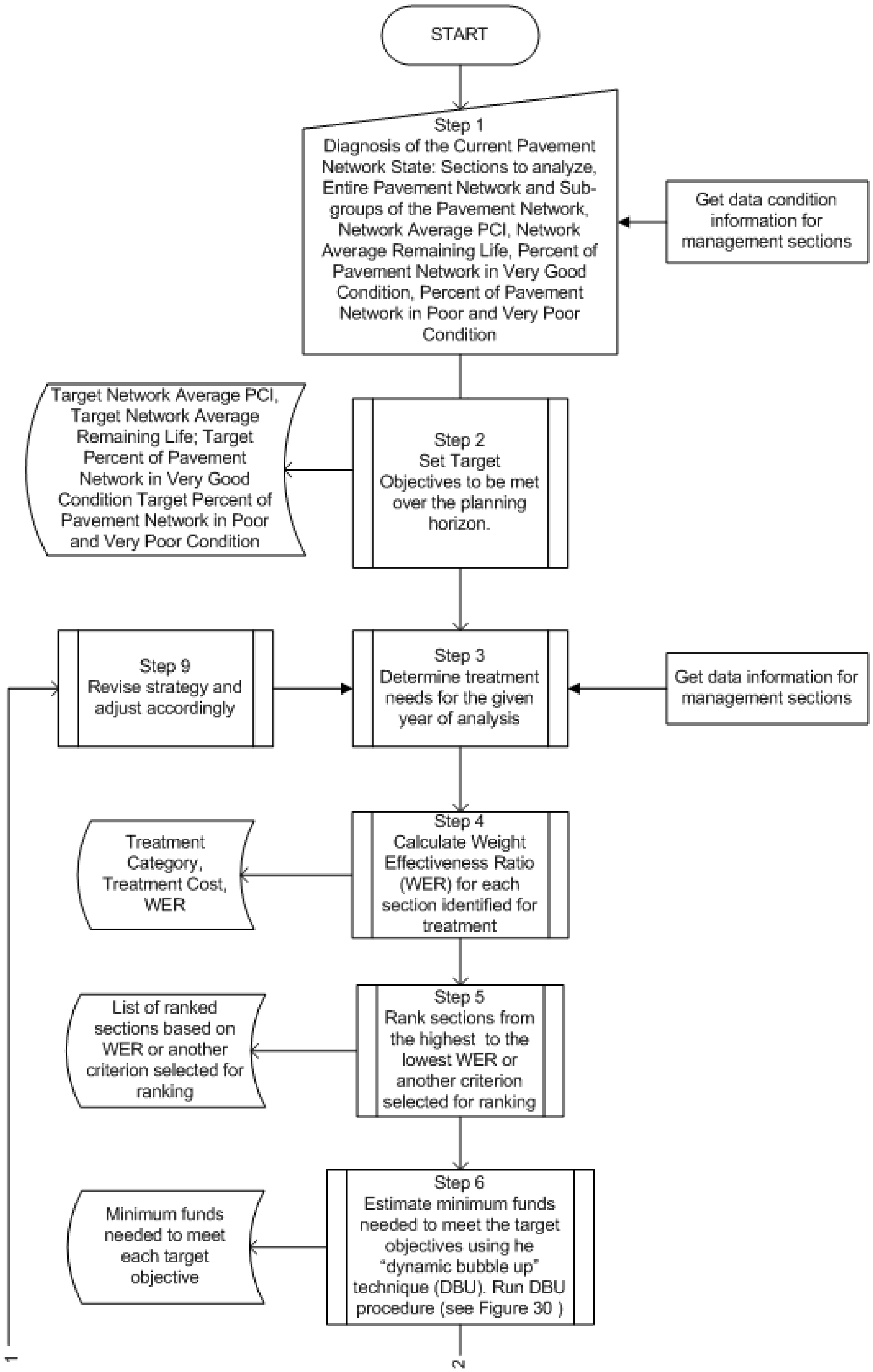

FIGURE 29 Flow chart to estimate the level of investment using DBU.

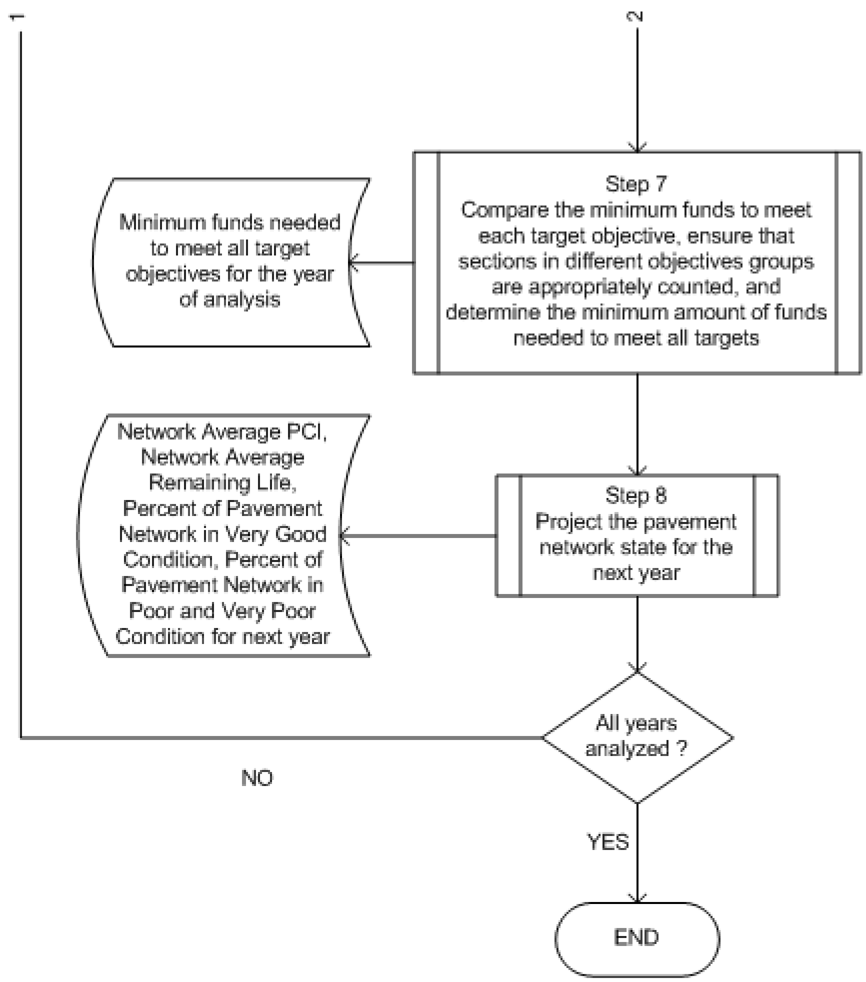

FIGURE 29 (Continued).

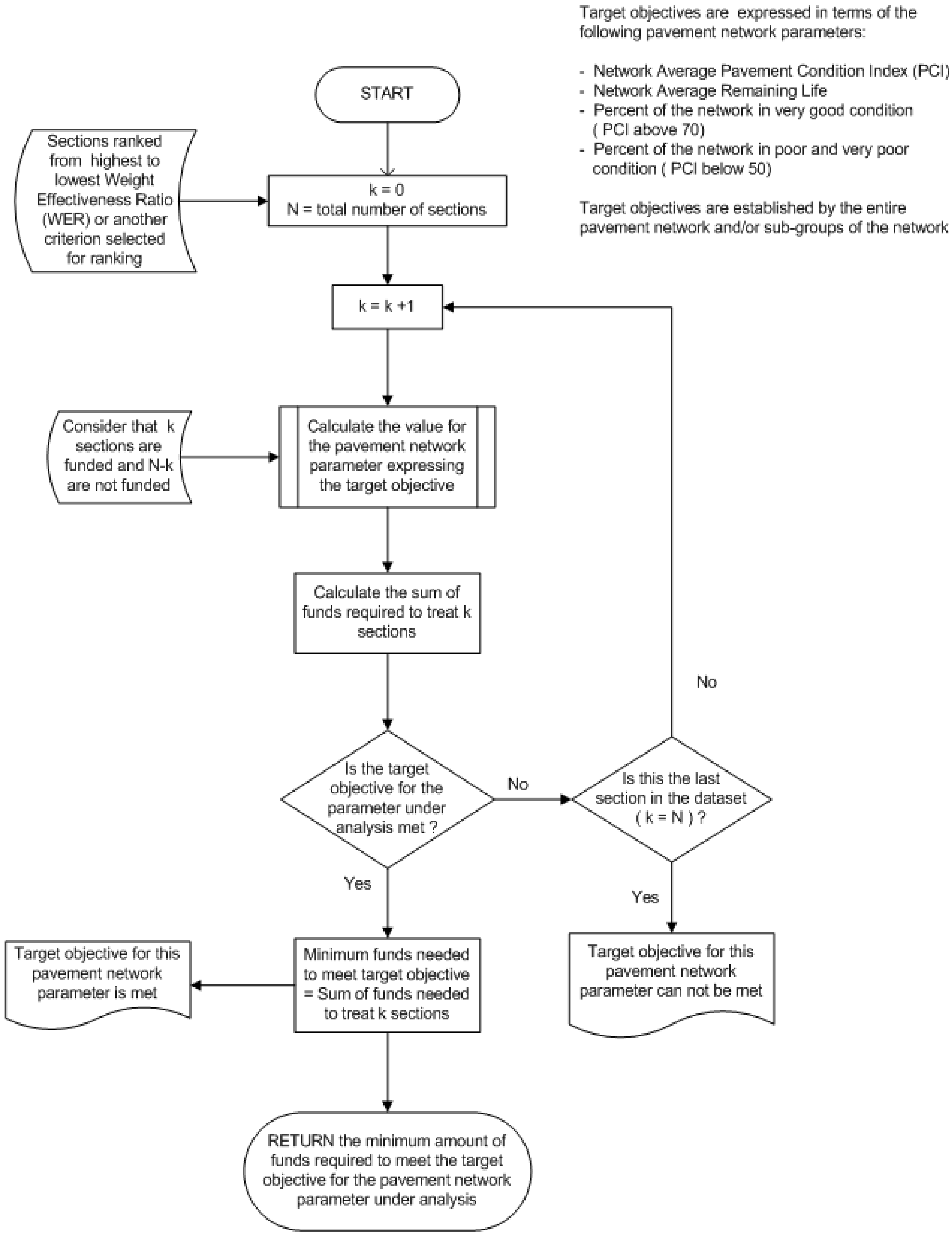

FIGURE 30 Flow chart for the dynamic bubble up procedure (DBU).

Optimization Using a Multi-objective Model

A multi-objective optimization model is used to formulate the funding allocation problem. Many applications, especially in the public sector, must be treated as multi-objective. Multi-objective optimization models have multiple objective functions *(60)*. In this case, two objective functions are set to formulate the problem. The first objective function is set to minimize the overall treatment costs required to meet the target objectives.

$$\text{Minimize } Z: \quad \sum_{i=1}^{N} C_i \quad X_i \qquad \text{(Eq.26)}$$

where

Z	=	objective function for minimizing treatment costs
X_i	=	1 if section "i" is selected for a treatment; 0 otherwise
N	=	total number of sections
C_i	=	cost associated with the treatment given to section "i"

The second objective function is set to maximize the overall Weighted Effectiveness Ratio (W).

$$\text{Maximize } W: \quad \sum_{i=1}^{N} WER_i \quad X_i \qquad \text{(Eq.27)}$$

where

WER	=	objective function for maximizing WER

Constraints for the mathematical formulation are established based on the target objectives set for the pavement network parameters. Equations for the constraints are expressed in terms of changes in the pavement network parameters (increments/decrements) required to meet the target objectives. Due to the application of a treatment, the network average PCI increases, likewise the network average remaining life increases. An increase in the pavement network condition may also cause the percent of the pavement network in very good condition to increase if sections moved to category I from another category, likewise the percent of the pavement network in poor and very poor condition may decrease if sections move out of category IV and V.

Following this concept, the target network average pavement condition (PCI^T) would be equal to the current pavement network condition (PCI^C) plus the overall increment in the pavement network condition (ΔPCI^N) required for achieving the target value.

A similar approach can be used for the network remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor and very poor condition. Therefore, the target value for the network remaining life (RL^T) would be equal to the current network remaining life (RL^C) plus the overall remaining life increment (ΔRL^N) required for achieving the target value. The target percent of the pavement network in very good condition (P^T) would be equal to the current percent (P^C) plus the percent of the pavement network that needs to be moved to a very good condition (ΔP^N). The target percent of the pavement network in poor and very poor condition (Q^T) would be equal to the current percent (Q^C) minus the percent of the pavement network that needs to be moved out of a poor or very poor condition (ΔQ^N). Using this terminology, target objectives for the entire pavement network are expressed as constraints in the mathematical formulation:

$$\sum_{i=1}^{N} a_i \ x \ (PCI_i + \Delta PCI_i \ X_i) \ / \sum_{i=1}^{N} a_i \ \geq \ PCI^T \qquad \text{(Eq.28)}$$

$$\sum_{i=1}^{N} a_i \ x \ (RL_i + \Delta RL_i \ X_i) \ / \sum_{i=1}^{N} a_i \ \geq \ RL^T \qquad \text{(Eq.29)}$$

$$\sum_{i=1}^{N} (a_{i1} + p_{i1} \ X_i) \ / \ \sum_{i=1}^{N} a_i \ \geq \ P^T \qquad \text{(Eq.30)}$$

$$\sum_{i=1}^{N} (a_{i4} - q_{i14} X_i + a_{i5} - r_{i5} X_i) \ / \ \sum_{i=1}^{N} a_i \ \leq \ Q^T \qquad \text{(Eq. 31)}$$

where

PCI_i = PCI associated to section "i"

ΔPCI_i = PCI increment for section "i" due to treatment

RL_i = remaining life associated to section "i"

ΔRL_i = remaining life increment for section "i" due to treatment

a_i = area of section "i"

a_{i1} = area of section "i" which is in very good condition (PCI above 70, condition category I)

p_{i1} = area of section "i" which is moved to very good condition due to treatment

a_{i4} = area of section "i" which condition is in poor condition (PCI below 50, condition category IV)

q_{i4} = area of section "i" which is recovered from poor condition due to treatment

a_{i5} = area of section "i" which condition is in very poor condition (PCI below 25, condition category V)

r_{i4} = area of section "i" which is recovered from very poor condition due to treatment

PCI^T = minimum average PCI for the entire pavement network

RL^T = minimum average remaining life for the entire pavement network

P^T = minimum percent of the pavement network in very good condition (PCI above 70)

Q^T = maximum percent of network in poor (PCI below 50) and very poor condition (PCI below 25)

Similar equations can be set for expressing the target objectives for the pavement network sub-groups: arterial, collector, residential/local, and other. There are up to twenty equations to formulate the constraints (four for each pavement network subgroup, which adds to a total of sixteen constraints, plus four constraints for the entire pavement network).

A preemptive optimization approach based on an integer program solving technique is applied to solve the mathematical problem. Preemptive multi-objective optimization solves the mathematical problem by first finding the optimum for the first objective, and then solving for the second objective by adding the first optimum to the set of constraints *(61)*.

In this problem formulation, the first objective function minimizes the total amount of investments needed to meet the target objectives. The optimum value found from solving the first objective function is then added as a constraint when solving the second objective function:

$$\sum_{i=1}^{N} C_i \ X_i \ \leq \ Z \qquad \text{(Eq.32)}$$

The second objective function W, maximize the overall WER, is then solved to get the final solution.

An integer program technique is used for solving the mathematical problem in both steps. "An integer program is a linear program with the additional restriction that the input variables be integers" *(62)*. The iteration process starts assuming all X_i variables equal to 0.

Each year of the planning horizon is independently considered, and an integer program solving technique is used to identify sections for treatment ($X_i = 1$) and estimate the investment needs required to meet the target objectives for that year. After each one-year period the pavement section condition is adjusted based on pavement performance family curves.

The steps to estimate investment needs to meet target objectives using the multi-objective optimization model and an integer program solving technique are summarized as follows:

1. Conduct a diagnosis of the current pavement network state. Calculate the PCI and remaining life for each section. Calculate the network average PCI, network average remaining life, percent of pavements in very good condition (PCI above 70), percent of pavements in poor and very poor condition (PCI below 50) for the entire pavement network and each sub-group of the pavement network (arterial, collector, residential, and other).
2. Set target objectives for the pavement network. Target objectives are expressed in terms of network average PCI, network average remaining life network, percent of pavement network in very good condition, and percent of pavement network in poor and very poor condition.
3. Identify treatment needs for each section of the pavement network for the given year of analysis.
4. Calculate WER for each pavement section identified as needing treatment.
5. Formulate the multi-objective optimization model to establish the objective functions and constraints for the given year of analysis.
6. Estimate the minimum amount of funds required to meet the target objectives set in step 2 by solving the multi-objective model with an integer program technique.
7. Project the pavement network state for the next year.
8. Revise the strategy and adjust accordingly. Repeat steps 3 to 7 for the remaining years of the planning horizon.

Figure 31 shows a flow chart with the steps to estimate the level of investment required to meet the target objectives using a multi-objective optimization model.

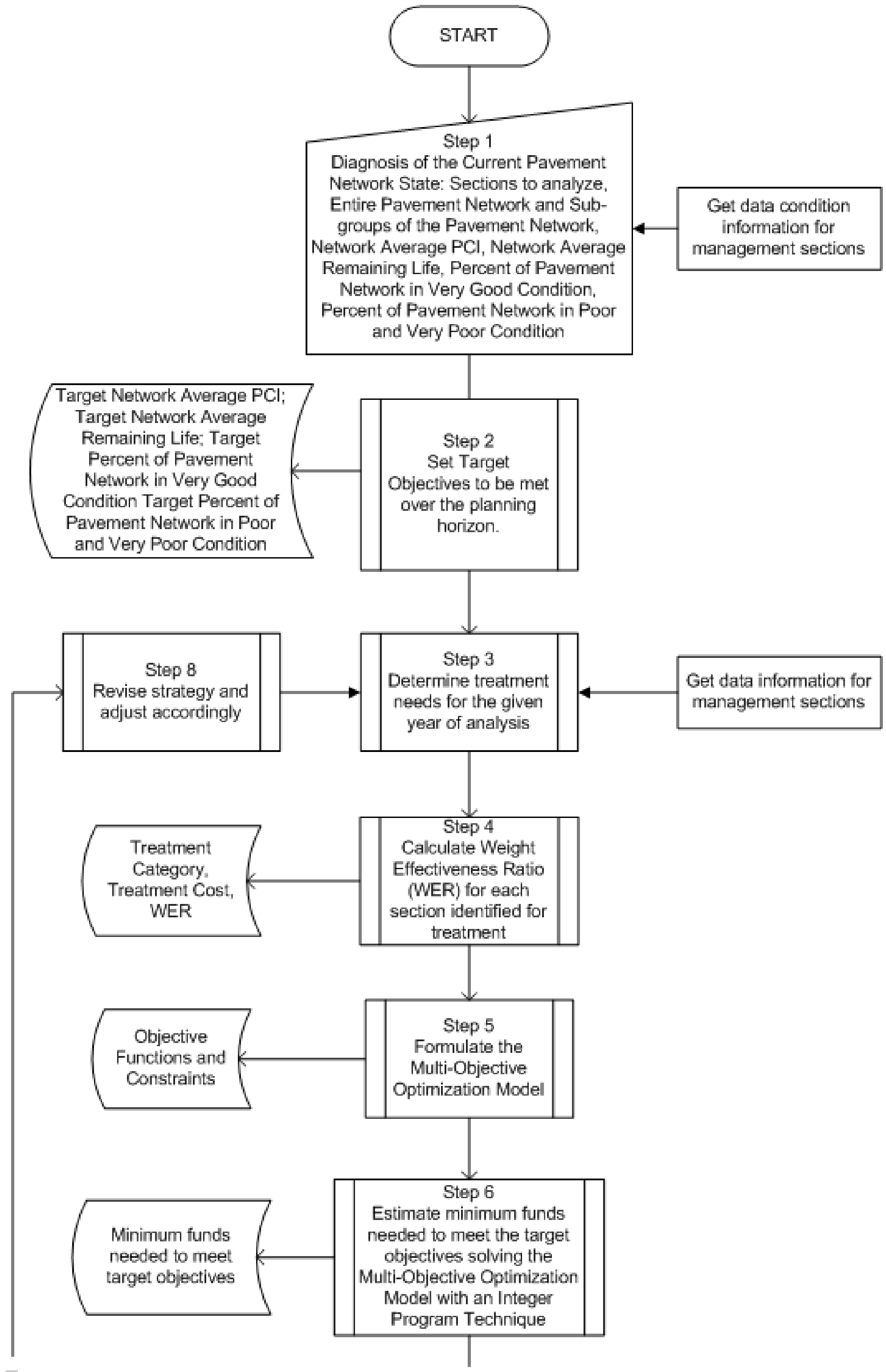

FIGURE 31 Flow chart to estimate the level of investment using optimization.

