NCHRP 02-26 Implementation of Life-Cycle Planning Analysis in a Transportation Asset Management Framework

Introduction

The Moving Ahead for Progress in the 21st Century Act (MAP-21) and the Fixing America's Surface Transportation (FAST) Act codified 23 Code of Federal Regulations (CFR) 515—Asset Management Plans and 23 United States Code (USC 119)—National Highway Performance Program. Since the adoption of these regulations, transportation agencies have developed risk-based transportation asset management plans (TAMPs) for preserving and improving the condition of the national highway system. Recently, the Bipartisan Infrastructure Law made some amendments to 23 USC 119 and updated the minimum requirements for developing TAMPs. American Association of State Highway and Transportation Officials (AASHTO) developed the Transportation Asset Management (TAM) Guide to help transportation agencies understand and advance the TAM processes.

This national momentum is underpinned by the work being done at the state and local transportation agency level in the areas of asset management. For example, state departments of transportation (DOTs) have been practicing some form of enterprise asset management for well over three decades. Transportation agencies routinely make decisions that influence the life-cycle performance of the assets they manage. Figure 1 illustrates AASHTO's TAM framework and how life-cycle management is inextricably linked to the TAM practice. However, formalized consideration of life-cycle planning (LCP) within a TAM framework is still a relatively new practice, and there is considerable opportunity for transportation agencies to enhance their practices in this area. As TAM processes continue to mature, agencies are seeking additional guidance on LCP. In this context, this study has developed guidance and analytical models to support transportation agencies with formal consideration of LCP as part of their asset management practice.

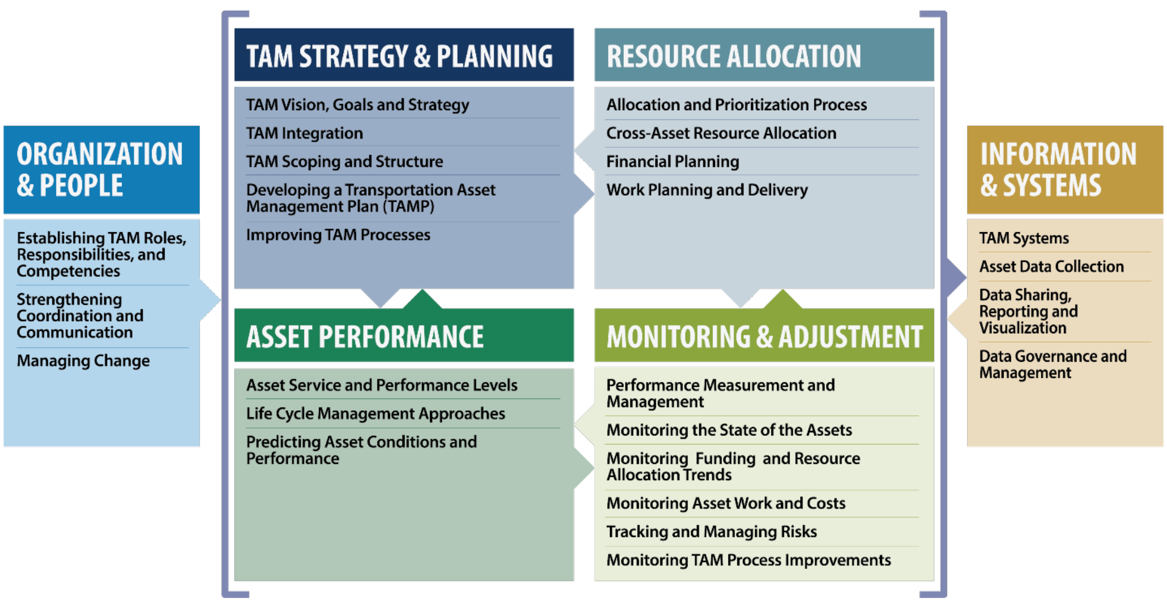

Figure 1. AASHTO's TAM framework showing life-cycle asset management as a core business process (Source: AASHTO TAM Guide, 2022).