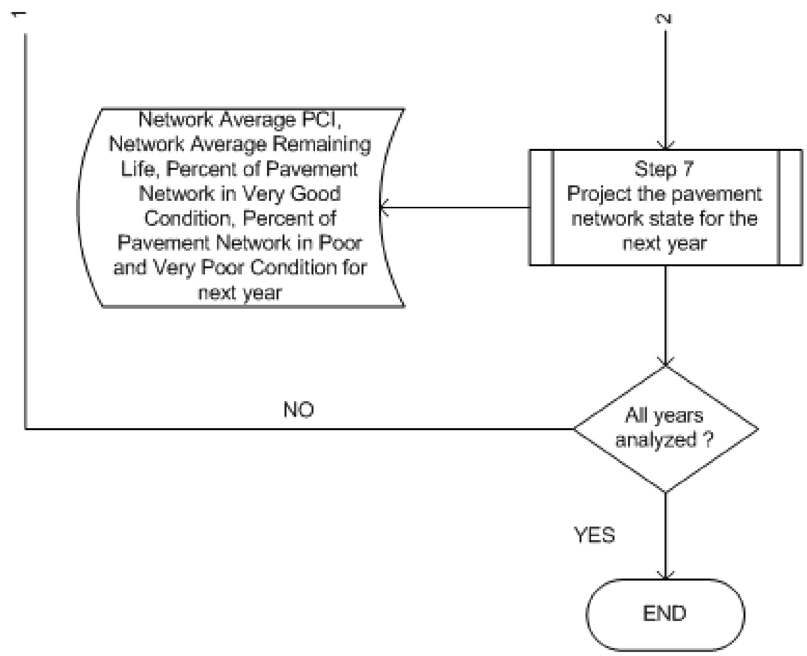

FIGURE 31 (Continued).

4.4 IMPLEMENTATION OF THE MULTI-OBJECTIVE STRATEGIC PAVEMENT MANAGEMENT APPROACH (MOSPMA)

The multi-objective strategic pavement management approach (MOSPMA) has been developed to assist local agencies to achieve multiple target objectives set for their pavement network. Target objectives for the entire pavement network or sub-groups of the network are expressed in terms of conditions set for selected pavement network parameters. For the MTC-PMS the network parameters include the network average PCI, network average remaining life, percent of the network or sub-groups of the network in good condition, percent of the network or sub-groups of the network in poor and very poor condition. The approach considers the relationship between funding levels and pavement network parameters.

The purpose of implementing a multi-objective strategic management approach is to facilitate identifying the minimum level of investments required to meet target objectives set by an agency over the planning horizon. The methodology proposed to estimate the investment needs to meet the target objectives is built upon concepts that are currently used by MTC-PMS. This increases the likelihood for implementation by MTC but does not eliminate the traditional barriers faced by pavement management systems during the implementation phase *(62)*.

4.4.1 Barriers to Overcome

From the technical point of view, the problem solving methodology considered in this approach should be able to be integrated into the current MTC-PMS system without any major problems. Programming of a new module requires effort and time, but it is feasible.

Barriers are more likely to come from institutional issues related to agency staff, current agency structure, and deployment-sustainability issues for the implementation of the approach. Probably the major barrier that may prevent implementation comes from human nature. Resistance to adopt new ways of making decisions may be a tough barrier to overcome *(62)*. Since MOSPMA may affect existing decision habits at the strategic level and impact work processes carried out at lower management levels, effective communication is essential to sustain the flow of information.

Other barriers to overcome might come from the agency's structure itself. Is the decision-making process centralized in one division or decentralized throughout different areas? Who in the agency ultimately decides how many funds will be allocated? Knowing the current decision-making process in the agency and management levels involved in the process will help to handle this aspect.

From the deployment and sustainability side, the challenge is to integrate the new approaching into existing management practices. This integration process goes beyond the pavement management area. At the strategic management level, decisions are not limited to pavement assets, and other interests may drive agency policies related to allocating funds among infrastructure assets. Unfortunately trade-offs for funding allocation among infrastructure assets are usually not clearly defined and might potentially impact deployment and sustainability of MOSPMA. Strategies about methods to deal with the complex issues related to the implementation process follow.

4.4.2 Strategies for Implementation

Implementation is not completed until the new approach becomes an essential component for making pavement management decisions within the agency. Having this principle in mind, successful deployment of the new approach does not assure sustainability. The methods to facilitate implementation involve commitment from policy makers and upper management.

Some strategies recommended to facilitate implementation are as follows:

- Showing the value of the new approach to a selected, small group of decision makers and practitioners that will be potential users of MOSPMA.
- Developing a high-level management network of "champions" that will drive a top-down effort to foster deployment and ensure sustainability of the new approach. These champions will mentor or coach other people leading to the formation of more champions at different management levels across the organization.
- Investing in "education" and "promotion" of the new approach through presentations, forums, and discussion threads at different management levels. This effort will reduce the "lack of understanding" which is one of the major reasons behind the "resistance to change".
- Emphasizing that the new approach relies upon pavement management principles currently being used by the agency, and that it expands the existing system capabilities by giving more flexibility for the development of investment strategies that fit the agency's needs. The new approach does not imply "reinventing the wheel", instead it uses existing concepts as a solid foundation.

- Applying effective communication strategies to support ample use of the new approach. Effective communication is critical for sustainability in the long-term. A communication strategy needs to clearly identify communication objectives, to prioritize areas for action, to open new channels to get top level strategies and actions across management levels, and to buy people's involvement by encouraging lateral communication and feedback.
- Monitoring results from usage of the new approach.

The strategies described above will facilitate the implementation of the multi-objective strategic pavement management approach proposed in this dissertation. However, broader vision is needed to get the most of the approach. The recommendation in this sense goes into the field of data integration and knowledge growth within an organization. The need to create a common platform to integrate management systems into an integrated decision support management system is certainly a topic to discuss. The use of GIS should play a major role for integrating data.

Regarding corporate knowledge growth within the agency, the systematic integration of knowledge management system components into pavement management systems for eliciting new knowledge, capturing existing knowledge, sharing acquired knowledge, and applying corporate knowledge, is probably the next step in the evolution of pavement management.

4.4.3 Benefits of Implementing a Multi-Objective Strategic Pavement Management Approach at MTC

The current version of MTC-PMS estimates budget needs for an unconstrained funding scenario, and forecasts the pavement network condition for a given funding scenario. Variation of the network average PCI over the planning horizon for an unconstrained funding scenario, a given funding scenario, and a no funds scenario can be compared as shown in Figure 32.

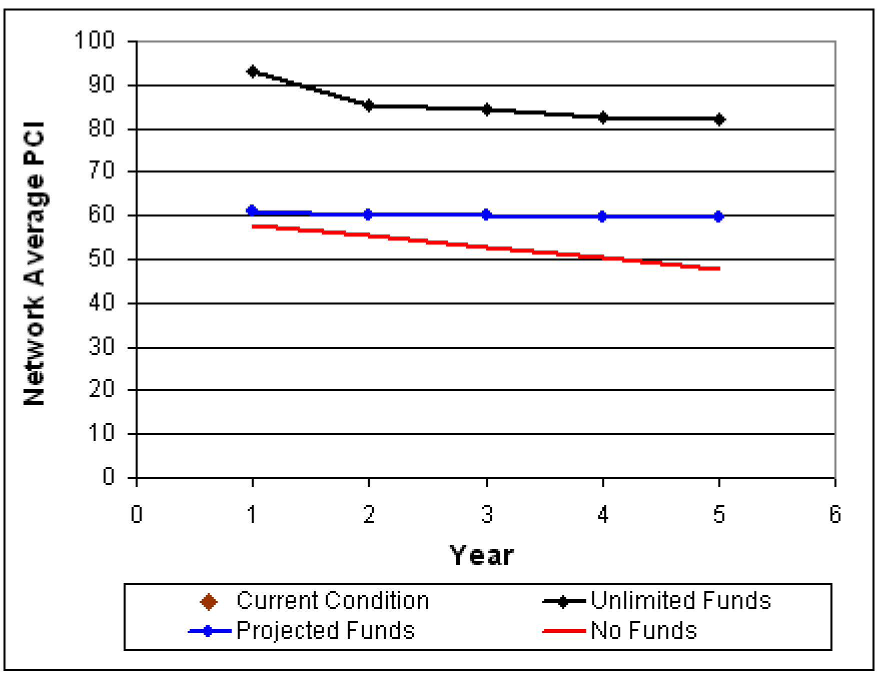

FIGURE 32 Current network PCI analysis for different funding scenarios.

Similar plots can be prepared to show variations over the planning horizon for other pavement network parameters: network average remaining life, percent of pavement in the entire network or sub-groups of the network in good condition, percent of pavement in the entire network or sub-groups of the network in poor and very poor condition, deferred maintenance, backlogged maintenance, or stop gap maintenance. These plots are helpful to decision makers to assess the impact of a proposed strategy but not enough to assist in developing a strategy to meet target objectives.

Figure 33 shows how decision makers can use the new approach (MOSPMA) to develop a strategy for recovering the network average PCI to the agency's desired level.

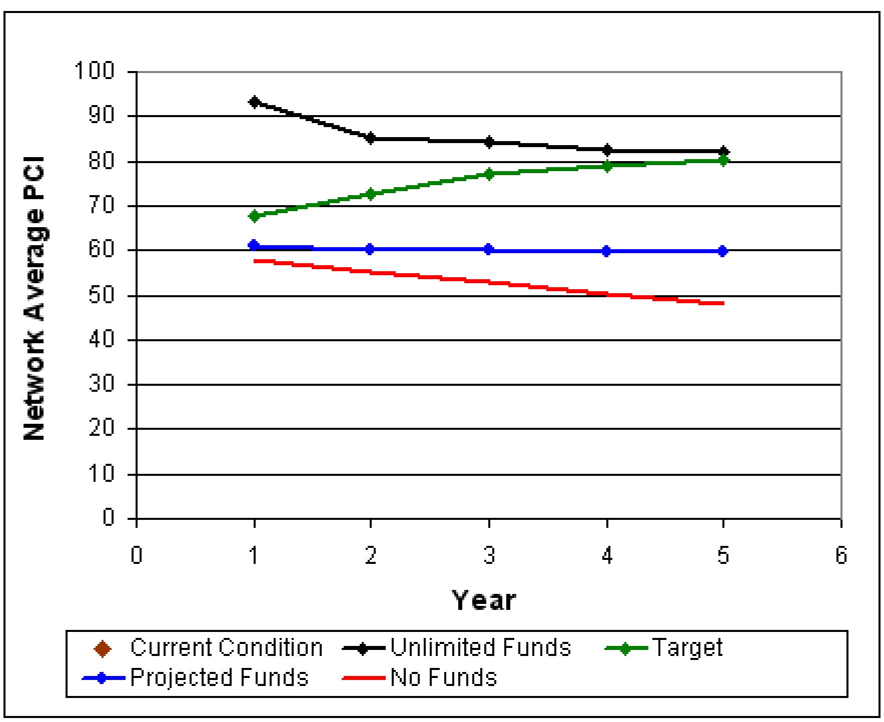

FIGURE 33 Setting the strategy to meet the target network average PCI.

Similar target objectives can be set for the pavement network based on the other three parameters. In addition, target objectives can be established for specific sub-groups of the pavement network including arterials, collectors, residential/local, and other.

MOSPMA offers decision makers more flexibility in the analysis and facilitates the development of a strategy to meet the target objectives. Target objectives established for the funding period may need to be adjusted over time due to changes in the agency's policies or the availability of funds.

An agency may be able to reach the target objectives by investing a considerable amount of funds at the first year of the planning horizon and then preserving the achieved stage in the next years. However, if the gap between the current network scenario and the target stage is large, a gradual investment strategy will probably be more realistic. The new approach allows decision makers to conduct this type of analysis to establish an investment strategy that fits better to their situation.

CHAPTER V

CASE STUDY: APPLICATION, INTERPRETATION, AND DISCUSSION

A case study is presented in this chapter to show how the methods developed in the multi-objective pavement management approach can assist an agency in developing an investment strategy to reach its target objectives. The alternative methods presented in chapter IV for determining funds required to meet multiple target objectives are compared. Interpretation of the results is presented with a discussion of the alternative methods used for solving the investment allocation problem.

5.1 CASE STUDY

The one-hundred section pavement database (100-DB) was selected for the case study. The 100-DB was developed in 1997 for the purpose of testing the MTC-PMS software. Since its creation the 100-DB has been considered as a primary source of reference for developing and testing of new modules, and it is currently being used by MTC for this purpose.

The advantage of using the 100-DB is that the case study can be run under a controlled environment so that the results can be better understood. Another reason is that the current capabilities of MTC-PMS makes it infeasible to run the case study for larger databases since there is a need to develop a new module with the method presented in this dissertation. To run the case study for the 100-DB, tools were developed in Excel© to reproduce the rules for treatment selection and PCI projection embedded in the professional MTC-PMS software called Street Saver© which was developed by a team of programmers and is supported by MTC. The special tools developed for the 100-DB case study rely upon the same principles and concepts enhanced by Street Saver, but they are hard-coded in an Excel© environment. A description of these tools is included in the appendix.

It is understood that findings from the 100-DB case study presented in this chapter will require additional validation through the implementation of a pilot project in order to analyze the results when the methodology is applied to larger databases. This pilot project can be conducted if the professional software supported by MTC is modified to include a new analysis module for the analytical procedure described in Chapter IV.

5.1.1 Pavement Network Composition of the 100-DB

The 100-DB is composed of four network sub-groups of twenty five sections each. The first sub-group is composed of arterial sections (A), the second sub-group of collector sections (C), the third sub-group of residential sections/local sections (R/L), and the fourth sub-group of other sections (O). In each sub-group there are five asphalt concrete (AC) sections, five asphalt concrete over asphalt concrete (AC/AC) sections, five asphalt concrete over portland cement concrete (AC/PCC) sections, five portland cement concrete (PCC) sections, and five surface treatment (ST) sections. Table 9 shows the street identification number, section identification number, year of construction, area of the section, functional class, surface type, current PCI, and remaining life for each section in the 100-DB.

TABLE 9 Pavement Section Characteristics for the 100-DB

Street ID	Section ID	Year Constructed	Area (sq ft)	Functional Class	Surface Type	PCI	Remaining Life (years)
1	0000	1990	10000	Arterial	AC	88.9	23.4
2	0100	1990	10000	Arterial	AC	68.0	15.1
3	0200	1990	10000	Arterial	AC	68.0	15.1
4	0300	1990	10000	Arterial	AC	43.9	4.8
5	0400	1990	10000	Arterial	AC	20.9	0.0
6	0010	1990	10000	Arterial	AC/AC	89.0	27.6
7	0110	1990	10000	Arterial	AC/AC	68.0	15.2
8	0210	1990	10000	Arterial	AC/AC	68.0	15.2
9	0310	1990	10000	Arterial	AC/AC	43.9	5.2
10	0410	1990	10000	Arterial	AC/AC	20.9	0.0
11	0020	1990	10000	Arterial	AC/PCC	89.0	27.6
12	0120	1990	10000	Arterial	AC/PCC	68.0	15.2
13	0220	1990	10000	Arterial	AC/PCC	68.0	15.2
14	0320	1990	10000	Arterial	AC/PCC	43.9	5.2
15	0420	1990	10000	Arterial	AC/PCC	20.9	0.0
16	0030	1958	10000	Arterial	PCC	89.0	56.2
17	0130	1958	10000	Arterial	PCC	68.0	29.3
18	0230	1958	10000	Arterial	PCC	68.0	29.3
19	0330	1958	10000	Arterial	PCC	44.0	10.2
20	0430	1958	10000	Arterial	PCC	20.9	0.0
21	0040	1992	10000	Arterial	ST	84.2	19.2
22	0140	1992	10000	Arterial	ST	68.0	9.8
23	0240	1992	10000	Arterial	ST	68.0	9.8
24	0340	1992	10000	Arterial	ST	43.9	4.6
25	0440	1992	10000	Arterial	ST	20.9	0.0
26	1000	1990	10000	Collector	AC	89.0	20.2
27	1100	1990	10000	Collector	AC	67.9	11.3
28	1200	1990	10000	Collector	AC	67.9	11.3
29	1300	1990	10000	Collector	AC	43.9	3.7
30	1400	1990	10000	Collector	AC	20.9	0.0
31	1010	1990	10000	Collector	AC/AC	88.9	28.2
32	1110	1990	10000	Collector	AC/AC	68.0	16.3
33	1210	1990	10000	Collector	AC/AC	68.0	16.3
34	1310	1990	10000	Collector	AC/AC	43.9	5.7
35	1410	1990	10000	Collector	AC/AC	20.9	0.0
36	1020	1990	10000	Collector	AC/PCC	88.9	28.2
37	1120	1990	10000	Collector	AC/PCC	68.0	16.3
38	1220	1990	10000	Collector	AC/PCC	68.0	16.3
39	1320	1990	10000	Collector	AC/PCC	43.9	5.7
40	1420	1990	10000	Collector	AC/PCC	20.9	0.0
41	1030	1958	10000	Collector	PCC	89.0	56.2
42	1130	1958	10000	Collector	PCC	68.0	29.3
43	1230	1958	10000	Collector	PCC	68.0	29.3
44	1330	1958	10000	Collector	PCC	44.0	10.2
45	1430	1958	10000	Collector	PCC	20.9	0.0
46	1040	1992	10000	Collector	ST	84.3	19.2
47	1140	1992	10000	Collector	ST	68.0	9.8
48	1240	1992	10000	Collector	ST	68.0	9.8
49	1340	1992	10000	Collector	ST	43.9	4.6
50	1440	1992	10000	Collector	ST	20.9	0.0

Table 9 (Continued)

Street ID	Section ID	Year Constructed	Area (sq ft)	Functional Class	Surface Type	PCI	Remaining Life (years)
51	2000	1990	10000	Residential/Local	AC	89.0	31.6
52	2100	1990	10000	Residential/Local	AC	68.0	18.9
53	2200	1990	10000	Residential/Local	AC	68.0	18.9
54	2300	1990	10000	Residential/Local	AC	43.9	6.9
55	2400	1990	10000	Residential/Local	AC	20.9	0.0
56	2010	1990	10000	Residential/Local	AC/AC	89.0	35.6
57	2110	1990	10000	Residential/Local	AC/AC	68.0	20.8
58	2210	1990	10000	Residential/Local	AC/AC	68.0	20.8
59	2310	1990	10000	Residential/Local	AC/AC	43.9	8.0
60	2410	1990	10000	Residential/Local	AC/AC	20.9	0.0
61	2020	1990	10000	Residential/Local	AC/PCC	89.0	35.6
62	2120	1990	10000	Residential/Local	AC/PCC	68.0	20.8
63	2220	1990	10000	Residential/Local	AC/PCC	68.0	20.8
64	2320	1990	10000	Residential/Local	AC/PCC	44.0	8.0
65	2420	1990	10000	Residential/Local	AC/PCC	20.9	0.0
66	2030	1958	10000	Residential/Local	PCC	89.0	66.4
67	2130	1958	10000	Residential/Local	PCC	68.0	34.6
68	2230	1958	10000	Residential/Local	PCC	68.0	34.6
69	2330	1958	10000	Residential/Local	PCC	44.0	12.3
70	2430	1958	10000	Residential/Local	PCC	21.0	0.0
71	2040	1992	10000	Residential/Local	ST	84.3	19.2
72	3040	1992	10000	Residential/Local	ST	68.0	9.8
73	2240	1992	10000	Residential/Local	ST	68.0	9.8
74	2340	1992	10000	Residential/Local	ST	43.9	4.6
75	2440	1992	10000	Residential/Local	ST	20.9	0.0
76	3000	1990	10000	Other	AC	89.0	31.6
77	3100	1990	10000	Other	AC	68.0	18.9
78	3200	1990	10000	Other	AC	68.0	18.9
79	3300	1990	10000	Other	AC	43.9	6.9
80	3410	1990	10000	Other	AC	20.9	0.0
81	3010	1990	10000	Other	AC/AC	89.0	35.6
82	3110	1990	10000	Other	AC/AC	68.0	20.8
83	3210	1990	10000	Other	AC/AC	68.0	20.8
84	3310	1990	10000	Other	AC/AC	43.9	8.0
85	3410	1990	10000	Other	AC/AC	20.9	0.0
86	3020	1990	10000	Other	AC/PCC	89.0	35.6
87	3120	1990	10000	Other	AC/PCC	68.0	20.8
88	3220	1990	10000	Other	AC/PCC	68.0	20.8
89	3320	1990	10000	Other	AC/PCC	44.0	8.0
90	3420	1990	10000	Other	AC/PCC	20.9	0.0
91	3030	1958	10000	Other	PCC	89.0	66.4
92	3130	1958	10000	Other	PCC	68.0	34.6
93	3330	1958	10000	Other	PCC	68.0	34.6
94	3330	1958	10000	Other	PCC	44.0	12.3
95	3430	1958	10000	Other	PCC	21.0	0.0
96	3040	1992	10000	Other	ST	84.3	19.2
97	3140	1992	10000	Other	ST	68.0	9.8
98	3240	1992	10000	Other	ST	68.0	9.8
99	3340	1992	10000	Other	ST	43.9	4.6
100	3440	1992	10000	Other	ST	20.9	0.0

Table 10 shows a summary of the pavement network composition organized by functional class and surface type.

TABLE 10 Pavement Network Composition by Functional Class and Surface Type

Functional Class	Number of Sections	Surface Type				
		AC Area (sq-ft)	AC/AC Area (sq-ft)	AC/PCC Area (sq-ft)	PCC Area (sq-ft)	ST Area (sq-ft)
Arterial	25	250,000	250,000	250,000	250,000	250,000
Collector	25	250,000	250,000	250,000	250,000	250,000
Residential/Local	25	250,000	250,000	250,000	250,000	250,000
Other	25	250,000	250,000	250,000	250,000	250,000
Entire Network	100	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000

5.1.2 Diagnosis of the 100-DB Current Pavement Network Stage

The current pavement network condition for the 100-DB is considered good since the network average pavement condition index (PCI) is 58. Twenty percent of the pavement network is in very good condition (condition category I, PCI above 70) while forty percent of the pavement network is in poor and very poor condition (condition category IV and V, PCI below 50). Table 11 shows a summary of the pavement network composition by functional class and condition category.

The network average remaining life is sixteen years. Twenty-two percent of the pavement network has a remaining life equal to or less than five years while forty percent of the network has a remaining life above twenty years. Table 12 shows the remaining life for the pavement network grouped by functional class and remaining life categories.

TABLE 11 Pavement Network Composition by Condition Category and Functional Class

Functional Class	Network Average PCI	Condition Category				
		Category I (% of network)	Category II (% of network)	Category III (% of network)	Category IV (% of network)	Category V (% of network)
Arterial	58	5	5	5	5	5
Collector	58	5	5	5	5	5
Residential/Local	58	5	5	5	5	5
Other	58	5	5	5	5	5
Entire Network	58	20	20	20	20	20

TABLE 12 Pavement Network Composition by Remaining Life Category and Functional Class

Functional Class	Network Average Remaining Life (Years)	Remaining Life Category				
		0 – 5 years (% of network)	5 – 10 years (% of network)	10 -15 years (% of network)	15 – 20 years (% of network)	Above 20 years (% of network)
Arterial	14	6	1	1	6	11
Collector	14	6	2	1	7	9
Residential/Local	18	5	4	1	5	10
Other	18	5	4	1	5	10
Entire Network	16	22	11	4	23	40

5.1.3 Needs Analysis for the 100-DB Network

A twenty-year needs analysis was performed for the 100-DB. Funding needs were estimated assuming an unconstrained funding scenario. An inflation rate of three percent was assumed to estimate the total funding needs. A total of US$ 1,052,345 is needed over the twenty year period as shown in Table 13. Under this funding scenario the pavement network condition is above 80 along the planning horizon.

Table 13 Pavement Network Funding Needs from Twenty-year Needs Analysis

Year	Untreated PCI	Need (US$)	Treated PCI
1	58	$451,755	93
2	55	$0	85
3	53	$877	84
4	50	$7	82
5	48	$1,184	82
6	46	$61,062	85
7	43	$37,944	89
8	41	$227	83
9	39	$550	82
10	37	$400	81
11	34	$52,256	83
12	31	$0	81
13	29	$59,296	86
14	28	$0	80
15	26	$92,652	82
16	25	$13,863	80
17	23	$54,281	81
18	22	$19,880	79
19	20	$129,752	87
20	19	$76,359	83
	Total	$1,052,345	

A major portion of the total funding needs should be allocated in the first year to recover the pavement network condition from 58 to 93. The funding needs required in year one are US$ 451,745, which is about forty-three percent of the twenty-year needs, for an unconstrained funding scenario. Table 14 shows the recommended treatment, treatment cost with corresponding WER, and changes in PCI and remaining life due to treatment for each section. The overall WER for treatments applied in year one under an unconstrained funding scenario would be 87,780,997.

TABLE 14 Recommended Treatments from 100-DB Needs Analysis (Year 1)

Street ID	PCI before treatment	Remaining Life before Treatment (Years)	Treatment Category	Treatment Cost (US $)	Weighted Effectiveness Ratio (WER)	Cost/WER US $)	PCI after Treatment	Remaining Life after Treatment
1	88.9	23.4	Seal Coat (S)	822	107491	76.5	94.5	25.1
2	68.0	15.1	Single Chip Seal	1233	160929	76.6	77.3	20.1
3	68.0	15.1	Thin AC Overlay (1.5)	4433	131020	338.4	100.0	29.4
4	43.9	4.8	Thick AC Overlay (2.5)	7078	114421	618.6	100.0	29.4
5	20.9	0.0	Reconstruction	15556	48063	3236.5	100.0	25.4
6	89.0	27.6	Seal Coat (S)	822	100241	82.0	94.5	29.3
7	68.0	15.2	Double Chip Seal	1689	131213	128.7	77.3	20.9
8	68.0	15.2	Heater Scarify & Overlay	6611	86153	767.4	100.0	29.4
9	43.9	5.2	Heater Scarify & Overlay	6822	118207	577.1	100.0	29.4
10	20.9	0.0	Reconstruction	15556	48063	3236.5	100.0	25.4
11	89.0	27.6	Seal Coat (S)	822	100252	82.0	94.5	29.3
12	68.0	15.2	Double Chip Seal	1689	131205	128.7	77.3	20.9
13	68.0	15.2	Heater Scarify & Overlay	6611	86153	767.4	100.0	29.4
14	43.9	5.2	Heater Scarify & Overlay	6822	118205	577.2	100.0	29.4
15	20.9	0.0	Reconstruction	15556	48063	3236.5	100.0	25.4
16	89.0	56.2	Crack Seal (C)	9	29035133	0.0	93.6	64.5
17	68.0	29.3	Do Nothing	0	0	1000000.0	68.0	29.3
18	68.0	29.3	Do Nothing	0	0	1000000.0	68.0	29.3
19	44.0	10.2	Thick AC Overlay (2.5)	7078	108813	650.5	100.0	29.4
20	20.9	0.0	Reconstruction	15556	95859	1622.8	100.0	72.6
21	84.2	19.2	Crack Seal (C)	18	70183	2.6	85.5	19.3
22	68.0	9.8	Single Chip Seal	1233	222148	55.5	100.0	19.3
23	68.0	9.8	Single Chip Seal	1678	163301	102.7	100.0	19.3
24	43.9	4.6	Single Chip Seal	2133	218444	97.7	100.0	19.3
25	20.9	0.0	Thick AC Overlay (2.5)	8522	59340	1436.2	100.0	19.3
26	89.0	20.2	Seal Coat (S)	822	131307	62.6	94.5	23.0
27	67.9	11.3	Single Chip Seal	1233	98249	125.5	77.3	15.3
28	67.9	11.3	Thin AC Overlay (1.5)	4433	104558	424.0	100.0	30.0
29	43.9	3.7	Thick AC Overlay (2.5)	6856	85581	801.1	100.0	30.0
30	20.9	0.0	Reconstruction	12644	46353	2727.8	100.0	24.3
31	88.9	28.2	Seal Coat (S)	822	71356	115.2	94.5	29.9
32	68.0	16.3	Double Chip Seal	1689	94145	179.4	77.3	22.0
33	68.0	16.3	Heater Scarify & Overlay	6611	60250	1097.3	100.0	30.0
34	43.9	5.7	Heater Scarify & Overlay	6822	84456	807.8	100.0	30.0
35	20.9	0.0	Reconstruction	12644	46353	2727.8	100.0	24.3
36	88.9	28.2	Seal Coat (S)	822	71364	115.2	94.5	29.9
37	68.0	16.3	Double Chip Seal	1689	94139	179.4	77.3	22.0
38	68.0	16.3	Heater Scarify & Overlay	6611	60251	1097.3	100.0	30.0
39	43.9	5.7	Heater Scarify & Overlay	6822	84456	807.8	100.0	30.0
40	20.9	0.0	Reconstruction	12644	46353	2727.8	100.0	24.3
41	89.0	56.2	Crack Seal (C)	9	20905296	0.0	93.6	64.5
42	68.0	29.3	Do Nothing	0	0	1000000.0	68.0	29.3
43	68.0	29.3	Do Nothing	0	0	1000000.0	68.0	29.3
44	44.0	10.2	Thick AC Overlay (2.5)	6856	80598	850.6	100.0	30.0
45	20.9	0.0	Reconstruction	12644	84908	1489.2	100.0	72.6
46	84.3	19.2	Crack Seal (C)	18	49354	3.7	85.6	19.3
47	68.0	9.8	Single Chip Seal	1233	159943	77.1	100.0	19.3
48	68.0	9.8	Single Chip Seal	1678	117574	142.7	100.0	19.3
49	43.9	4.6	Single Chip Seal	2133	157279	135.6	100.0	19.3
50	20.9	0.0	Thick AC Overlay (2.5)	8300	43869	1892.0	100.0	19.3

TABLE 14 (Continued)

Street ID	PCI before treatment	Remaining Life before Treatment (Years)	Treatment Category	Treatment Cost (US $)	Weighted Effectiveness Ratio (WER)	Cost/WER US $)	PCI after Treatment	Remaining Life after Treatment
50	20.9	0.0	Thick AC Overlay (2.5)	8300	43869	1892.0	100.0	19.3
51	89.0	31.6	Seal Coat (S)	822	67882	121.1	94.5	33.8
52	68.0	18.9	Single Chip Seal	1233	96150	128.3	77.3	24.7
53	68.0	18.9	Thin AC Overlay (1.5)	4433	82258	539.0	100.0	38.5
54	43.9	6.9	Thick AC Overlay (2.5)	6633	75469	879.0	100.0	38.5
55	20.9	0.0	Reconstruction	9722	50748	1915.8	100.0	34.1
56	89.0	35.6	Seal Coat (S)	822	73243	112.3	94.5	38.1
57	68.0	20.8	Double Chip Seal	1689	70935	238.1	77.3	26.9
58	68.0	20.8	Heater Scarify & Overlay	6611	53031	1246.7	100.0	38.5
59	43.9	8.0	Heater Scarify & Overlay	6822	72848	936.5	100.0	38.5
60	20.9	0.0	Reconstruction	9722	50748	1915.8	100.0	34.1
61	89.0	35.6	Seal Coat (S)	822	73247	112.3	94.5	38.1
62	68.0	20.8	Double Chip Seal	1689	70929	238.1	77.3	26.9
63	68.0	20.8	Heater Scarify & Overlay	6611	53032	1246.6	100.0	38.5
64	44.0	8.0	Heater Scarify & Overlay	6822	72848	936.5	100.0	38.5
65	20.9	0.0	Reconstruction	9722	50748	1915.8	100.0	34.1
66	89.0	66.4	Crack Seal (C)	9	15174656	0.0	93.6	75.2
67	68.0	34.6	Do Nothing	0	0	1000000.0	68.0	34.6
68	68.0	34.6	Do Nothing	0	0	1000000.0	68.0	34.6
69	44.0	12.3	Thick AC Overlay (2.5)	6633	72589	913.8	100.0	38.5
70	21.0	0.0	Reconstruction	9722	84419	1151.7	100.0	81.9
71	84.3	19.2	Crack Seal (C)	18	37701	4.8	85.6	19.3
72	68.0	9.8	Single Chip Seal	1233	122179	100.9	100.0	19.3
73	68.0	9.8	Single Chip Seal	1678	89814	186.8	100.0	19.3
74	43.9	4.6	Single Chip Seal	2133	120144	177.6	100.0	19.3
75	20.9	0.0	Thick AC Overlay (2.5)	8078	34433	2345.9	100.0	19.3
76	89.0	31.6	Seal Coat (S)	822	67882	121.1	94.5	33.8
77	68.0	18.9	Single Chip Seal	1233	96150	128.3	77.3	24.7
78	68.0	18.9	Thin AC Overlay (1.5)	4433	82258	539.0	100.0	38.5
79	43.9	6.9	Thick AC Overlay (2.5)	6633	75469	879.0	100.0	38.5
80	20.9	0.0	Reconstruction	9722	50748	1915.8	100.0	34.1
81	89.0	35.6	Seal Coat (S)	822	73243	112.3	94.5	38.1
82	68.0	20.8	Double Chip Seal	1689	70935	238.1	77.3	26.9
83	68.0	20.8	Heater Scarify & Overlay	6611	53031	1246.7	100.0	38.5
84	43.9	8.0	Heater Scarify & Overlay	6822	72848	936.5	100.0	38.5
85	20.9	0.0	Reconstruction	9722	50748	1915.8	100.0	34.1
86	89.0	35.6	Seal Coat (S)	822	73247	112.3	94.5	38.1
87	68.0	20.8	Double Chip Seal	1689	70929	238.1	77.3	26.9
88	68.0	20.8	Heater Scarify & Overlay	6611	53032	1246.6	100.0	38.5
89	44.0	8.0	Heater Scarify & Overlay	6822	72848	936.5	100.0	38.5
90	20.9	0.0	Reconstruction	9722	50748	1915.8	100.0	34.1
91	89.0	66.4	Crack Seal (C)	9	15174656	0.0	93.6	75.2
92	68.0	34.6	Do Nothing	0	0	1000000.0	68.0	34.6
93	68.0	34.6	Do Nothing	0	0	1000000.0	68.0	34.6
94	44.0	12.3	Thick AC Overlay (2.5)	6633	72589	913.8	100.0	38.5
95	21.0	0.0	Reconstruction	9722	84419	1151.7	100.0	81.9
96	84.3	19.2	Crack Seal (C)	18	37701	4.8	85.6	19.3
97	68.0	9.8	Single Chip Seal	1233	122179	100.9	100.0	19.3
98	68.0	9.8	Single Chip Seal	1678	89814	186.8	100.0	19.3
99	43.9	4.6	Single Chip Seal	2133	120144	177.6	100.0	19.3
100	20.9	0.0	Thick AC Overlay (2.5)	8078	34433	2345.9	100.0	19.3
			Total	451,755	87,780,997			

5.2 TARGET OBJECTIVES FOR THE 100-DB NETWORK

Long-term strategic planning is laid out through budget estimates tied to funding periods. Funding periods are usually set based on legislative periods. Funding needs to meet target objectives should be set considering the way strategic planning is carried out by a local agency. For the purpose of the case study a five-year funding period is assumed.

In this case study the investment strategy consisted of gradually improving the current pavement network stage during the first five years and then preserving the network condition during the remaining years of the planning horizon. Table 15 shows the pavement network parameters for the current network state.

TABLE 15 Pavement Network Parameters for the Current State

Functional Class	Network Average Pavement Condition Index (PCI)	Network Average Remaining Life (years)	Percent of the Pavement Network Group in Very Good Condition (%)	Percent of the Pavement Network Group in Poor and Very Poor Condition (%)
Arterial	58	14	5	10
Collector	58	14	5	10
Residential/Local	58	18	5	10
Other	58	18	5	10
Entire Network	58	16	20	40

Target objectives were set for the network average PCI, network average remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor and very poor condition for each year of the funding period. Table 16 shows the network average PCI target matrix for the five-year funding period. Table 17 shows the network average remaining life target matrix for a five-year funding period.