Definition of Life-Cycle Planning

LCP, as defined in 23 CFR 515.5, is "a process to estimate the cost of managing an asset class, or asset sub-group over its whole life with consideration for minimizing cost while preserving or improving the condition." LCP applies the principles of economics and engineering to formulate life-cycle activity plans for asset classes. In doing so, LCP balances cost (investment), risks, and performance to achieve an optimal balance between maximizing service delivery outcomes (e.g., condition, performance,) and minimizing life-cycle costs.

The primary output of the LCP process is a life-cycle activity plan for an asset that entails selecting a sequence of maintenance, preservation, rehabilitation, and reconstruction actions that result in the lowest practicable costs over the asset's life cycle, while meeting the service delivery objectives. This optimal sequence of treatment actions is predicated on selecting the right treatment at the right time at the asset level and selecting the right project at the network level.

Role of Life-Cycle Planning in Transportation Asset Management

LCP lays out the processes and procedures for the life-cycle management of every asset class. Table 1 provides a brief description of how the various LCP activities and elements of the TAM framework (shown in Figure 1) relate to each other. As detailed in the table, LCP leverages the policies, business processes, procedures, service standards, asset inventory, asset-specific design and maintenance practices, performance measurement, data, and analytical models to achieve optimal asset life-cycle management outcomes. The details of a life-cycle plan will depend on the maturity of the asset management practice for a given asset class. Generally speaking, LCP practices mature as TAM processes mature.

Table 1. Relating building blocks of TAM to LCP.

LCP Activities [Corresponding TAM Framework Process]	Description and Purpose
DOT Policies, Strategies, and Plan [TAM Strategy and Planning]	Outlines an approach to guide the overall LCP process; pursue activities; and achieve desired outcomes at asset, network, and system levels. Outlines the roles, responsibilities, and accountabilities of the asset owner.
Asset Inventory [Information and Systems]	Maintains information on asset classes of interest that includes type, location, number, service class, construction and maintenance history, and other data attributes to capture what assets a DOT owns. Access, consistency, and quality of this information is fundamental to a robust, data-driven LCP.
Condition Assessment [Monitoring and Adjustment]	Measures the assets' current condition or allows prediction of future condition and system performance using performance indicators to capture the observed physical state and the perceived level of service the asset provides. Periodic inspection and assessment, monitoring, forecasting, and modeling are a part of this activity. Access, consistency, and quality of this information is fundamental for a robust, data-driven LCP.

Level of Service Requirements (LOS) [Asset Performance]	Defines the agency's commitment to deliver service at a specified standard or level of quality and reliability (i.e., targets for each performance indicator) against which performance is assessed.
Performance Monitoring [Monitoring and Adjustment]	Compares measured performance indicators against the LOS requirements to assess how well the agency is offering service.
Demand Forecasting [Asset Performance]	Estimates the future demand (traffic, environmental, and resilience) on service requirements and asset performance because they have a direct impact on the ability to deliver service to LOS standards.
Needs Identification [Asset Performance]	Helps determine whether one or more performance measures have exceeded a threshold which trigger the need for an intervention. Helps determine whether an asset requires a maintenance action to restore or continue to deliver the LOS cost effectively, and accordingly, identifies one of the following approaches: preservation or proactive/preventive maintenance, or rehabilitation, and reconstruction.
Treatment Selection [Resource Allocation]	The process of selecting the optimal treatment type and timing for an asset to address a specific need cost effectively. Costs of immediate actions are used in budgeting or selection of the work program, while the future costs are used in forecasting capital and maintenance budgets.
Risk Assessment [Monitoring and Adjustment]	Helps document risks that would affect the ability to deliver service cost effectively. Incorporates funding, data, technical, or hazard-related risks into the treatment selection process.
Prioritization and Optimization [Monitoring and Adjustment]	Process of selecting projects for the work program based on funding availability, asset or service hierarchy rules, and performance constraints. Prioritizes factors using a prioritization or optimization algorithms.
Financial Planning and Performance Gap Analysis [Resource Allocation]	An estimation of the financial needs to upkeep the system at desired levels, ascertain expected funding levels, and shortfalls. Assesses gaps between expected and desired performance to understand the implications of the financial plan.

Life-Cycle Planning State of the Practice

Transportation agencies routinely make decisions regarding the life-cycle performance of assets. These decisions are largely guided by the policies, processes, and capabilities set within the agency's TAM framework. To improve overall TAM practice maturity, transportation agencies strive to follow a set of common approaches and principles as detailed in the AASHTO TAM Guide. However, the state of the practice reveals some challenges with the implementation of the LCP framework.

Diversity of TAM Practices: To some extent, each agency has a unique set of TAM practices, which invariably influences the way the agency plans for its assets' life cycles. Agencies use their own set of condition measures, forecasting models, performance requirements, treatment types, treatment effectiveness, cost models, and selection criteria and algorithms for a given asset class. For example, the definition and formulation of pavement condition measures are not consistent across the country. Even within an agency, the TAM practices are not the same for all asset classes. Most transportation agencies have more mature LCP practices predominantly for pavements and bridges, whereas the LCP practice is still evolving for other high-value assets, such as Transportation Systems Management and Operations (TSMO) or geotechnical assets. No "one size fits all" approach is available for LCP implementation. Therefore, a standard LCP framework that builds on the existing practice, is broad enough to include all assets, and is adaptable to agency-specific practices is necessary.

Maturity of LCP Enablers: LCP, as practiced today, is enabled and shaped by an agency's TAM capabilities for a given asset class. The outcomes of the LCP process depend on the quality and sophistication of these essential capabilities or "enablers": condition and performance data; performance indicators; forecasting and decision models; and policies and business processes. The state of the practice indicates LCP enablers of varied maturity levels are being used in practice. This diversity should be considered in the LCP framework.

Computational Bottlenecks with Mathematical Optimization. As discussed earlier, the primary objective of an LCP process is to develop a life-cycle activity plan that optimizes costs, service delivery, and performance. This decision process entails data-intensive optimization exercises to select the right treatment type at the right time at an asset level and the right project at the program level. These types of analysis are typically handled through information systems with sophistical algorithms and high computational resources.

Theoretically, the number of such possible combinations in the optimization exercise is generally near infinite. If '*I'* represents the number of assets in a network, '*Intr'* represents the number of treatments (in treatments library) that can be performed on a network, and '*T'* represents the number of time intervals in the life-cycle analysis period, then the total number of decision variables to be solved will be $I*Intr^{T}$. For example, for a single asset (i.e., I = 1), if four treatment categories are considered over 10-time intervals (T), then the optimization problem must analyze 1,048,576 possible combinations of treatment categories to find an optimal solution. The number of combinations of treatment categories increases to 1,099,511,627,776 for a single asset when the analysis period is increased to 20-time intervals. The optimization process will take a long time and use considerable resources to solve the near infinite combinations, creating computational bottlenecks. This is often referred to as the Generalized Asset Management Problem (GAMP)**.**

In practice, dimensionality reduction techniques, such as pre-defined cutoff values of performance measures in decision trees, are often used to reduce the total number of required combinations. However, because these reduction techniques are quasi-arbitrary in nature, their ability to produce a truly optimal solution for decisions in the LCP process is not guaranteed. Therefore, the LCP process needs a balance between the degree of optimization and computational resource needs.

Need to consider risks and uncertainties. LCP is a data-intensive effort. Transportation agencies rely on forecasting models, which are developed empirically using historical data, to make deterministic decisions on life-cycle management of assets. However, life-cycle management of highway infrastructure assets is inherently fraught with risks and uncertainties over the lifetime of these assets. Failure to effectively manage risks could result in a wide range of negative consequences. The effectiveness of the LCP process itself will be affected by risks and uncertainties.