TABLE 16 Network Average PCI Target Matrix for a Five-year Funding Period

Functional Class	Current (PCI)	Target Network Average PCI				
		Year 1	Year 2	Year 3	Year 4	Year 5
Arterial	58	68	73	76	78	81
Collector	58	63	70	74	75	81
Residential/Local	58	59	67	73	75	80
Other	58	59	67	73	75	80
Entire Network	58	62	69	74	76	81

TABLE 17 Network Average Remaining Life Target Matrix for a Five-year Funding Period

Functional Class	Current (years)	Target Network Average Remaining Life (years)				
		Year 1	Year 2	Year 3	Year 4	Year 5
Arterial	14	16	20	24	25	25
Collector	14	16	20	24	24	25
Residential/Local	18	18	20	24	24	25
Other	18	18	20	24	24	25
Entire Network	16	17	20	24	24	25

Table 18 shows the target matrix for the percentage of the pavement network in very good condition. Table 19 shows the target matrix for the percentage of the pavement network in poor and very poor condition.

TABLE 18 Target Matrix for the Percent of the Pavement Network in Very Good Condition

Functional Class	Current (%)	Target Percent of Pavement Network (%)				
		Year 1	Year 2	Year 3	Year 4	Year 5
Arterial	5	12	19	21	22	23
Collector	5	9	18	20	21	23
Residential/Local	5	6	16	18	20	21
Other	5	6	16	18	20	21
Entire Network	20	33	69	77	83	88

TABLE 19 Target Matrix for the Percent of the Pavement Network in Poor and Very Poor Condition

Functional Class	Current (%)	Target Percent of Pavement Network (%)				
		Year 1	Year 2	Year 3	Year 4	Year 5
Arterial	10	8	4	2	1	0
Collector	10	10	5	3	2	0
Residential/Local	10	10	7	4	3	2
Other	10	10	7	4	3	2
Entire Network	40	38	23	13	9	4

5.3 INVESTMENT NEEDS TO MEET TARGET OBJECTIVES

Investment needs to meet the target objectives for recovering the pavement network state to the desired pavement network state were determined using the two methods presented in Chapter IV, section 4.3.3: (1) a sequential year ranking method using the "dynamic bubble up" procedure (DBU), and (2) a multi-objective optimization model coupled with and integer program solving technique.

It was assumed that once the pavement network was brought back to the desired pavement network state, funding needs estimated for an unconstrained funding scenario could be allocated by the agency since the major investment effort was taken during the first five-year funding period. Therefore, the tools developed in Excel© for the case study were prepared to run for a five-year period. Consecutive runs could be used for longer terms, but this effort was beyond the scope of this dissertation. The main purpose of the case study was to illustrate the methods, and to observe if there were differences in future funding needs and pavement network state due to the use of different funding allocation methods.

5.3.1 Investment Needs for the First Year of the Funding Period

The multi-objective target matrix for the first year of the funding period is shown in Table 20. One of the advantages of the multi-objective management approach is that different target objectives can be set for each sub-group of the pavement network. As observed in Table 20, higher targets were set for the arterial sub-group when compared to targets set for the other sub-groups.

TABLE 20 Multi-objective Target Matrix for the First Year of the Funding Period

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life (years)	Minimum Percent of the Pavement Network Group in Very Good Condition (%)	Maximum Percent of the Pavement Network Group in Poor and Very Poor Condition (%)
Arterial	68	16	12	8
Collector	63	16	9	10
Residential/Local	59	18	6	10
Other	59	18	6	10
Entire Network	62	17	33	38

Using the "Dynamic Bubble Up" Technique (DBU) Based on WER (Year 1)

The "dynamic bubble up" technique based on WER was used to estimate the investment needs to meet the target objectives set for the network average PCI, network average remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor condition and very poor condition.

The treatment selection process followed MTC-PMS rules for needs analysis. The Weight Effectiveness Ratio (WER) was calculated for each section in the 100-DB identified as needing treatment, and sections were ranked from highest to lowest WER. An iterative process followed to calculate investment needs to meet the target objectives. The process assumed that k sections were funded and 100 - k were not. If the calculated value for the pavement network parameter did not meet the target, the next section was "bubbled up" (k increases) and a new value was calculated until the target was met or the last section in the list was reached. The aim of this method is to minimize the level of investments required to meet the targets while, at the same time, maximizing the overall treatment effectiveness.

Using the "bubble up" technique based on WER the investment needs to meet target objectives were estimated at US$ 40,537 for the first year of the funding period as shown in Table 21. More funds are needed by the arterial pavement network sub-group followed by the collector pavement network sub-group, and then the residential and other sub-groups. These results were expected since target objectives set for arterials were higher than the targets set for other network sub-groups.

TABLE 21 Investment Needs to Meet Target Objectives Using DBU based on WER (Year 1)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	9	27733	27742
Collector	833	9478	10311
Residential	9	1233	1242
Other	9	1233	1242
Entire Network	860	39677	40537

Using the Multi-Objective Optimization Model with Integer Programming (Year 1)

Using the optimization technique to solve the problem, investment needs to meet target objectives were estimated at US$ 34,699 for the first year of the funding period. As shown in Table 22 the optimization solution indicated that more funds should be allocated to the arterial pavement network sub-group followed by the collector pavement network sub-group, and then the residual and other sub-groups. This situation was expected since target objectives set for arterials were higher when compared to targets set for the other sub-groups.

TABLE 22 Investment Needs to Meet Target Objectives Using Optimization (Year 1)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	2494	20911	23405
Collector	1672	6278	7950
Residential	28	1233	1261
Other	850	1233	2083
Entire Network	5044	29655	34699

Solving the model formulation was a computer intensive task that took about twenty hours in total to provide a solution for this very small 100 section database over a five year analysis period. The process could be sped up considerably by assuming at the beginning of the iteration process a set of variables X_i (1 if section "i" is selected for a treatment; 0 otherwise) close to the solution. A test was conducted by starting the optimization process with results obtained from DBU, and this test reduced processing time for solving the problem to less than one hour.

Comparing Results from Alternative Funding Allocation Methods (Year 1)

Investment needs using DBU based on WER were higher than investment needs using the optimization technique (US$ 40,537 versus US$ 34,699). The list of sections selected for funding varies depending on the funding allocation method used to estimate investments. Table 23 shows sections selected for funding using DBU based on WER and sections selected for funding using the optimization technique.

Twenty sections were selected for funding using the "dynamic bubble up" technique with an overall WER of 82,599,432 while twenty-eight sections were selected for funding with an overall WER of 83,122,454 using the optimization technique. There were five sections selected for preventive treatment and fifteen sections selected for rehabilitation when using DBU based on WER. On the other hand, there were fourteen sections selected for preventive treatment and fourteen sections selected for rehabilitation using the optimization technique.

TABLE 23 Sections Selected for Funding Using DBU Based on WER When Compared to Optimization (Year 1)

Street_ID	Functional Class	Surface Type	DBU based on WER			Optimization		
			Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER
1	Arterial	AC	0	0	0	1	822	107491
2	Arterial	AC	1	1233	160929	1	1233	160929
3	Arterial	AC	1	4433	131020	1	4433	131020
4	Arterial	AC	0	0	0	0	0	0
5	Arterial	AC	0	0	0	0	0	0
6	Arterial	AC/AC	0	0	0	1	822	100241
7	Arterial	AC/AC	1	1689	131213	1	1689	131213
8	Arterial	AC/AC	0	0	0	0	0	0
9	Arterial	AC/AC	1	6822	118207	1	6822	118207
10	Arterial	AC/AC	0	0	0	0	0	0
11	Arterial	AC/PCC	0	0	0	1	822	100252
12	Arterial	AC/PCC	1	1689	131205	1	1689	131205
13	Arterial	AC/PCC	0	0	0	0	0	0
14	Arterial	AC/PCC	1	6822	118205	0	0	0
15	Arterial	AC/PCC	0	0	0	0	0	0
16	Arterial	PCC	1	9	29035133	1	9	29035133
17	Arterial	PCC	0	0	0	0	0	0
18	Arterial	PCC	0	0	0	0	0	0
19	Arterial	PCC	0	0	0	0	0	0
20	Arterial	PCC	0	0	0	0	0	0
21	Arterial	ST	0	0	0	1	18	70183
22	Arterial	ST	1	1233	222148	1	1233	222148
23	Arterial	ST	1	1678	163301	1	1678	163301
24	Arterial	ST	1	2133	218444	1	2133	218444
25	Arterial	ST	0	0	0	0	0	0
26	Collector	AC	1	822	131307	1	822	131307
27	Collector	AC	0	0	0	1	1233	98249
28	Collector	AC	1	4433	104558	0	0	0
29	Collector	AC	0	0	0	0	0	0
30	Collector	AC	0	0	0	0	0	0
31	Collector	AC/AC	0	0	0	0	0	0
32	Collector	AC/AC	0	0	0	0	0	0
33	Collector	AC/AC	0	0	0	0	0	0
34	Collector	AC/AC	0	0	0	0	0	0
35	Collector	AC/AC	0	0	0	0	0	0
36	Collector	AC/PCC	0	0	0	1	822	71364
37	Collector	AC/PCC	0	0	0	0	0	0
38	Collector	AC/PCC	0	0	0	0	0	0
39	Collector	AC/PCC	0	0	0	0	0	0
40	Collector	AC/PCC	0	0	0	0	0	0
41	Collector	PCC	1	9	20905296	1	9	20905296
42	Collector	PCC	0	0	0	0	0	0
43	Collector	PCC	0	0	0	0	0	0
44	Collector	PCC	0	0	0	0	0	0
45	Collector	PCC	0	0	0	0	0	0
46	Collector	ST	0	0	0	1	18	49354
47	Collector	ST	1	1233	159943	1	1233	159943
48	Collector	ST	1	1678	117574	1	1678	117574
49	Collector	ST	1	2133	157279	1	2133	157279
50	Collector	ST	0	0	0	0	0	0

TABLE 23 (Continued)

Street_ID	Functional Class	Surface Type	DBU based on WER			Optimization		
			Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER
51	Residential/Local	AC	0	0	0	0	0	0
52	Residential/Local	AC	0	0	0	0	0	0
53	Residential/Local	AC	0	0	0	0	0	0
54	Residential/Local	AC	0	0	0	0	0	0
55	Residential/Local	AC	0	0	0	0	0	0
56	Residential/Local	AC/AC	0	0	0	0	0	0
57	Residential/Local	AC/AC	0	0	0	0	0	0
58	Residential/Local	AC/AC	0	0	0	0	0	0
59	Residential/Local	AC/AC	0	0	0	0	0	0
60	Residential/Local	AC/AC	0	0	0	0	0	0
61	Residential/Local	AC/PCC	0	0	0	0	0	0
62	Residential/Local	AC/PCC	0	0	0	0	0	0
63	Residential/Local	AC/PCC	0	0	0	0	0	0
64	Residential/Local	AC/PCC	0	0	0	0	0	0
65	Residential/Local	AC/PCC	0	0	0	0	0	0
66	Residential/Local	PCC	1	9	15174656	1	9	15174656
67	Residential/Local	PCC	0	0	0	0	0	0
68	Residential/Local	PCC	0	0	0	0	0	0
69	Residential/Local	PCC	0	0	0	0	0	0
70	Residential/Local	PCC	0	0	0	0	0	0
71	Residential/Local	ST	0	0	0	1	18	37701
72	Residential/Local	ST	1	1233	122179	1	1233	122179
73	Residential/Local	ST	0	0	0	0	0	0
74	Residential/Local	ST	0	0	0	0	0	0
75	Residential/Local	ST	0	0	0	0	0	0
76	Other	AC	0	0	0	0	0	0
77	Other	AC	0	0	0	0	0	0
78	Other	AC	0	0	0	0	0	0
79	Other	AC	0	0	0	0	0	0
80	Other	AC	0	0	0	0	0	0
81	Other	AC/AC	0	0	0	0	0	0
82	Other	AC/AC	0	0	0	0	0	0
83	Other	AC/AC	0	0	0	0	0	0
84	Other	AC/AC	0	0	0	0	0	0
85	Other	AC/AC	0	0	0	0	0	0
86	Other	AC/PCC	0	0	0	1	822	73247
87	Other	AC/PCC	0	0	0	0	0	0
88	Other	AC/PCC	0	0	0	0	0	0
89	Other	AC/PCC	0	0	0	0	0	0
90	Other	AC/PCC	0	0	0	0	0	0
91	Other	PCC	1	9	15174656	1	9	15174656
92	Other	PCC	0	0	0	0	0	0
93	Other	PCC	0	0	0	0	0	0
94	Other	PCC	0	0	0	0	0	0
95	Other	PCC	0	0	0	0	0	0
96	Other	ST	0	0	0	1	18	37701
97	Other	ST	1	1233	122179	1	1233	122179
98	Other	ST	0	0	0	0	0	0
99	Other	ST	0	0	0	0	0	0
100	Other	ST	0	0	0	0	0	0
			20	40,537	82,599,432	28	34,699	83,122,454

Although there were eight more sections selected for funding using the optimization technique when compared to the bubble up technique, needed funds to meet the target objectives were lower and the overall WER was higher than the solution provided by DBU. Sections 1, 6, 11, 21, 27, 36, 46, 71, 86, and 96 identified as needing preventive maintenance were selected by optimization but not by DBU because target objectives were satisfied before “bubbling up” these sections. Sections 14 and 28 that are in need of rehabilitation were selected by DBU but not by optimization. Allocating funds to more sections in need of preventive maintenance instead of sections in need of rehabilitation led to meeting the target objectives at a lower cost and resulted in a higher overall WER.

Needed funds estimated using DBU technique varies with the criterion used for ranking. WER was proposed for ranking sections from highest to lowest. Other parameters were considered for ranking such as PCI increment (descending order), Cost/PCI (ascending order), and Cost/WER (ascending order). It was found that DBU provided similar results to the optimization technique if sections were ranked form lowest to highest Cost/WER

Using the “Dynamic Bubble Up” Technique (DBU) Based on Cost/WER (Year 1)

Using the “dynamic bubble up” (DBU) technique based on Cost/WER, investment needs to meet the first year target objectives were US$ 34,699 and the overall WER was 83,120,563. Table 24 summarizes the investment needs using DBU based on Cost/WER.

TABLE 24 Investment Needs to Meet Target Objectives Using DBU Based on Cost/WER (Year 1)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	2494	20911	23405
Collector	2494	6278	8772
Residential	28	1233	1261
Other	28	1233	1261
Entire Network	5044	29655	34699

The level of investment required to meet target objectives was the same as for the optimization technique,but overall WER was slightly lower. Table 25 shows sections selected for funding using optimization and sections selected for funding using DBU based on WER/Cost. Twenty-eight sections were selected for treatment using DBU based on Cost/WER. Fourteen sections were identified for preventive maintenance and fourteen sections for rehabilitation.

The difference between sections selected for funding by optimization and DBU was that DBU selected section 31 instead of section 86 that was selected by optimization. Both sections required a seal coat and the treatment cost was the same for both sections, but section 31 was an AC/AC-Collector while section 86 was an AC/PCC-Other. The WER for section 86 was higher than the WER for section 31. This difference led the overall WER of sections selected by optimization to increase to a value more than the overall WER of sections selected by DBU based on Cost/WER.

TABLE 25 Sections Selected for Funding Using Optimization When Compared to DBU Based on Cost/WER (Year 1)

Street_ID	Functional Class	Surface Type	Optimization			DBU based on Cost/WER		
			Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER
1	Arterial	AC	1	822	107491	1	822	107491
2	Arterial	AC	1	1233	160929	1	1233	160929
3	Arterial	AC	1	4433	131020	1	4433	131020
4	Arterial	AC	0	0	0	0	0	0
5	Arterial	AC	0	0	0	0	0	0
6	Arterial	AC/AC	1	822	100241	1	822	100241
7	Arterial	AC/AC	1	1689	131213	1	1689	131213
8	Arterial	AC/AC	0	0	0	0	0	0
9	Arterial	AC/AC	1	6822	118207	1	6822	118207
10	Arterial	AC/AC	0	0	0	0	0	0
11	Arterial	AC/PCC	1	822	100252	1	822	100252
12	Arterial	AC/PCC	1	1689	131205	1	1689	131205
13	Arterial	AC/PCC	0	0	0	0	0	0
14	Arterial	AC/PCC	0	0	0	0	0	0
15	Arterial	AC/PCC	0	0	0	0	0	0
16	Arterial	PCC	1	9	29035133	1	9	29035133
17	Arterial	PCC	0	0	0	0	0	0
18	Arterial	PCC	0	0	0	0	0	0
19	Arterial	PCC	0	0	0	0	0	0
20	Arterial	PCC	0	0	0	0	0	0
21	Arterial	ST	1	18	70183	1	18	70183
22	Arterial	ST	1	1233	222148	1	1233	222148
23	Arterial	ST	1	1678	163301	1	1678	163301
24	Arterial	ST	1	2133	218444	1	2133	218444
25	Arterial	ST	0	0	0	0	0	0
26	Collector	AC	1	822	131307	1	822	131307
27	Collector	AC	1	1233	98249	1	1233	98249
28	Collector	AC	0	0	0	0	0	0
29	Collector	AC	0	0	0	0	0	0
30	Collector	AC	0	0	0	0	0	0
31	Collector	AC/AC	0	0	0	1	822	71356
32	Collector	AC/AC	0	0	0	0	0	0
33	Collector	AC/AC	0	0	0	0	0	0
34	Collector	AC/AC	0	0	0	0	0	0
35	Collector	AC/AC	0	0	0	0	0	0
36	Collector	AC/PCC	1	822	71364	1	822	71364
37	Collector	AC/PCC	0	0	0	0	0	0
38	Collector	AC/PCC	0	0	0	0	0	0
39	Collector	AC/PCC	0	0	0	0	0	0
40	Collector	AC/PCC	0	0	0	0	0	0
41	Collector	PCC	1	9	20905296	1	9	20905296
42	Collector	PCC	0	0	0	0	0	0
43	Collector	PCC	0	0	0	0	0	0
44	Collector	PCC	0	0	0	0	0	0
45	Collector	PCC	0	0	0	0	0	0
46	Collector	ST	1	18	49354	1	18	49354
47	Collector	ST	1	1233	159943	1	1233	159943
48	Collector	ST	1	1678	117574	1	1678	117574
49	Collector	ST	1	2133	157279	1	2133	157279
50	Collector	ST	0	0	0	0	0	0

TABLE 25 (Continued)

Street_ID	Functional Class	Surface Type	Optimization			DBU based on Cost/WER		
			Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER
51	Residential/Local	AC	0	0	0	0	0	0
52	Residential/Local	AC	0	0	0	0	0	0
53	Residential/Local	AC	0	0	0	0	0	0
54	Residential/Local	AC	0	0	0	0	0	0
55	Residential/Local	AC	0	0	0	0	0	0
56	Residential/Local	AC/AC	0	0	0	0	0	0
57	Residential/Local	AC/AC	0	0	0	0	0	0
58	Residential/Local	AC/AC	0	0	0	0	0	0
59	Residential/Local	AC/AC	0	0	0	0	0	0
60	Residential/Local	AC/AC	0	0	0	0	0	0
61	Residential/Local	AC/PCC	0	0	0	0	0	0
62	Residential/Local	AC/PCC	0	0	0	0	0	0
63	Residential/Local	AC/PCC	0	0	0	0	0	0
64	Residential/Local	AC/PCC	0	0	0	0	0	0
65	Residential/Local	AC/PCC	0	0	0	0	0	0
66	Residential/Local	PCC	1	9	15174656	1	9	15174656
67	Residential/Local	PCC	0	0	0	0	0	0
68	Residential/Local	PCC	0	0	0	0	0	0
69	Residential/Local	PCC	0	0	0	0	0	0
70	Residential/Local	PCC	0	0	0	0	0	0
71	Residential/Local	ST	1	18	37701	1	18	37701
72	Residential/Local	ST	1	1233	122179	1	1233	122179
73	Residential/Local	ST	0	0	0	0	0	0
74	Residential/Local	ST	0	0	0	0	0	0
75	Residential/Local	ST	0	0	0	0	0	0
76	Other	AC	0	0	0	0	0	0
77	Other	AC	0	0	0	0	0	0
78	Other	AC	0	0	0	0	0	0
79	Other	AC	0	0	0	0	0	0
80	Other	AC	0	0	0	0	0	0
81	Other	AC/AC	0	0	0	0	0	0
82	Other	AC/AC	0	0	0	0	0	0
83	Other	AC/AC	0	0	0	0	0	0
84	Other	AC/AC	0	0	0	0	0	0
85	Other	AC/AC	0	0	0	0	0	0
86	Other	AC/PCC	1	822	73247	0	0	0
87	Other	AC/PCC	0	0	0	0	0	0
88	Other	AC/PCC	0	0	0	0	0	0
89	Other	AC/PCC	0	0	0	0	0	0
90	Other	AC/PCC	0	0	0	0	0	0
91	Other	PCC	1	9	15174656	1	9	15174656
92	Other	PCC	0	0	0	0	0	0
93	Other	PCC	0	0	0	0	0	0
94	Other	PCC	0	0	0	0	0	0
95	Other	PCC	0	0	0	0	0	0
96	Other	ST	1	18	37701	1	18	37701
97	Other	ST	1	1233	122179	1	1233	122179
98	Other	ST	0	0	0	0	0	0
99	Other	ST	0	0	0	0	0	0
100	Other	ST	0	0	0	0	0	0
			28	34,699	83,122,454	28	34,699	83,120,563

DBU technique based on WER, optimization, and DBU based on Cost/WER were used to independently estimate investment needs required to meet the target objectives for the remaining years of the five-year funding period. The purpose of this comparison was to see if the same trends in the results observed for the first year also occurred during the remaining years of the analysis. Since the methods were used independently, some sort of balance in the overall cost or treatment effectiveness at the end of the funding period was expected.