In addition, the cone of uncertainty increases over time, possibly beyond 10 years, because transportation agencies lack reliable long-term forecasts of traffic and environmental demand and revenue. Note that almost all empirical models exhibit intrinsic variance in their predictions and are prone to errors when predicting the future, particularly when future trends deviate from the bounds of historical data. As transportation agencies recognize how risks and uncertainties impede their ability to achieve LCP objectives, it becomes more important to incorporate risks into the LCP framework.

Project Objectives and Research Methodology

The stated objective of the NCHRP 02-26 study is to develop guidance in conjunction with one or more prototypical, analytical models to support LCP and decision-making that applies life-cycle cost analysis as a part of a system-wide TAM program.

To achieve this objective, the research team developed a framework to perform LCP. The proposed framework identifies LCP as a specific process that is applied at asset and network levels to select an optimal subset of projects annually with cost-effective treatment options to achieve TAM goals. The proposed framework identifies high-level steps and specific work steps that can be incorporated into current agency practices.

To accomplish the research objectives, this study included the following tasks:

- **Literature Review**: The research team reviewed national and international literature to establish a state-of-the-practice benchmark for TAM, infrastructure life-cycle management, risk management, and life-cycle cost analysis practices. More than a dozen TAM plans were reviewed to understand how transportation agencies envision LCP in practice.
- **Benchmarking**: Recognizing the diversity of TAM practices among transportation agencies and across asset classes, the research team conducted a benchmarking exercise to identify LCP enablers of importance, compare how agencies define and use the enablers, and establish maturity levels.
- **LCP Framework Development**: At the onset, a series of research questions was used in the LCP framework development to reinforce the current practices and find gaps for additional development. The individual enablers and component models of the proposed LCP framework were investigated for their readiness to be used within the proposed framework.
- **Additional Investigations**: The research team conducted detailed investigations and analyses to assess the feasibility of deploying component models in the LCP framework. Additional guidance on LCP enablers was provided as necessary. To support the optimization of life-cycle activity sequences, the windows of opportunity concept was demonstrated using an illustrative spreadsheet. The research team developed

methodologies to facilitate the integration of risks and uncertainties within the LCP framework. In response to the data challenges associated with incorporating risks into the LCP framework, the team developed a simplified risk score-based approach for use in the prioritization process.

- **Validation and Illustrations**: In addition to the state-of-the-practice review, the research team conducted questionnaire interviews with four DOTs to solicit feedback on the proposed framework. The information received from the DOTs was used to validate and update the framework. The team also conducted two case studies to demonstrate and validate the proposed LCP framework using information gathered from Michigan and Virginia DOTs on bridge and pavement assets, respectively.

Key Findings

The key findings of this study are summarized under the following topics.

Benchmarking

Through the benchmarking exercise, this study established the maturity levels of various LCP enablers. The key observations of the benchmarking exercise are summarized as follows:

- Transportation agencies use a range of measures to indicate the condition of highway assets. The condition measures are based on asset age, general condition rating, serviceability-based component rating, or indices representing individual distresses. The LCP practice could benefit from additional measures for various asset classes that indicate:
    - The end-of-life condition state, or irreversible damage caused by physical phenomena, such as structural adequacy of pavements.
    - The deterioration mechanisms and failure modes, such as element-level condition states associated with general condition ratings of bridge components and chloride-induced corrosion indicators.
    - The reliability of asset performance, such as mean time-between failures for TSMO assets
- Most forecasting models use the asset age as the predictor variable. In addition to age, these models may include limited causal factors (e.g., traffic volume) and stratification factors (e.g., geographic region). The deterioration models might not incorporate traffic volume (e.g., pavements), truck size and weight (e.g., bridges), construction quality, and long-term climate change impacts. These models can indicate the time of or time to the next intervention. The DOTs are less likely to have data or analytical models to capture future changes in causal factors and asset deterioration patterns.
- Most DOTs have construction cost models that track historical information using construction cost indices, while only a few of them develop forecasts that use economic drivers, such as inflation. The DOTs in general lack models to forecast long-term traffic demand, climate and extreme weather, and revenue.