5.3.2 Investment Needs for the Second Year of the Funding Period

The multi-objective target matrix for the second year of the funding period is shown in Table 26. Again higher target objectives were set for arterials followed by collectors, while lower target objectives were set for residential/local and other sub-groups.

TABLE 26 Multi-objective Target Matrix for the Second Year of the Funding Period

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life (years)	Minimum Percent of the Pavement Network Group in Very Good Condition (%)	Maximum Percent of the Pavement Network Group in Poor and Very Poor Condition (%)
Arterial	73	20	19	4
Collector	70	20	18	5
Residential/Local	67	20	18	7
Other	67	20	16	7
Entire Network	69	20	69	23

Table 27 shows the investment needs for the second year of the funding period estimated using DBU based on WER. The investment needs estimate was US$ 145,610 for the entire network. Forty-three sections were funded of which fifteen sections were identified for preventive maintenance and twenty-eight sections for rehabilitation. This estimate was higher than the solution provided by optimization. Investment needs estimated using optimization were US$ 137,127 as shown in Table 28**.**

TABLE 27 Investment Needs to Meet Target Objectives Using DBU Based on WER (Year 2)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	2561	34082	36643
Collector	1714	42367	44081
Residential	2561	29882	32443
Other	2561	29882	32443
Entire Network	9397	136213	145610

TABLE 28 Investment Needs to Meet Target Objectives Using Optimization (Year 2)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	0	33864	33864
Collector	847	37892	39739
Residential	2541	26631	29172
Other	1694	33658	35352
Entire Network	5082	132045	137127

Using optimization there were forty-two sections selected for funding from which six sections were identified for preventive maintenance and thirty-six sections for rehabilitation. DBU based on WER/Cost provided a slightly lower funding needs estimate than optimization, US$ 134,575, as shown in Table 29.

TABLE 29 Investment Needs to Meet Target Objectives Using DBU Based on Cost/WER (Year 2)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	0	33864	33864
Collector	0	42367	42367
Residential	2541	26631	29172
Other	2541	26631	29172
Entire Network	5082	129493	134575

Table 30 shows the list of sections selected for funding using the three different allocation methods. There is a considerable difference between the list of sections selected using DBU based on WER and the list of sections selected using optimization. Several sections that were selected by optimization during the first year of the funding period (sections 1, 6, 11, 21, 27, 36, 46, 71, 86, and 96) were selected by DBU based on WER during the second year.

TABLE 30 Sections Selected for Funding Using Different Allocation Methods (Year 2)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	10,000 * Cost/WER
1	1	847	138399	0	0	0	0	0	0	-
2	0	0	0	0	0	0	0	0	0	-
3	0	0	0	0	0	0	0	0	0	-
4	1	7290	112806	1	7290	112806	1	7290	112806	646
5	0	0	0	0	0	0	0	0	0	-
6	1	847	139324	0	0	0	0	0	0	-
7	0	0	0	0	0	0	0	0	0	-
8	1	1740	123679	1	1740	123679	1	1740	123679	141
9	0	0	0	0	0	0	0	0	0	-
10	0	0	0	0	0	0	0	0	0	-
11	1	847	139333	0	0	0	0	0	0	-
12	0	0	0	0	0	0	0	0	0	-
13	1	1740	123672	1	1740	123672	1	1740	123672	141
14	0	0	0	1	7027	116568	1	7027	116568	603
15	0	0	0	0	0	0	0	0	0	-
16	0	0	0	0	0	0	0	0	0	-
17	0	0	0	0	0	0	0	0	0	-
18	0	0	0	0	0	0	0	0	0	-
19	1	7290	107465	1	7290	107465	1	7290	107465	678
20	1	16022	93067	0	0	0	0	0	0	-
21	1	21	1070976	0	0	0	0	0	0	-
22	0	0	0	0	0	0	0	0	0	-
23	0	0	0	0	0	0	0	0	0	-
24	0	0	0	0	0	0	0	0	0	-
25	0	0	0	1	8778	57612	1	8778	57612	1524
26	0	0	0	0	0	0	0	0	0	-
27	1	1270	90384	0	0	0	0	0	0	-
28	0	0	0	1	1270	90384	1	1270	90384	141
29	0	0	0	0	0	0	0	0	0	-
30	0	0	0	0	0	0	0	0	0	-
31	1	847	98382	1	847	98382	0	0	0	-
32	1	1740	89232	1	1740	89232	1	1740	89232	195
33	1	1740	89232	1	1740	89232	1	1740	89232	195
34	1	7027	83294	1	7027	83294	1	7027	83294	844
35	0	0	0	0	0	0	0	0	0	-
36	1	847	98388	0	0	0	0	0	0	-
37	1	1740	89226	1	1740	89226	1	1740	89226	195
38	1	1740	89226	1	1740	89226	1	1740	89226	195
39	1	7027	83294	1	7027	83294	1	7027	83294	844
40	0	0	0	0	0	0	0	0	0	-
41	0	0	0	0	0	0	0	0	0	-
42	0	0	0	0	0	0	0	0	0	-
43	0	0	0	0	0	0	0	0	0	-
44	1	7061	79593	1	7061	79593	1	7061	79593	887
45	1	13024	82435	0	0	0	1	13024	82435	1580
46	1	21	770509	0	0	0	0	0	0	-
47	0	0	0	0	0	0	0	0	0	-
48	0	0	0	0	0	0	0	0	0	-
49	0	0	0	0	0	0	0	0	0	-
50	0	0	0	1	8549	42591	0	0	0	-

TABLE 30 (Continued)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	10,000 * Cost/WER
51	1	847	84192	1	847	84192	1	847	84192	101
52	1	1270	92166	1	1270	92166	1	1270	92166	138
53	1	1270	92166	1	1270	92166	1	1270	92166	138
54	1	6832	74203	1	6832	74203	1	6832	74203	921
55	0	0	0	0	0	0	0	0	0	-
56	1	847	88188	1	847	88188	1	847	88188	96
57	0	0	0	1	1740	68404	1	1740	68404	254
58	0	0	0	1	1740	68404	1	1740	68404	254
59	1	7027	71641	0	0	0	0	0	0	-
60	0	0	0	0	0	0	0	0	0	-
61	1	847	88192	1	847	88192	1	847	88192	96
62	0	0	0	1	1740	68399	1	1740	68399	254
63	0	0	0	1	1740	68399	1	1740	68399	254
64	0	0	0	0	0	0	0	0	0	-
65	0	0	0	0	0	0	0	0	0	-
66	0	0	0	0	0	0	0	0	0	-
67	0	0	0	0	0	0	0	0	0	-
68	0	0	0	0	0	0	0	0	0	-
69	0	0	0	1	6832	71437	1	6832	71437	956
70	1	10014	81960	0	0	0	0	0	0	-
71	1	21	588583	0	0	0	0	0	0	-
72	0	0	0	0	0	0	0	0	0	-
73	1	1270	133808	1	1270	133808	1	1270	133808	95
74	1	2197	120257	1	2197	120257	1	2197	120257	183
75	0	0	0	0	0	0	0	0	0	-
76	1	847	84192	1	847	84192	1	847	84192	101
77	1	1270	92166	1	1270	92166	1	1270	92166	138
78	1	1270	92166	1	1270	92166	1	1270	92166	138
79	1	6832	74203	1	6832	74203	1	6832	74203	921
80	0	0	0	0	0	0	0	0	0	-
81	1	847	88188	1	847	88188	1	847	88188	96
82	0	0	0	1	1740	68404	1	1740	68404	254
83	0	0	0	1	1740	68404	1	1740	68404	254
84	1	7027	71641	1	7027	71641	0	0	0	-
85	0	0	0	0	0	0	0	0	0	-
86	1	847	88192	0	0	0	1	847	88192	96
87	0	0	0	1	1740	68399	1	1740	68399	254
88	0	0	0	1	1740	68399	1	1740	68399	254
89	0	0	0	0	0	0	0	0	0	-
90	0	0	0	0	0	0	0	0	0	-
91	0	0	0	0	0	0	0	0	0	-
92	0	0	0	0	0	0	0	0	0	-
93	0	0	0	0	0	0	0	0	0	-
94	0	0	0	1	6832	71437	1	6832	71437	956
95	1	10014	81960	0	0	0	0	0	0	-
96	1	21	588583	0	0	0	0	0	0	-
97	0	0	0	0	0	0	0	0	0	-
98	1	1270	133808	1	1270	133808	1	1270	133808	95
99	1	2197	120257	1	2197	120257	1	2197	120257	183
100	0	0	0	0	0	0	0	0	0	-
Total	43	145,610	6,822,629	42	137,127	3,696,134	41	134,575	3,654,147	

Some sections in need of reconstruction were selected in the second year by the DBU (sections 20, 45, 70, and 95) but not by the optimization technique. The overall WER for treatments selected using DBU based on WER was 6,822,629, while the overall WER using optimization was 3,696,134. This difference was mainly due to the higher number of sections in need of preventive maintenance that were selected by DBU when compared to sections selected by optimization.

Sections selected for funding during the second year of funding period by DBU based on Cost/WER were almost identical to sections selected by optimization. The overall WER for treatments selected by DBU based on Cost/WER was 3,654,147. Forty-one sections were selected using DBU based on Cost/WER, of which six sections were identified for preventive maintenance and thirty-five sections for rehabilitation.

The overall WER of treatments selected by optimization (3,696,134) was slightly higher than the overall WER of treatments selected by DBU based on Cost/WER (3,654,147). Optimization also resulted in a higher cost (US$ 137,127 versus US$ 134,575) because there was a need to fund section 84 to meet the PCI target for the other network sub-group (PCI above 67), otherwise the average PCI would have been 66.

5.3.3 Investment Needs for the Third Year of the Funding Period

The multi-objective target matrix for the third year of the funding period is shown in Table 31. Target objectives for residential/local and other network subgroups are similar, while higher targets were set for collectors and arterials.

TABLE 31 Multi-objective Target Matrix for the Third Year of the Funding Period

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life (years)	Minimum Percent of the Pavement Network Group in Very Good Condition (%)	Maximum Percent of the Pavement Network Group in Poor and Very Poor Condition (%)
Arterial	76	24	21	2
Collector	74	24	20	3
Residential/Local	73	24	18	4
Other	73	24	18	4
Entire Network	74	24	77	13

Table 32 shows that investment needs for the third year of the funding period using DBU based on WER were US$ 122,291 for the entire network. This estimate was higher than the estimate provided by optimization (US$ 120,350) as shown in Table 33. DBU based on WER/Cost resulted in a slightly lower investment needs estimate, US$ 117,487, as shown in Table 34.

TABLE 32 Investment Needs to Meet Target Objectives using DBU Based on WER (Year 3)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	143	25544	25687
Collector	69	26829	26898
Residential	20	34833	34853
Others	20	34833	34853
Entire Network	252	122039	122291

TABLE 33 Investment Needs to Meet Target Objectives Using Optimization (Year 3)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	175	33006	33181
Collector	118	26829	26947
Residential	40	29199	29239
Others	40	30943	30983
Entire Network	373	119977	120350

TABLE 34 Investment Needs to Meet Target Objectives Using DBU Based on Cost/WER (Year 3)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	175	33006	33181
Collector	120	22220	22340
Residential	40	30943	30983
Others	40	30943	30983
Entire Network	375	117112	117487

Table 35 shows the list of sections selected for funding using the three different allocation methods. Thirty-four sections were selected for funding by DBU based on WER of which sixteen sections were identified for preventive maintenance and eighteen sections for rehabilitation**.** Using the optimization technique thirty-three sections were selected for funding of which twenty-three sections were identified for preventive maintenance and ten sections for rehabilitation. Thirty-four sections were selected for funding by DBU based on WER/Cost of which twenty-four sections were identified for preventive maintenance and ten sections for rehabilitation.

TABLE 35 Sections Selected for Funding Using Different Allocation Methods (Year 3)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	10,000 * Cost/WER
1	0	0	0	1	11	1626649	1	11	1626649	0.1
2	1	27	2048233	1	27	2048233	1	27	2048233	0.1
3	1	1	32189458	1	1	32189458	1	1	32189458	0.0002
4	0	0	0	0	0	0	0	0	0	-
5	1	16503	45304	0	0	0	1	16,503	45304	3643
6	0	0	0	1	1	15314633	1	1	15314633	0
7	1	27	2348847	1	27	2348847	1	27	2348847	0
8	0	0	0	0	0	0	0	0	0	-
9	1	1	32189458	1	1	32189458	1	1	32189458	0
10	0	0	0	1	16503	45304	0	0	0	-
11	0	0	0	1	1	15312410	1	1	15312410	0
12	1	27	2348648	1	27	2348648	1	27	2348648	0
13	0	0	0	0	0	0	0	0	0	-
14	1	1	32189458	0	0	0	0	0	0	-
15	0	0	0	0	0	0	0	0	0	-
16	0	0	0	0	0	0	0	0	0	-
17	0	0	0	0	0	0	0	0	0	-
18	0	0	0	0	0	0	0	0	0	-
19	0	0	0	0	0	0	0	0	0	-
20	0	0	0	1	16503	90356	1	16,503	90356	1826
21	0	0	0	1	20	1749529	1	20	1749529	0
22	1	20	1745334	1	20	1745334	1	20	1745334	0
23	1	20	1745334	1	20	1745334	1	20	1745334	0
24	1	20	1745334	1	20	1745334	1	20	1745334	0
25	1	9041	55934	0	0	0	0	0	0	-
26	1	8	1437078	1	8	1437078	1	8	1437078	0
27	0	0	0	1	28	1221415	1	28	1221415	0
28	1	1	24751082	0	0	0	0	0	0	-
29	0	0	0	0	0	0	0	0	0	-
30	1	13414	43693	1	13414	43693	1	13,414	43693	3070
31	0	0	0	0	0	0	1	1	9912985	0
32	0	0	0	0	0	0	0	0	0	-
33	0	0	0	0	0	0	0	0	0	-
34	0	0	0	0	0	0	0	0	0	-
35	1	13414	43693	0	0	0	0	0	0	-
36	0	0	0	1	1	9911441	1	1	9911441	0
37	0	0	0	0	0	0	0	0	0	-
38	0	0	0	0	0	0	0	0	0	-
39	0	0	0	0	0	0	0	0	0	-
40	0	0	0	0	0	0	0	0	0	-
41	0	0	0	0	0	0	0	0	0	-
42	0	0	0	0	0	0	0	0	0	-
43	0	0	0	0	0	0	0	0	0	-
44	0	0	0	0	0	0	0	0	0	-
45	0	0	0	1	13414	80034	0	0	0	-
46	0	0	0	1	20	1259511	1	20	1259511	0
47	1	20	1256640	1	20	1256640	1	20	1256640	0
48	1	20	1256640	1	20	1256640	1	20	1256640	0
49	1	20	1256640	1	20	1256640	1	20	1256640	0
50	0	0	0	0	0	0	1	8,805	41351	2129

TABLE 35 (Continued)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	10,000 * Cost/WER
51	0	0	0	0	0	0	0	0	0	-
52	0	0	0	0	0	0	0	0	0	-
53	0	0	0	0	0	0	0	0	0	-
54	0	0	0	0	0	0	0	0	0	-
55	1	10314	47835	1	10314	47835	1	10,314	47835	2156
56	0	0	0	0	0	0	0	0	0	-
57	1	1792	65871	0	0	0	0	0	0	-
58	1	1792	65871	0	0	0	0	0	0	-
59	0	0	0	0	0	0	0	0	0	-
60	1	10314	47835	0	0	0	1	10,314	47835	2156
61	0	0	0	0	0	0	0	0	0	-
62	1	1792	65866	0	0	0	0	0	0	-
63	1	1792	65866	0	0	0	0	0	0	-
64	0	0	0	0	0	0	0	0	0	-
65	0	0	0	0	0	0	0	0	0	-
66	0	0	0	0	0	0	0	0	0	-
67	0	0	0	0	0	0	0	0	0	-
68	0	0	0	0	0	0	0	0	0	-
69	1	7037	70220	0	0	0	0	0	0	-
70	0	0	0	1	10314	79573	1	10,314	79573	1296
71	0	0	0	1	20	962126	1	20	962126	0
72	1	20	959933	1	20	959933	1	20	959933	0
73	0	0	0	0	0	0	0	0	0	-
74	0	0	0	0	0	0	0	0	0	-
75	0	0	0	1	8570	32456	0	0	0	-
76	0	0	0	0	0	0	0	0	0	-
77	0	0	0	0	0	0	0	0	0	-
78	0	0	0	0	0	0	0	0	0	-
79	0	0	0	0	0	0	0	0	0	-
80	1	10314	47835	0	0	0	1	10,314	47835	2156
81	0	0	0	0	0	0	0	0	0	-
82	1	1792	65871	0	0	0	0	0	0	-
83	1	1792	65871	0	0	0	0	0	0	-
84	0	0	0	0	0	0	0	0	0	-
85	1	10314	47835	1	10314	47835	1	10,314	47835	2156
86	0	0	0	0	0	0	0	0	0	-
87	1	1792	65866	0	0	0	0	0	0	-
88	1	1792	65866	0	0	0	0	0	0	-
89	0	0	0	0	0	0	0	0	0	-
90	0	0	0	1	10314	47835	0	0	0	-
91	0	0	0	0	0	0	0	0	0	-
92	0	0	0	0	0	0	0	0	0	-
93	0	0	0	0	0	0	0	0	0	-
94	1	7037	70220	0	0	0	0	0	0	-
95	0	0	0	1	10314	79573	1	10,314	79573	1296
96	0	0	0	1	20	962126	1	20	962126	0
97	1	20	959933	1	20	959933	1	20	959933	0
98	0	0	0	0	0	0	0	0	0	-
99	0	0	0	0	0	0	0	0	0	-
100	0	0	0	0	0	0	0	0	0	-
Total	34	122,291	141,475,402	33	120,350	132,401,843	34	117,487	142,291,523	

A large difference was observed between the list of sections selected using DBU based on WER and the list of sections selected using optimization. Several sections that were selected by the optimization technique during the second year of the funding period (sections 14, 28, 57, 58, 62, 63, 69, 82, 83, 87, 88, and 94) were selected by DBU based on WER during the third year. Some sections in need of rehabilitation (sections 5, 35, and 80) were selected by DBU during the third year but not by optimization.