- TAM systems are typically not federated or integrated to exchange data with safety, construction management, and mobility information systems.
- Most DOTs use either decision trees for singular selection of treatments and/or benefit-cost analyses through an evaluation of multiple alternatives. Some DOTs perform asset-level treatment selection followed by prioritization of projects at the network level, while some DOTs conduct treatment and project selection using multi-year optimization. The DOTs appear to depend on the computational and analytical capabilities of their asset information systems.

Framework Development

Building on the state-of-the-practice review and benchmark analysis, key research questions were used to guide the development of framework:

- What are the intervention principles?
- What is an end-of-life condition or terminal state?
- What is the optimal intervention principle (optimum performance threshold) for a given asset, treatment type, and condition indicator?
- What performance indicators should be forecasted for establishing intervention needs?
- What is a window of opportunity in treatment selection?
- How are the consequences of delayed maintenance evaluated?
- How is resilience planning (or risk mitigation) incorporated into the treatment planning process?
- How can risks and resilience be incorporated into the optimization process?
- How should the issue of loss of forecasting accuracy over time be handled in life-cycle optimization modeling?
- What are the competing objectives (performance measures and objective functions) for each asset type?
- Are there computational bottlenecks for optimization (related to the GAMP)? If so, what improvements would improve optimization?

The answers to these questions culminated in the development of the high-level steps of the LCP framework.

The LCP process follows the prevailing practices established for managing a given asset class and uses existing asset registers, information systems, condition assessment tools and processes, performance models, asset maintenance strategies, and cost information. The robustness of the LCP analysis and its ability to achieve the intended objectives depends on the maturity and sophistication of these enablers and processes.

To help systematically integrate LCP into the TAM framework, this guide presents a framework comprising four high-level steps and a series of work tasks within each step. The proposed LCP framework can be performed for both individual assets and at the network level. The proposed high-level steps are depicted in Figure 2 and are described in the following paragraphs.

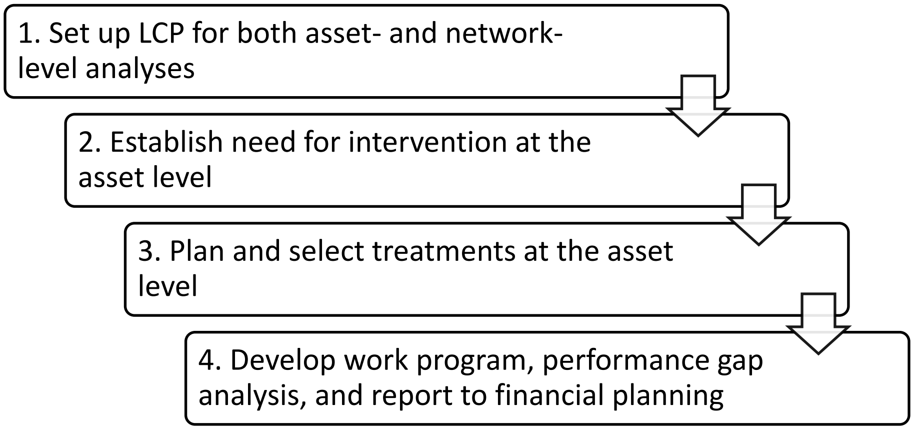

Figure 2. High-level steps of the LCP framework.

1. **Setting up LCP for both asset and network levels:** This high-level step sets up the policies, enablers, and controls for conducting LCP at both the asset level (termed ALCP) and network level (termed NLCP). Work tasks under this high-level step include:
    a. Select asset classes and subgroups of asset classes. Define homogeneous asset groups by asset families that have similar characteristics, deterioration patterns, and system hierarchy.
    b. Establish performance measures.
    c. Establish criteria for intervention needs.
    d. Establish life-cycle analysis parameters.
        - Cost models
        - User benefit models
        - Analysis period (also a function of optimization capabilities, i.e., how far into the future can optimization support)
        - Discount rates.
    e. Update asset-level histories and forecasts, including condition and inspection data, traffic volumes, truck weights, construction history, crash history, hazard history, and environmental demand.
    f. Update condition deterioration models as necessary.
    g. Formulate feasible ALCP strategies.
    h. Formulate feasible NLCP scenarios.