The overall WER of treatments selected using optimization (132,401,843) was lower than the overall WER of treatments selected by DBU based on Cost/WER (142,291,523), and investment needs based on DBU were higher than optimization (US$ 120,350 versus US$ 117,487).

The list of sections selected for treatment in the third year of the funding period using DBU based on Cost/WER was again almost identical to the list provided by optimization. Thirty-four sections were selected using DBU based on Cost/WER of which twenty-four sections were identified for maintenance and ten sections for rehabilitation. Sections 31, 60, and 80 were selected for funding by DBU based on Cost/WER but not by optimization. On the other hand, sections 45, 75, and 90 were identified for rehabilitation by optimization but not by DBU based on Cost/WER. It was observed that section 45 was identified for reconstruction in the second year by DBU.

5.3.4 Investment Needs for the Fourth Year of the Funding Period

The multi-objective target matrix for the fourth year of the funding period is shown in Table 36. Target objectives for collectors, residential/local, and other network subgroups are similar, while slightly higher targets were set for arterials.

TABLE 36 Multi-objective Target Matrix for the Fourth Year of the Funding Period

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life (years)	Minimum Percent of the Pavement Network Group in Very Good Condition (%)	Maximum Percent of the Pavement Network Group in Poor and Very Poor Condition (%)
Arterial	78	25	22	1
Collector	75	24	21	2
Residential/Local	75	24	20	3
Other	75	24	20	3
Entire Network	76	24	83	9

Table 37 shows investment needs for the fourth year of the funding period using DBU based on WER. The investment needs estimate was US$ 52,593 for the entire network. This estimate was lower than the solution provided by optimization (US $ 52,765) as shown in Table 38, while DBU based on WER/Cost provided an estimate that is in between the other two methods (US$ 52,740) as shown in Table 39.

Table 40 shows the list of sections selected for funding in the fourth year of the funding period using the three different allocation methods.

TABLE 37 Investment Needs to Meet Target Objectives Using DBU Based on WER (Year 4)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	96	16998	17094
Collector	174	13817	13991
Residential	130	10624	10754
Others	130	10624	10754
Entire Network	530	52063	52593

TABLE 38 Investment Needs to Meet Target Objectives Using Optimization (Year 4)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	80	16998	17078
Collector	172	13817	13989
Residential	225	10623	10848
Others	226	10624	10850
Entire Network	703	52062	52765

TABLE 39 Investment Needs to Meet Target Objectives Using DBU Based on Cost/WER (Year 4)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	80	16998	17078
Collector	148	13817	13965
Residential	225	10624	10849
Others	225	10623	10848
Entire Network	678	52062	52740

TABLE 40 Sections Selected for Funding Using Different Allocation Methods (Year 4)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	10,000 * Cost/WER
1	1	12	1668784	0	0	0	0	0	0	-
2	0	0	0	0	0	0	0	0	0	-
3	0	0	0	0	0	0	0	0	0	-
4	1	1	31251901	1	1	31251901	1	1	31251901	0
5	0	0	0	0	0	0	0	0	0	-
6	1	3	8254002	0	0	0	0	0	0	-
7	0	0	0	0	0	0	0	0	0	-
8	1	29	2203711	1	29	2203711	1	29	2203711	0
9	0	0	0	0	0	0	0	0	0	-
10	1	16998	43985	0	0	0	1	16998	43985	3865
11	1	3	8253075	0	0	0	0	0	0	-
12	0	0	0	0	0	0	0	0	0	-
13	1	29	2203544	1	29	2203544	1	29	2203544	0
14	0	0	0	1	1	31251901	1	1	31251901	0
15	0	0	0	1	16998	0	0	0	0	-
16	0	0	0	0	0	0	0	0	0	-
17	0	0	0	0	0	0	0	0	0	-
18	0	0	0	0	0	0	0	0	0	-
19	1	1	31251901	1	1	31251901	1	1	31251901	0
20	0	0	0	0	0	0	0	0	0	-
21	1	20	2020490	0	0	0	0	0	0	-
22	0	0	0	0	0	0	0	0	0	-
23	0	0	0	0	0	0	0	0	0	-
24	0	0	0	0	0	0	0	0	0	-
25	0	0	0	1	21	0	1	21	1694499	0
26	0	0	0	0	0	0	0	0	0	-
27	1	32	1075542	0	0	0	0	0	0	-
28	0	0	0	1	32	1075542	1	32	1075542	0
29	0	0	0	0	0	0	0	0	0	-
30	0	0	0	0	0	0	0	0	0	-
31	1	3	5264001	1	3	5264001	0	0	0	-
32	1	29	1579079	1	29	1579079	1	29	1579079	0
33	1	29	1579079	1	29	1579079	1	29	1579079	0
34	1	1	24030177	1	1	24030177	1	1	24030177	0
35	0	0	0	1	13817	42420	1	13817	42420	3257
36	1	3	5263417	0	0	0	0	0	0	-
37	1	29	1578949	1	29	1578949	1	29	1578949	0
38	1	29	1578949	1	29	1578949	1	29	1578949	0
39	1	1	24030177	1	1	24030177	1	1	24030177	0
40	1	13817	42420	0	0	0	0	0	0	-
41	0	0	0	0	0	0	0	0	0	-
42	0	0	0	0	0	0	0	0	0	-
43	0	0	0	0	0	0	0	0	0	-
44	1	1	24030177	1	1	24030177	1	1	24030177	0
45	0	0	0	0	0	0	0	0	0	-
46	1	20	1454491	0	0	0	0	0	0	-
47	0	0	0	0	0	0	0	0	0	-
48	0	0	0	0	0	0	0	0	0	-
49	0	0	0	0	0	0	0	0	0	-
50	0	0	0	1	21	1220039	0	0	0	-

TABLE 40 (Continued)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	10,000 * Cost/WER
51	1	10	996744	1	10	996744	1	10	996744	0
52	1	29	1144958	1	29	1144958	1	29	1144958	0
53	1	29	1144958	1	29	1144958	1	29	1144958	0
54	1	0	0	0	0	0	1	0	0	-
55	0	0	0	0	0	0	0	0	0	-
56	1	0	0	0	0	0	1	0	0	-
57	0	0	0	1	29	1180139	1	29	1180139	0
58	0	0	0	1	29	1180139	1	29	1180139	0
59	1	0	0	0	0	0	0	0	0	-
60	0	0	0	1	10624	0	0	0	0	-
61	1	0	0	0	0	0	1	0	0	-
62	0	0	0	1	29	1180025	1	29	1180025	0
63	0	0	0	1	29	1180025	1	29	1180025	0
64	0	0	0	0	0	0	0	0	0	-
65	1	10624	46442	0	0	0	1	10624	46442	2288
66	0	0	0	0	0	0	0	0	0	-
67	0	0	0	0	0	0	0	0	0	-
68	0	0	0	0	0	0	0	0	0	-
69	0	0	0	0	0	0	1	0	0	-
70	0	0	0	0	0	0	0	0	0	-
71	1	20	1111069	0	0	0	0	0	0	-
72	0	0	0	0	0	0	0	0	0	-
73	1	21	931974	1	21	931974	1	21	931974	0
74	1	21	931974	1	21	931974	1	21	931974	0
75	0	0	0	0	0	0	0	0	0	-
76	1	10	996744	1	10	996744	1	10	996744	0
77	1	29	1144958	1	29	1144958	1	29	1144958	0
78	1	29	1144958	1	29	1144958	1	29	1144958	0
79	1	0	0	0	0	0	1	0	0	-
80	0	0	0	1	10624	46442	0	0	0	-
81	1	0	0	0	0	0	1	0	0	-
82	0	0	0	1	29	1180139	1	29	1180139	0
83	0	0	0	1	29	1180139	1	29	1180139	0
84	1	0	0	0	0	0	0	0	0	-
85	0	0	0	0	0	0	0	0	0	-
86	1	0	0	1	2	6653904	1	0	0	-
87	0	0	0	1	29	1180025	1	29	1180025	0
88	0	0	0	1	29	1180025	1	29	1180025	0
89	0	0	0	0	0	0	0	0	0	-
90	1	10624	46442	0	0	0	1	10624	46442	2288
91	0	0	0	0	0	0	0	0	0	-
92	0	0	0	0	0	0	0	0	0	-
93	0	0	0	0	0	0	0	0	0	-
94	0	0	0	0	0	0	1	0	0	-
95	0	0	0	0	0	0	0	0	0	-
96	1	20	1111069	0	0	0	0	0	0	-
97	0	0	0	0	0	0	0	0	0	-
98	1	21	931974	1	21	931974	1	21	931974	0
99	1	21	931974	1	21	931974	1	21	931974	0
100	0	0	0	0	0	0	0	0	0	-
Total	43	52,593	191,274,089	39	52,765	210,613,762	44	52,740	199,260,743	

Forty-two sections were selected for funding by DBU based on WER, of which fifteen were identified for maintenance and twenty-eight for rehabilitation. The overall WER of treatments selected using DBU based on WER was 191,274,089.

Many sections that were selected for funding by DBU based on WER during the fourth year of the funding period (sections 1, 6, 10, 11, 21, 27, 36, 46, 71, 90, and 96) were selected by optimization in the third year. Two sections in need of reconstruction (sections 40 and 65) and six sections in need of maintenance (sections 54, 56, 59, 61, 79, and 81) were selected in the fourth year by DBU based on WER but not by optimization.

The overall WER of treatments for sections selected using optimization was 210,613,762. This overall WER of sections selected by optimization was higher than the overall WER of sections selected by DBU based on WER (191,274,089). It was observed that from the thirty-nine sections selected by optimization, thirty-five sections were identified for maintenance and four sections for rehabilitation.

The list of sections selected for funding using DBU based on Cost/WER was again similar to the list provided by optimization. The overall WER for sections selected by DBU based on Cost/WER was 199,260,143. There were four sections selected using optimization (sections 15, 31, 50, and 80) which were not selected by DBU based on Cost/WER. Sections 15 and 80 were in need of reconstruction, while sections 31 and 50 were in need of maintenance in the optimization list during the fourth year of the funding period. Sections 31, 50, and 80 were identified for treatment by DBU based on Cost/WER during the third year of the funding period.

5.3.5 Investment Needs for the Fifth Year of the Funding Period

The multi-objective target matrix for the fifth year of the funding period is shown in Table 41. Target objectives for arterials and collectors were almost identical, and targets for residential/local and other network subgroups were equivalent. The objective was to bring the network average pavement condition of the network back to 80 with an network average remaining life of twenty-five years with eighty-eight percent of the pavement network in very good condition, and only four percent in poor and very poor condition.

TABLE 41 Multi-objective Target Matrix for the Fifth Year of the Funding Period

Functional Class	Minimum Network Average PCI	Minimum Network Average Remaining Life (years)	Minimum Percent of the Pavement Network Group in Very Good Condition (%)	Maximum Percent of the Pavement Network Group in Poor and Very Poor Condition (%)
Arterial	81	25	23	0
Collector	80	25	23	0
Residential/Local	80	25	21	2
Other	80	25	21	2
Entire Network	80	25	88	4

Table 42 shows investment needs using DBU based on WER. The investment needs estimate was US$ 59,891 for the entire network. This estimate was lower than the estimate provided by optimization (US$ 66,514) as shown in Table 43. DBU based on WER/Cost showed a higher investment needs estimate (US$ 64,678) as shown in Table 44.

TABLE 42 Investment Needs to Meet Target Objectives Using DBU Based on WER (Year 5)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	206	17508	17714
Collector	94	23573	23667
Residential	163	9092	9255
Others	163	9092	9255
Entire Network	627	59264	59891

TABLE 43 Investment Needs to Meet Target Objectives Using Optimization (Year 5)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	230	17508	17738
Collector	140	28463	28603
Residential	77	10942	11019
Others	62	9092	9154
Entire Network	509	66005	66514

TABLE 44 Investment Needs to Meet Target Objectives Using DBU Based on Cost/WER (Year 5)

Functional Class	Investments for Preservation (US$)	Investments for Rehabilitation (US$)	Total Investments (US $)
Arterial	230	17508	17738
Collector	171	28463	28634
Residential	61	9092	9153
Others	61	9092	9153
Entire Network	524	64154	64678

Table 45 shows the list of sections selected for funding in the fifth year of the funding period using the three different allocation methods. Forty-seven sections were selected for funding by DBU based on WER, of which forty-two sections were identified for maintenance and five sections for rehabilitation while forty-two sections were selected by optimization of which thirty-seven were identified for maintenance and five for rehabilitation. The overall WER of treatments for sections selected by DBU based on WER was 83,362,622 while the overall WER of treatments for sections selected by optimization was 64,225,650. Many sections that were selected for funding during the fifth year using DBU based on WER (sections 14, 15, 25, 28, 35, 50, 57, 58, 60, 62, 63, 80, 82, 83, 86, 87, and 88) were selected by optimization during the fourth year of the funding period.

The list of sections selected for funding by DBU based on Cost/WER was similar to the list provided by optimization. Forty-four sections were selected for funding by DBU based on Cost/WER. Thirty-nine sections were identified for maintenance and five sections for rehabilitation. The overall WER of treatments for sections selected by DBU based on Cost/WER was 87,512,283. There were five section selected for funding by DBU based on Cost/WER (sections 15, 31, 50, 60, 80, and 86) that were not selected by optimization. These five sections were selected for funding by optimization during the fourth year of the funding period.

TABLE 45 Sections Selected for Funding Using Different Allocation Methods (Year 5)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No	Allocated Funds	WER	10,000 * Cost/WER
1	0	0	0	1	16	1777383	1	16	1777383	0
2	1	30	1861488	1	30	1861488	1	30	1861488	0
3	1	9	3318042	1	9	3318042	1	9	3318042	0
4	0	0	0	0	0	0	0	0	0	-
5	1	10	1441605	1	17508	42704	1	10	1441605	0
6	0	0	0	1	10	3238468	1	10	3238468	0
7	1	29	2178400	1	29	2178400	1	29	2178400	0
8	0	0	0	0	0	0	0	0	0	-
9	1	9	3318042	1	9	3318042	1	9	3318042	0
10	0	0	0	1	10	1441605	0	0	0	-
11	0	0	0	1	10	3238446	1	10	3238446	0
12	1	29	2178215	1	29	2178215	1	29	2178215	0
13	0	0	0	0	0	0	0	0	0	-
14	1	9	3318042	0	0	0	0	0	0	-
15	1	17508	42704	0	0	0	1	17508	42704	4100
16	0	0	0	0	0	0	0	0	0	-
17	0	0	0	0	0	0	0	0	0	-
18	0	0	0	0	0	0	0	0	0	-
19	0	0	0	0	0	0	0	0	0	-
20	0	0	0	0	0	0	0	0	0	-
21	0	0	0	1	20	2322917	1	20	2322917	0
22	1	20	2320543	1	20	2320543	1	20	2320543	0
23	1	20	2320543	1	20	2320543	1	20	2320543	0
24	1	20	2320543	1	20	2320543	1	20	2320543	0
25	1	21	1645144	0	0	0	0	0	0	-
26	1	12	1504020	1	12	1504020	1	12	1504020	0
27	0	0	0	1	32	1059751	1	32	1059751	0
28	1	9	2251207	0	0	0	0	0	0	-
29	1	14231	41184	1	14231	41184	1	14231	41184	3456
30	1	7	994275	1	7	994275	1	7	994275	0
31	0	0	0	0	0	0	1	10	2189058	0
32	0	0	0	0	0	0	0	0	0	-
33	0	0	0	0	0	0	0	0	0	-
34	0	0	0	0	0	0	0	0	0	-
35	1	7	994275	0	0	0	0	0	0	-
36	0	0	0	1	10	2189042	1	10	2189042	0
37	0	0	0	0	0	0	0	0	0	-
38	0	0	0	0	0	0	0	0	0	-
39	0	0	0	0	0	0	0	0	0	-
40	0	0	0	1	14231	41184	1	14231	41184	3456
41	0	0	0	0	0	0	0	0	0	-
42	0	0	0	0	0	0	0	0	0	-
43	0	0	0	0	0	0	0	0	0	-
44	0	0	0	0	0	0	0	0	0	-
45	0	0	0	0	0	0	0	0	0	-
46	0	0	0	1	20	1672415	1	20	1672415	0
47	1	20	1670791	1	20	1670791	1	20	1670791	0
48	1	20	1670791	1	20	1670791	1	20	1670791	0
49	1	20	1670791	1	20	1670791	1	20	1670791	0
50	1	9342	38977	0	0	0	1	21	1184504	0

TABLE 45 (Continued)

Street_ID	DBU based on WER			Optimization			DBU based on Cost/WER			
	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No 1=Yes)	Allocated Funds	WER	Selected ? (0=No	Allocated Funds	WER	10,000 * Cost/WER
51	0	0	0	0	0	0	0	0	0	-
52	0	0	0	0	0	0	0	0	0	-
53	0	0	0	0	0	0	0	0	0	-
54	1	0	0	1	0	0	1	0	0	-
55	1	9	834246	1	9	834246	1	9	834246	0
56	1	2	7811192	1	4	3747829	1	2	7811192	0
57	1	30	1133920	0	0	0	0	0	0	-
58	1	30	1133920	0	0	0	0	0	0	-
59	1	0	0	0	0	0	0	0	0	-
60	1	9	834246	0	0	0	1	9	834246	0
61	1	2	7809452	1	4	3747478	1	2	7809452	0
62	1	30	1133815	0	0	0	0	0	0	-
63	1	30	1133815	0	0	0	0	0	0	-
64	0	0	0	0	0	0	0	0	0	-
65	0	0	0	1	10942	45089	0	0	0	-
66	0	0	0	0	0	0	0	0	0	-
67	0	0	0	0	0	0	0	0	0	-
68	0	0	0	0	0	0	0	0	0	-
69	1	0	0	1	0	0	1	0	0	-
70	0	0	0	0	0	0	0	0	0	-
71	0	0	0	1	20	1277539	1	20	1277539	0
72	1	20	1276299	1	20	1276299	1	20	1276299	0
73	0	0	0	0	0	0	0	0	0	-
74	0	0	0	0	0	0	0	0	0	-
75	1	9092	30593	1	21	904829	1	9092	30593	2972
76	0	0	0	0	0	0	0	0	0	-
77	0	0	0	0	0	0	0	0	0	-
78	0	0	0	0	0	0	0	0	0	-
79	1	0	0	1	0	0	1	0	0	-
80	1	9	834246	0	0	0	1	9	834246	0
81	1	2	7811192	1	4	3747829	1	2	7811192	0
82	1	30	1133920	0	0	0	0	0	0	-
83	1	30	1133920	0	0	0	0	0	0	-
84	1	0	0	1	0	0	0	0	0	-
85	1	9	834246	1	9	834246	1	9	834246	0
86	1	2	7809452	0	0	0	1	2	7809452	0
87	1	30	1133815	0	0	0	0	0	0	-
88	1	30	1133815	0	0	0	0	0	0	-
89	0	0	0	0	0	0	0	0	0	-
90	0	0	0	1	9	834246	0	0	0	-
91	0	0	0	0	0	0	0	0	0	-
92	0	0	0	0	0	0	0	0	0	-
93	0	0	0	0	0	0	0	0	0	-
94	1	0	0	1	0	0	1	0	0	-
95	0	0	0	0	0	0	0	0	0	-
96	0	0	0	1	20	1277539	1	20	1277539	0
97	1	20	1276299	1	20	1276299	1	20	1276299	0
98	0	0	0	0	0	0	0	0	0	-
99	0	0	0	0	0	0	0	0	0	-
100	1	9092	30593	1	9092	30593	1	9092	30,593	2972
Total	47	59,891	83,362,622	42	66,514	64,225,650	44	64,678	87,512,283	

5.4 INTERPRETATION AND DISCUSSION

When a local agency sets its target objectives for the planning period, the transition from the current stage to the target stage could be gradual and follow an incremental approach. The agency may choose to allocate more funds at an early stage and then preserve the achieved condition over the remaining years of the planning period. However, due to funding constraints, the incremental approach is more realistic.