2. **Establish Intervention Needs at Asset Level (ALCP)**
    a. Define LCP enablers that help establish reasonable life-cycle plans.
    b. Screen for deficiencies for a given analysis year by comparing the current condition states against their corresponding performance targets.
    c. Forecast the future condition state using appropriate techniques (e.g., deterioration models for pavements, transition matrices for bridge or other assets) to identify the timing of the next intervention need. Repeat steps 2b and 2c, as necessary.

3. **Treatment Planning and Selection at Asset Level (ALCP)**
    a. Identify feasible asset-level LCP strategies, including potential treatment types, costs, condition resets, and effectiveness.
    b. Select the preferred treatment type using a life-cycle cost-based treatment selection model. The focus is on selecting the "right treatment type at the right time" that results in the lowest practical life-cycle costs.
    c. Incorporate resilience planning, which includes climate change-induced accelerated deterioration, extreme weather, bridge collision, rock falls, and other stochastic threats, into the treatment selection process.
4. **Develop Network Level Work Program, Conduct Performance Gap Analysis, and Report to Financial Planning (NLCP)**
    a. Develop an unprioritized list for the work program for the network.
    b. Establish objective functions for prioritization (or optimization).
    c. Perform prioritization (or optimization) to develop a work program based on funding levels and resource allocation policies.
    d. Conduct a performance gap analysis to evaluate the consequences.
    e. Revisit the assumptions and rerun prioritization (or optimization) for various scenarios.
    f. Select the preferred profile of the work program.
    g. Prepare a final, multi-year profile of work program, conditions, and costs as inputs to financial planning.

The specific work steps, identified above, can be incorporated into existing asset management planning and implementation processes at a transportation agency. The proposed LCP framework aligns with the condition- and interval-based management approaches of many transportation agencies DOTs. LCP analyses are expected to be advanced for asset classes with high asset management maturity (e.g., pavements and bridges). LCP analyses can also be undertaken for other high-value assets with low asset management maturity, such as geotechnical and TSMO assets. The Life-Cycle Planning Guide and Final Report, which were developed as a part of this study, provide detailed guidance on each of the work steps.

Additional Guidance on Enablers and Models

As mentioned earlier, the effectiveness of LCP depends on the quality and sophistication of LCP enablers. Agencies need to consider the maturity of the overall practice and identify the enablers of LCP to tailor the LCP framework to suit their operating context. Furthermore, building on current competencies through continual improvement is a cornerstone in TAM practice. Benchmarking will help the agencies understand what their current capabilities are, assess what will work or will not work for their organization and their asset portfolio, and accordingly, improve the maturity of enablers.

To augment the LCP practice, the research team conducted further investigations and provided additional guidance on the following specific enablers and component models:

- Performance measures

- Criteria for treatment intervention
- End-of-life criteria
- Performance models
- Probabilistic approach to deterioration modeling
- Window of opportunity concept
- User disbenefits
- Economic equivalence
- Treatment and project selection algorithms

The Life-Cycle Planning Guide and Final Report provide detailed guidance on the LCP enablers and component models.

Using Local Optimization Techniques

The research team investigated the GAMP problem using scenario analyses of illustrative examples to understand the magnitude of computational needs of global optimization, identify heuristic techniques for the reduction of analysis variables, and evaluate the need for conducting such analyses. The scenario analyses indicated that the numerical solutions of global optimization are prone to produce errors and unreasonable solutions, such as consecutive applications of a treatment type (e.g., preservation in two consecutive years), and undesirable timing of a treatment application when the condition rating does not warrant an intervention (e.g., reconstruction at higher condition rating). However, global optimization confirmed the key postulates of LCP, including the effectiveness of preservation actions and the windows of opportunity concepts. Building on these findings, this study proposes an alternative solution using local optimization, where the window of opportunity analysis could be used to optimize treatment timings around intervention needs.

Incorporating Risks and Uncertainties in Life-Cycle Planning

This study synthesized a comprehensive list of risks that are likely to affect the ability of transportation agencies to achieve their intended objectives of LCP. This list, which is further categorized into three groups below, will be useful in improving the risk awareness of "what can deviate" from the anticipated life-cycle plan:

- **Asset/Service Failure Risks**: Risks that cause a loss in asset value, and consequently, increase life-cycle costs.
    - Accelerated deterioration.
    - Catastrophic or unexpected asset failure.
- **Decision Quality Risks**: Lack of reliability with input factors due to inherent variability or uncertainty, affect the precision of anticipated outcomes.
    - Future cost increase and/or cost uncertainty.
    - Reliability of technology (system), data, and analytical capabilities.
- **Funding Risks**: Risks that affect the ability to carry out maintenance activities as planned, ultimately increase life-cycle costs.

- Uncertain and insufficient funding.
- Deferred asset maintenance.

This group of risks can be handled through resilience planning with some consideration of frequency-based or Bayesian probabilities. Resilience planning can be undertaken either as an integral part of treatment planning or as a stand-alone exercise. Nevertheless, resilience planning follows the same principles and process steps as treatment planning. Figure 3 illustrates how risk and resilience considerations can be integrated into the regular LCP process at the asset and network levels to reduce the vulnerability of assets and the likelihood of failure. Adaptation measures can be planned either as a part of treatment planning or a stand-alone exercise.

Although many resilience studies are currently underway, transportation agencies currently lack "production-ready" analytical models to incorporate them into the LCP process; rather, they can adopt an incremental approach to integrate resilience considerations into the LCP process. In the interim, this study proposes a risk-based scoring methodology for use in the multi-criteria evaluation of treatment and project selection. This methodology proposes a composite score based on expert elicitation that considers the probabilities of hazard occurrence and intensity, the damage potential of assets in response to hazard intensity, the relative priority of assets, and the anticipated time of recovery efforts.