5.4.1 Findings from the 100-DB Case Study

Using available funds and resources in an effective manner is a key aspect of strategic management. The case study shows that there is more than one method to determine investment needs required to meet the target objectives. However, the method used to select sections for funding influences future funding needs.

Table 46 shows a summary of results from the three methods used to select sections for funding to meet the target objectives for the five-year funding period along with the unconstrained funding results. Investment needs are also divided into preventive maintenance and rehabilitation categories. The overall WER and number of sections selected are reported for DBU based on WER, optimization, and DBU based on Cost/WER. Results for an unconstrained funding analysis are also included for comparison. Figure 34 shows the results from each of the three methods used to select sections for funding allocation to meet targets and for an unconstrained funding scenario.

TABLE 46 Summary of Investment Needs from Methods Used to Select Sections for Funding

Method	Results	Year 1	Year 2	Year 3	Year 4	Year 5	Total
DBU based on WER	Network Investment Needs (US $)	40,537	145,610	122,291	52,593	59,891	420,922
	Preservation	860	9,397	252	530	627	11,666
	Rehabilitation	39,677	136,213	122,039	52,063	59,264	409,256
	Overall WER	82,599,432	6,822,629	141,475,402	191,274,089	83,362,622	505,534,174
	Sections Selected for Funding	20	43	34	43	47	187
Optimization	Network Investment Needs (US $)	34,699	137,127	120,350	52,765	66,514	411,455
	Preservation	5,044	5,082	373	703	509	11,711
	Rehabilitation	29,655	132,045	119,977	52,062	66,005	399,744
	Overall WER	83,122,454	3,696,134	132,401,843	210,613,762	64,225,650	494,059,843
	Sections Selected for Funding	28	42	33	39	42	184
DBU based on Cost/WER	Network Investment Needs (US $)	34,699	134,575	117,487	52,740	64,678	404,179
	Preservation	5,044	5,082	375	678	524	11,703
	Rehabilitation	29,655	129,493	117,112	52,062	64,154	392,476
	Overall WER	83,120,563	3,654,147	142,291,523	199,260,743	87,512,283	515,839,259
	Sections Selected for Funding	28	41	34	44	44	191
Unconstrained Funding	Network Investment Needs (US $)	451,755	0	877	7	1,184	453,823
	Preservation	9,977	0	877	7	1,184	12,045
	Rehabilitation	441,778	0	0	0	0	441,778
	Overall WER	87,780,997	0	510,375,640	450,589,026	121,507,762	1,170,253,425
	Sections Selected for Funding	92	0	84	18	31	225

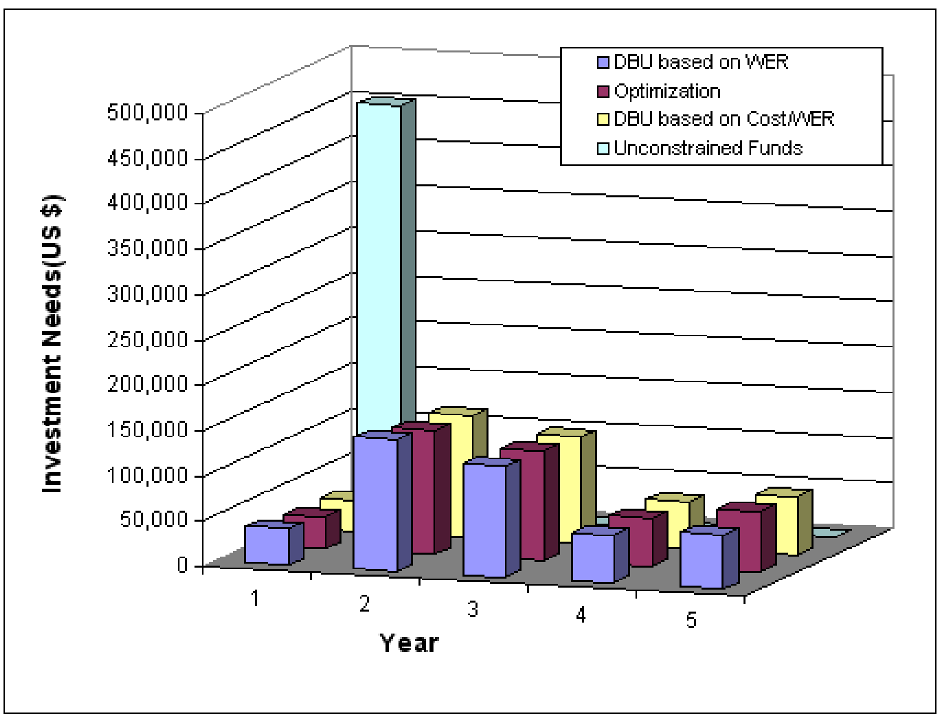

FIGURE 34 Comparing investment needs obtained by different methods.

The pavement network parameters over the funding period obtained from each of the three funding allocation methods are summarized in Table 47. As shown in the table the three methods were able to estimate needed funds to achieve the target objectives. The unconstrained funding scenario and the “no funds” scenario were added for comparison.

TABLE 47 Summary of Pavement Network Parameters from Methods Used to Select Sections for Funding

Method	Network Pavement Parameter	Current	Year 1	Year 2	Year 3	Year 4	Year 5
Target Objetives	Network Average PCI	58	62	69	74	76	80
	Network Average Remaining Life (years)	16	17	20	24	24	25
	Minimum Percent of the Network in Very Good Condition	20	33	69	77	83	88
	Maximum Percent of the Pavement Network in Poor and Very Poor Condition	40	38	23	13	9	4
DBU based on WER	Network Average PCI	58	63	71	76	78	81
	Network Average Remaining Life (years)	16	18	24	27	27	28
	Minimum Percent of the Network in Very Good Condition	20	35	63	81	85	90
	Maximum Percent of the Pavement Network in Poor and Very Poor Condition	40	36	21	11	7	2
Optimization	Network Average PCI	58	63	70	75	77	80
	Network Average Remaining Life (years)	16	18	22	26	27	27
	Minimum Percent of the Network in Very Good Condition	20	34	70	80	84	89
	Maximum Percent of the Pavement Network in Poor and Very Poor Condition	40	37	22	12	8	3
DBU based on Cost/WER	Network Average PCI	58	63	70	75	76	80
	Network Average Remaining Life (years)	16	18	22	26	27	27
	Minimum Percent of the Network in Very Good Condition	20	34	69	79	83	88
	Maximum Percent of the Pavement Network in Poor and Very Poor Condition	40	37	23	13	9	4
Unconstrained Funding	Network Average PCI	58	93	85	84	82	81
	Network Average Remaining Life (years)	16	32	31	31	30	29
	Minimum Percent of the Network in Very Good Condition	20	92	92	92	92	92
	Maximum Percent of the Pavement Network in Poor and Very Poor Condition	40	0	0	0	0	0
No Funds	Network Average PCI	58	58	55	53	50	48
	Network Average Remaining Life (years)	16	16	15	14	13	13
	Minimum Percent of the Network in Very Good Condition	20	20	20	20	20	16
	Maximum Percent of the Pavement Network in Poor and Very Poor Condition	40	40	40	40	40	44

Figure 35 shows network average PCI results obtained from different funding allocation methods compared to unconstrained funding and a “no funds” scenario.

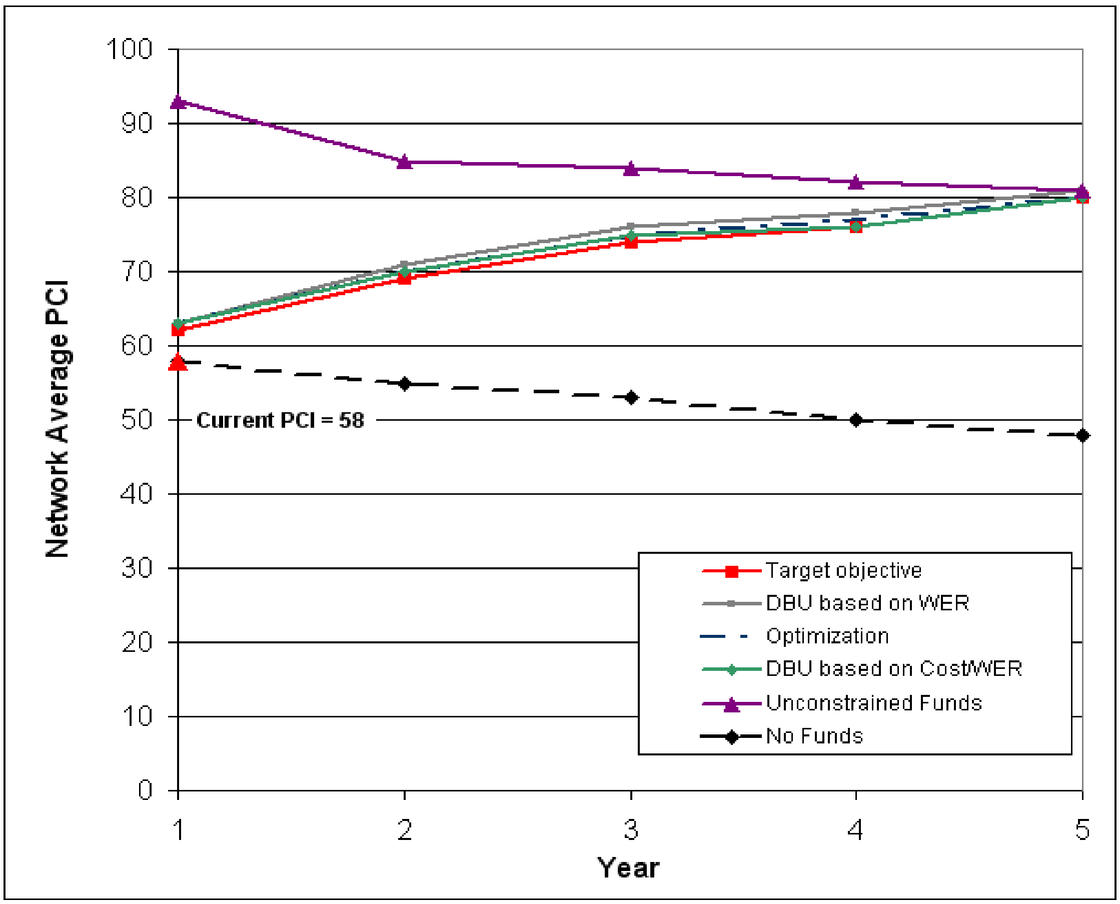

FIGURE 35 Network average PCI from different funding allocation methods.

Figure 36 shows the network average remaining life obtained from different funding allocation methods and a comparison to unconstrained funding and a “no funds” scenario.

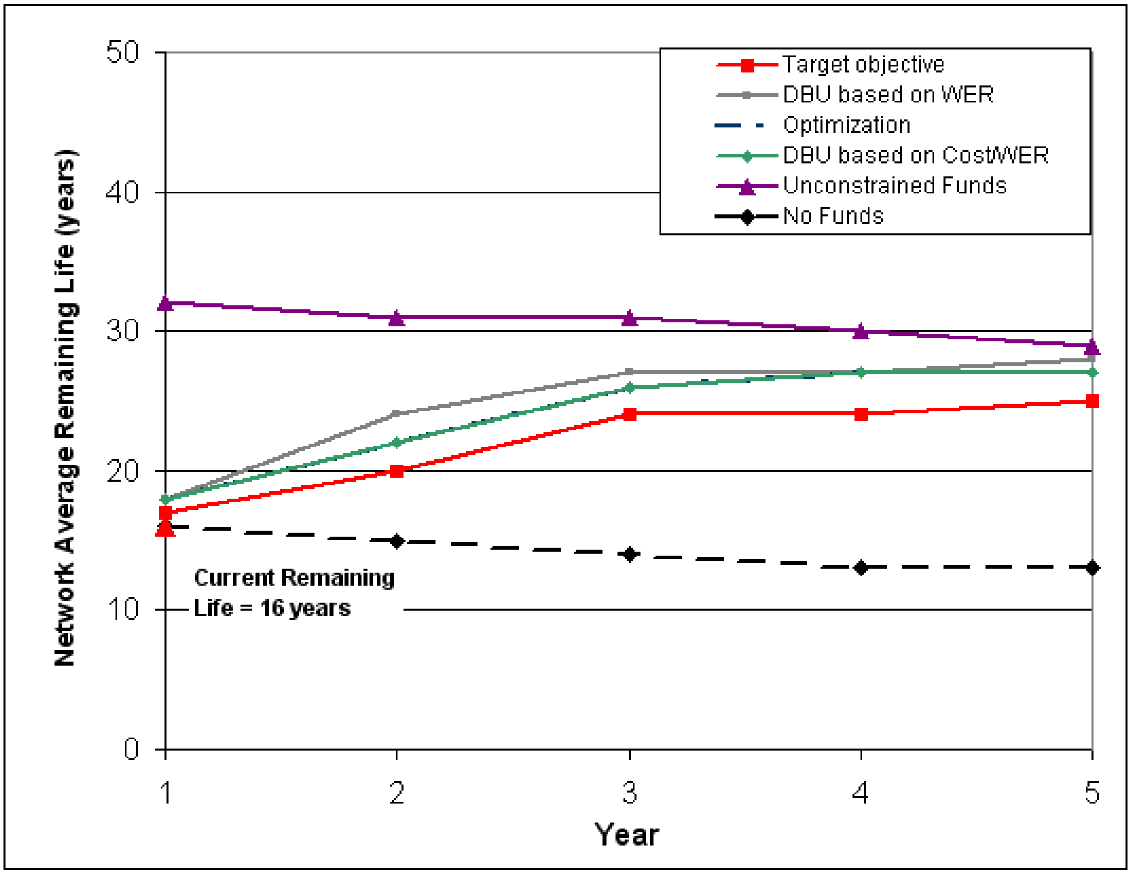

FIGURE 36 Network average remaining life from different funding allocation methods.

Figure 37 shows the percent of the network in very good condition (condition category I, PCI above 70) for the entire network obtained from different allocation methods compared to unconstrained funding and “no funds”.

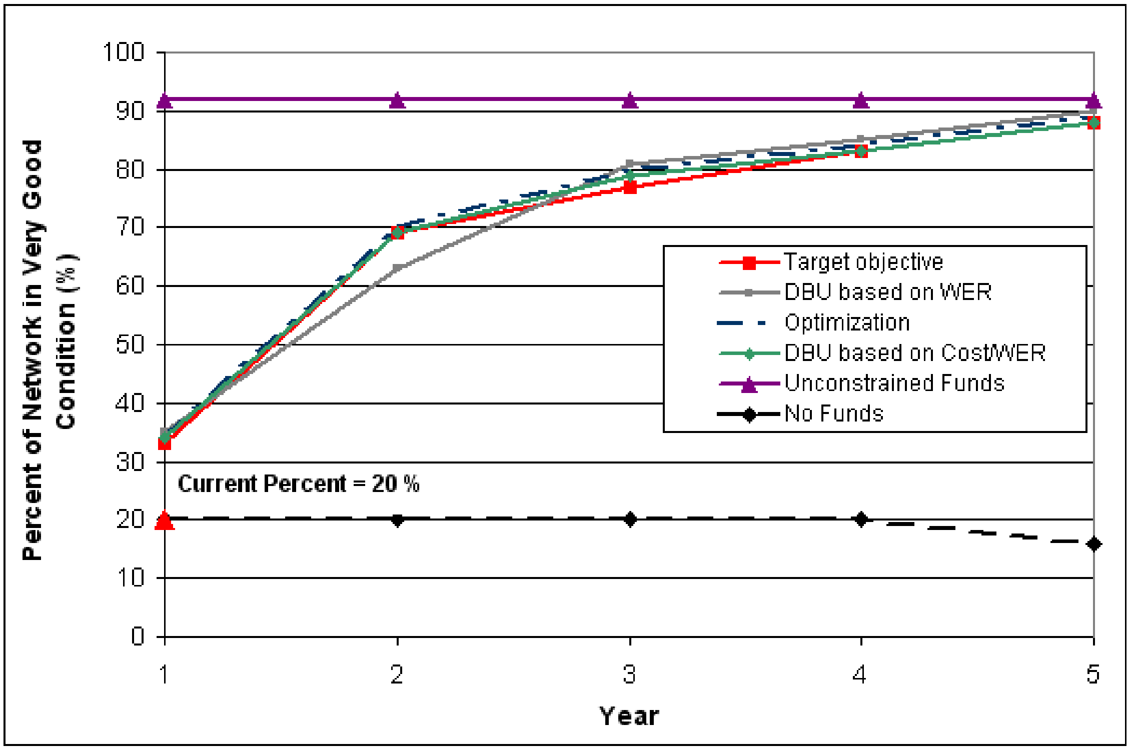

FIGURE 37 Percent of the pavement network in very good condition from different funding allocation methods.