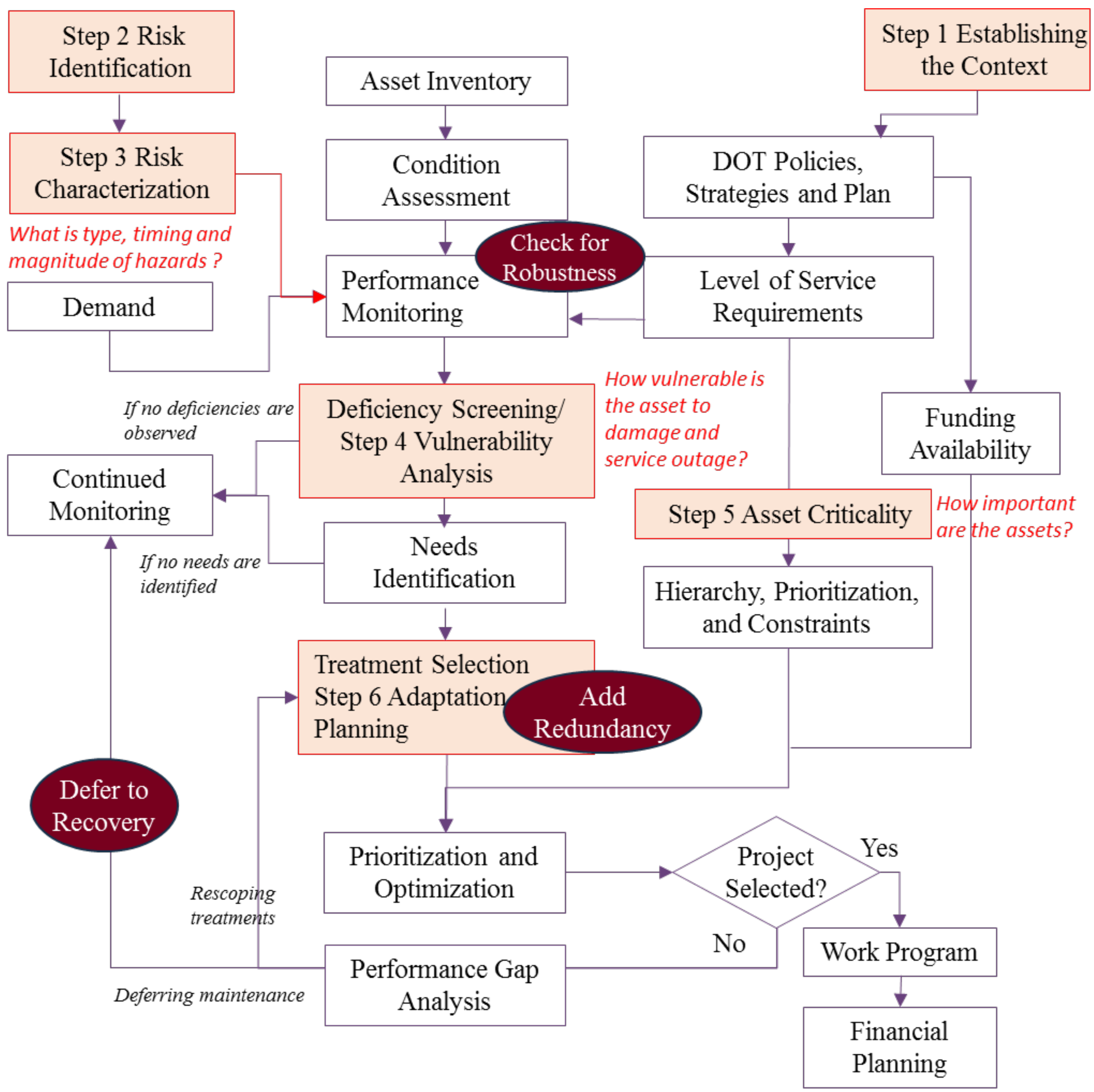

Figure 3. Incorporating asset failure risks into the ALCP treatment planning process.

Recommendations

Research Products

The research products developed under this study include:

- A final report that documents the research activities and findings of this study.
- The LCP Guide that presents the LCP framework and provides detailed guidance on specific work steps and enablers.

- An Implementation plan that describes strategies for agencies that are interested in improving the overall TAM practice for enhanced LCP analyses.
- A PowerPoint presentation.

These products are intended to assist state DOTs and other transportation agencies to successfully incorportate the LCP process as part of TAM decision-making.

Suggestions for Future Research

This study recognizes the current gaps in analytical capabilities to perform LCP analysis effectively:

- Lack of element-level deterioration models for bridge structures.
- Lack of translation between element- and component-level deterioration for bridge structures.
- Non-availability of maintenance costs and effectiveness.
- Lack of robust models to incorporate the effectiveness of treatments applied to pavement and bridge assets.
- Lack of practice maturity to enable LCP analyses for high-level assets, including intelligent transportation systems and geotechnical assets.
- Lack of design standards and related analytical models for incorporating resilience for highway infrastructure assets.

Many ongoing NCHRP and Transportation Pooled Fund studies are investigating these gaps. The completion of those research studies might address the gaps mentioned above.

To further support the implementation of the LCP framework, suggested future research could focus on the following topics:

- Developing a life-cycle data model that houses all data relating to the life cycle of an asset or group of assets in a facility.
- Developing a set of methodologies, capabilities, and practices that dynamically or continuously account for a broad set of threats and opportunities in LCP as a part of TAM business processes.
- Incorporating equity in LCP decision-making to evaluate the potential disparities in asset condition and performance among various geographic areas and their implications to both users and communities.