Figure 38 shows the percent of the network in poor and very poor condition (condition categories IV and V, PCI below 50) for the entire network obtained from different allocation methods and compared to unconstrained funding and "no funds" scenarios.

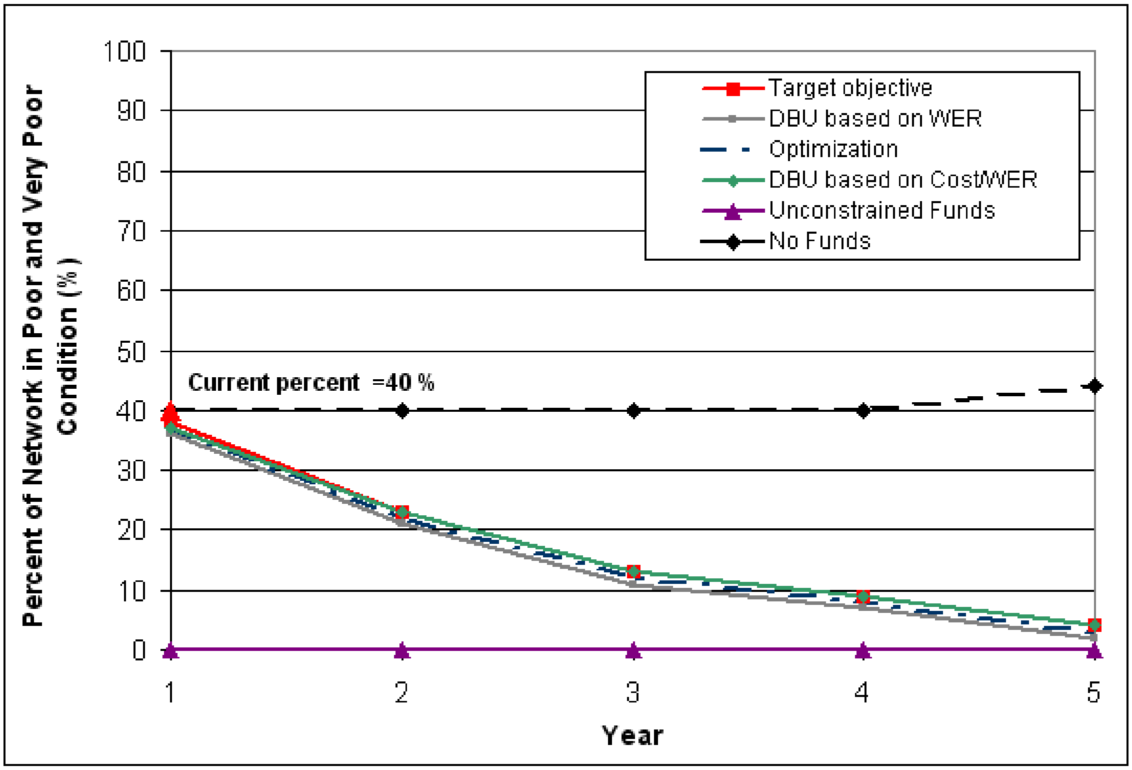

FIGURE 38 Percent of the pavement network in poor and very poor condition from different funding allocation methods.

5.4.2 Interpreting the Results from the 100-DB Case Study

The three allocation methods worked quite well when the entire funding period is analyzed. DBU based on Cost/WER provided the lowest overall investment needs estimate (US$ 404,178) at the end of the five-year funding period. The highest overall investment needs estimate was produced by DBU based on WER (US$ 420,922). There was a difference of 4.1 percent between the results obtained using DBU based on Cost/WER and that based on WER alone.

The difference between the investment needs estimate obtained by optimization (US$ 411,455) and the investment needs estimate provided by DBU based on Cost/WER(US$ 404,178) was small (US$ 7,277). Table 46 shows that the optimization technique resulted in the same investment needs estimate in year one, and a lower estimate in year five. The overall 1.8 percent difference in the investment needs estimate provided by optimization when compared to DBU based on Cost/WER typically would not be considered critical, and probably is within the expected error range of the cost estimation process used to develop unit repair costs.

From the description of the results obtained for each year of the funding period in section 5.3, it seems that timing in applying the "right treatment" makes a difference in the investment needs estimate. Applying preventive maintenance at the "right time" reduces future investment needs and increases overall effectiveness. Therefore, preventive maintenance is considered a good pavement management practice.

5.4.3 Discussing Techniques for Solving the Funding Allocation Problem

The optimization technique used a tool developed in an Excel© environment for solving the mathematical problem. This tool used Excel's solver capabilities. The optimization runs for the 100-DB took from one hour to twenty hours depending on how close the initial set given to start the iteration was to the optimum. Some runs went into an endless loop when the targets could not be met and the method did not converge to a solution. A more effective technique for solving integer linear programming problems is desirable, but development of such a technique was beyond the scope of this dissertation.

However, a study in the operations research field for solving funding allocation problems should be encouraged since larger databases may lead to greater differences in the estimates.

Runs with DBU were much faster and took less than one hour each. The tools used for the calculations are in their first generation of development and are hard-coded to the 100-DB requiring manual interaction to complete the solving process. Time for solving the funding allocation problem using DBU should considerably decrease if the entire process requires less interaction from the user.

When addressing a multi-objective optimization problem there typically is not a single best solution. Feasible solutions are more appropriate assumptions. Developing a method for finding feasible solutions and "efficient points" is a complex issue for multiple objectives with several variables. A feasible solution can be considered an efficient point only if the solution meets all objective functions and is considered the best for one of the objective functions. Rather than finding one point, the real challenge is building the "efficient frontier" of the multi-objective optimization model.

Constructing the "efficient frontier" means solving the problem by repeated optimization where one objective is enforced for achieving levels while the others are treated as single objectives. Due to the computational effort required for building the "efficient frontier", it was infeasible to undertake this task with the current capabilities of MTC-PMS because it does not perform the calculations required to estimate needed funds for a set of given conditions. It was also not possible to build the "efficient frontier" with the tools developed in this research because they are limited in their solving capacity.

DBU based on Cost/WER generates a "good solution" which is close to that found using optimization and provides a reasonable approach for estimating the investment needs required to meet the target objectives set by local agencies.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Pavement management encompasses many activities including but not limited to establishing goals and objectives for the pavement network, using methods to assess the current pavement network state, identifying funds required to address preventive maintenance and rehabilitation treatment needs, prioritizing the allocation of funds among pavement sections in need of treatment when funds are constrained, developing pavement network scenarios for different pavement management strategies, assessing the impact of the pavement management strategies, communicating the effects of pavement management strategies across management levels, and justifying funding needs before funding authorities.

From a strategic management perspective it is essential to inter-connect these activities in an orchestrated manner. The ultimate goal of this integrated approach is to assist decision makers in allocating funds wisely to achieve the agency's target objectives at the minimum cost. Multiple objectives in an agency make achieving this goal challenging. The challenge is even greater in local agencies due to limited resources.

Lessons learned from experience will be valuable for improving existing pavement management practices. Combining traditional pavement management systems components with selected components from asset management systems, geographic information systems, and knowledge management systems should provide decision makers with improved information. Combining these modern technologies with lessons learned from previous experiences can also lead to more effective investment strategies and general improvement in existing pavement management practices.

The pavement management system (PMS) of the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area was used as a basis to develop a multi-objective pavement management approach. The main focus of the multi-objective strategic management approach is to tie the agency's objectives to key pavement network parameters that can be monitored over time. The key pavement network parameters selected in the multi-objective strategic pavement management approach to express target objectives are: average network pavement condition index (PCI), average network pavement remaining life, percent of the pavement network in good condition, and percent of the pavement network in poor and very poor condition.

The multi-objective strategic management approach also emphasizes the need for a method for investment analysis. Alternative methods proposed for determining the level of investment required to meet multiple target objectives were compared. A case study using the100-DB, which is used for testing the pavement management system supported by MTC, was presented in Chapter V. Therefore, conclusions and recommendations from this study must be interpreted within the context of the principles followed by the MTC pavement management system and its application to local agency pavement management.

6.1 CONCLUSIONS

The following can be concluded from this study:

a. Results from the 100-DB case study show that funding allocation methods used for estimating needed funds to achieve multiple pavement network objectives over a planning horizon influence the allocation of preservation and rehabilitation funds among pavement network groups, affecting budget estimates and future condition of the pavement network. The adoption of the multi-objective strategic pavement management approach developed in this dissertation should lead to identifying more efficient investment strategies for achieving the pavement network state desired by a local agency at a minimum cost.

b. Two alternative methods were developed in this dissertation for estimating needed funds to meet target objectives. The first method is the dynamic bubble up procedure (DBU) which is based on a sequential year ranking method. The second method is a multi-objective optimization model that uses integer program solving techniques. It was observed from the case study that both methods were able to estimate the level of investment needed to achieve multiple target objectives over a planning horizon.

c. The optimization method was used to compare results obtained with DBU when different ranking criterion was applied to the sections. From a case study it was found that DBU based on Cost/WER as a ranking criterion (ascending order) produces better results than DBU based on WER (descending order).

d. DBU estimates funds to meet target objectives and identifies a group of candidate sections for funding to achieve these targets at minimum overall cost while maximizing treatment effectiveness. DBU based on Cost/WER as a ranking criterion leads to a solution similar to that from optimization.

e. DBU based on Cost/WER is recommended for use by local agencies because of the ease of use and transparency compared to an optimization technique, increasing credibility in its results and likelihood of use by local agency personnel.

f. Timing in applying the "right treatment" makes a difference in future investment needs and the future condition of the pavement network. In the case study, it was observed that applying preventive maintenance at the "right time" reduces future investment needs and increases overall effectiveness. Therefore, preventive maintenance is considered a good pavement management practice.

g. The use of geographic information systems (GIS) as a platform to facilitate data integration, and knowledge management tools for discovering, capturing, sharing, and applying of corporate knowledge throughout the pavement management cycle should contribute to sustaining the multi-objective strategic management approach.

h. Pavement management systems should be considered as tools to assist an agency in eliciting and using knowledge so that existing pavement management practices can be improved over time.

6.2 CONTRIBUTIONS OF RESEARCH

The major contribution of this research is the development of a multi-objective strategic management approach that ties multiple objectives to network pavement performance parameters and that provides methods for a local agency to estimate investment needs for achieving its target objectives over a planning horizon.

Beyond this major contribution, the dissertation presents an overall framework to assimilate pavement management systems components with selected components from asset management systems, geographic information systems, and knowledge management systems into an integrated decision support system. The goal of the integrated system is to provide decision makers with improved information from combining modern technologies with lessons learned from previous experiences, thereby leading to more effective investment strategies and general improvement of existing pavement management practices.

6.3 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The following research is recommended for future consideration:

a. The network average pavement condition index, the network average pavement remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor and very poor condition are parameters proposed in this dissertation to characterize the pavement network status and to monitor network performance over time. At the strategic management level, other network parameters may be of interest of a local agency. Research to expand the current set of network parameters to address target objectives such as the preservation of the pavement network asset value, or savings in user costs is desirable.

b. Case studies using pavement networks of different size to evaluate the investment analysis procedures developed in this dissertation should provide additional insights about potential savings due to the implementation of the methods used in the multi-objective strategic management approach.

c. A pilot project with a local agency of the Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area is recommended to introduce the multi-objective strategic pavement management approach. Results from this pilot project should encourage the use of the approach in other local agencies by showing its practical benefits.

d. Since the level of investment required over the planning horizon to carry out a strategy is really a point estimate, the use of risk assessment techniques should be considered in future development in order to assess the level of confidence of the estimates.

e. Feedback obtained from monitoring changes in the pavement network performance allows adjustments in the pavement management strategy. Lessons learned from previous experiences should contribute to the growth of corporate knowledge.

f. The on-going flow of knowledge in a systematic manner throughout the pavement management cycle is considered a key element for the efficiency of the management process. Research to explore techniques for discovering, capturing, sharing, and applying knowledge for its systematic use into existing pavement management practices should be considered in future research.

g. The integration of a case-based knowledge management system with a traditional pavement management system is an area of research to explore. The objective of conducting this research would be to improve the decision-making process in a local agency. Knowledge can be organized in categories for ease of storage and retrieval and expressed as knowledge cases that can be used to explain a certain approach or methodology, to present results from previous studies, to communicate agency policies, or to introduce new tools for pavement management practices. These knowledge cases can be stored into a repository of knowledge that practitioners can use in search of relevant information to help them to solve pavement management problems.
h. A web-based system is recommended as a supporting platform for knowledge capturing and sharing of best pavement management practices. Development of a peer-network among pavement management practitioners is recommended to share experiences that will contribute to the improvement of existing management practices.

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APPENDIX

TOOLS DEVELOPED FOR THE MULTI-OBJECTIVE PAVEMENT MANAGEMENT APPROACH

The appendix describes three tools developed in Excel© for illustrating the methodology developed under the framework of the multi-objective strategic pavement management approach. At their current stage of development these tools are hard-coded for the 100-DB.

A.1 Multi-Objective Strategic Pavement Management Tool

The Multi-Objective Strategic Pavement Management Tool (MOSPMT) has been developed to assist a local agency to set an investment strategy to meet multiple target objectives. MOSPMT estimates pavement network investment needs to meet agency target objectives for the network average pavement condition index, the network average remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor and very poor condition.

Data Needed

Data to run MOSPMT is extracted from MTC-PMS including section characteristics (street identification number, section identification number, year constructed, area of the section), functional class, surface type, pavement condition, and pavement deterioration curve parameters. Treatment costs for each maintenance and rehabilitation treatment category are also needed as inputs. The decision tree for treatment selection is based on functional class, surface pavement type, and pavement condition.

Techniques Used by MOSPT

MOPSPMT uses the “dynamic bubble up” procedure (DBU) to estimate the minimum funds needed to meet target objectives. Pavement sections are ranked from the lowest Cost/Weight Effectiveness Ratio (WER) ratio to the highest. The minimum level of investment to meet the targets for the network average pavement condition index, the network average remaining life, percent of pavements in very good condition, and percent of sections in poor condition is calculated through an iterative process. DBU starts from the top of the list of sections calculating each of the target network parameters. Starting at the top of the list, the calculation process considers that k sections are being funded and N-k are not funded (k starts with 1, and N is the total number of sections in the dataset). If the value calculated for the parameter does not meet the target value, the next section is “bubbled up” (k increases) and the new value for this parameter is calculated until the target value is met, or the last section in the dataset is reached (k = N).

Information Provided by MOSPT

MOSPMT provides information on the level of investments required to meet target objectives set by the agency. MOSPMT is flexible enough to allow the user to establish the investment strategy for each year of the analysis by having the capability to forecast the pavement network scenario for the next year.

A.2 Multi-Objective Strategic Optimization Tool

The Multi-Objective Strategic Investment Optimization Tool (MOSIOT) has been developed to minimize the amount of funds needed to meet pavement network objectives for a given year. MOSIOT solves two objective functions: minimizing the amount of investments and maximizing the Weight Effectiveness Ratio (WER) using a multi-objective integer linear programming model.

MOSIOT reduces the multi-objective model to a sequence of two step single objective optimizations. A preemptive optimization technique is used to solve the mathematical problem. The first objective function, minimizing the amount of investments, is solved first; then the second objective function, maximizing WER, is optimized subject to a requirement that the first objective function achieves its optimal value. MOSIOT is embedded in Excel and uses its Solver tool as the main engine to solve the mathematical problem.

Data Needed

MOSIOT requires information about the pavement sections (street identification number, section identification number, year constructed, area of the section), functional class, surface type, pavement condition index, remaining life, treatment category, treatment costs, WER, and target values set for the network average pavement condition index, the network average remaining life, percent of the pavement network in very good condition, and the percent of the pavement network in poor and very poor condition.

Mathematical Model used by MOSIOT

The first objective function is set to minimize the cost (Z)

Minimize Z: $$\sum_{i=1}^{N} C_i \quad X_i$$

where

Z	=	objective function for minimizing treatment costs
X_i	=	1 if section "i" is selected for a treatment; 0 otherwise
N	=	total number of sections
C_i	=	cost associated with the treatment given to section "i"

The second objective function is set to maximize the overall Weight Effectiveness Ratio (WER).

Maximize W: $$\sum_{i=1}^{N} WER_i \quad X_i$$

where

W	=	objective function for maximizing WER

subject to:

$$\sum_{i=1}^{N} a_i \ x \ (PCI_i + \Delta PCI_i \ X_i) \ / \sum_{i=1}^{N} a_i \ \geq \ PCI^T$$

$$\sum_{i=1}^{N} a_i \ x \ (RL_i + \Delta RL_i \ X_i) \ / \sum_{i=1}^{N} a_i \ \geq \ RL^T$$

$$\sum_{i=1}^{N} (a_{i1} + p_{i1} \ X_i) \ / \ \sum_{i=1}^{N} a_i \ \geq P^T$$

$$\sum_{i=1}^{N} (a_{i4} - q_{i14} X_i + a_{i5} - r_{i5} X_i) \ / \ \sum_{i=1}^{N} a_i \ \leq \ Q^T$$

where

PCI_i = PCI associated to section "i"

ΔPCI_i = PCI increment for section "i" due to treatment

RL_i = remaining life associated to section "i"

ΔRL_i = remaining life increment for section "i" due to treatment

a_i = area of section "i"

a_{i1} = area of section "i" which is in very good condition (PCI above 70, condition category I)

p_{i1} = area of section "i" which is moved to very good condition due to treatment

a_{i4} = area of section "i" which condition is in poor condition (PCI below 50, condition category IV)

$q_{i\,4}$ = area of section "i" which is recovered from poor condition due to treatment

$a_{i\,5}$ = area of section "i" which condition is in very poor condition (PCI below 25, condition category V)

$r_{i\,4}$ = area of section "i" which is recovered from very poor condition due to treatment

PCI^{T} = minimum network average PCI for the pavement network

RL^{T} = minimum network average remaining life for the pavement network

P^{T} = minimum percentage of sections in very good condition (PCI above 70)

Q^{T} = maximum percentage of sections in poor (PCI below 50) and very poor condition (PCI below 25)

Information Provided by MOSIOT

MOSIOT provides the minimum amount of investment needed to meet the target objectives at a given year of the planning horizon, and identifies the group of sections that maximizes the overall WER for that level of investment.

A.3 Strategic Pavement Network Scenario Analysis Tool

The Strategic Pavement Network Scenario Analysis Tool (SPNSAT) analyzes the impact on the network average pavement condition index, the network average remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor and very poor condition due to allocating funds to a given group of pavement sections.

Data Needed

SPNSAT requires information about the pavement sections (street identification number, section identification number, year constructed, area of the section), functional class, surface type, pavement condition index, remaining life, treatment category, treatment costs for each pavement section, and the sections selected for funding.

Information Provided by SPNSAT

SPNSAT provides information about key pavement network parameters including the network average pavement condition index, the network average remaining life, percent of the pavement network in very good condition, and percent of the pavement network in poor and very poor condition. This information is provided for the entire pavement network and for each sub-group of the pavement network for a given year of the investment period.

VITA

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