University Transportation Research Center - Region 2

Final Report

Review of Asset Hierarchy Criticality Assessment and Risk Analysis Practices

Performing Organization: Rutgers University

January 2014

Sponsor:
Metropolitan Transportation Authority (MTA)

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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16. Abstract

The MTA NYC Transit (NYCT) has begun an enterprise-wide Asset Management Improvement Program (AMIP). In 2012, NYCT developed an executive-level concept of operations that defined a new asset management framework following a systems engineering approach. NYCT has recognized the need for a fully developed asset hierarchy to enable the evaluation of performance and cost at different levels within the agency. To that end, NYCT has initiated this project as one of the initial steps in better understanding the state of the art in asset management.

This report presents methodologies used for asset registration, asset hierarchy, and criticality and risk assessment, gathered from an extensive literature review and interviews with industry experts. The interviews included companies from the water, oil and gas, and rail industry in the US and UK; however, their names need to remain confidential. In addition, a review of asset management standards is included as an appendix to this document.

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REVIEW OF ASSET HIERARCHY, CRITICALITY ASSESSMENT AND RISK ANALYSIS PRACTICES

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Contents

List of Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACRP	Airport Cooperative Research Program
AMIP	Asset Management Improvement Program
EPA	US Environmental Protection Agency
CAPEX	Capital Expenses
CIP	Capital and Investment Plan
CMMS	Computerized Maintenance Management System
FMEA	Failure Mode and Effect Analysis
FTA	Federal Transit Administration
GIS	Geographical Information System
GPS	Global Positioning System
H&S	Health and Safety
IEAM	Integrated Engineering Asset Management
KPI's	Key Performance Indicators
LCC	Lifecycle and Replacement costs
LCH	Lost Customer Hours
LOS	Levels of Service
MADM	Multi-Attribute Decision Making
MMI	Maintenance Managed Item
MTA	Metropolitan Transportation Authority
NYCT	New York City Transit
OPEX	Operational Expenses
O&G	Oil and Gas
O&M	Operations and Maintenance
PI's	Performance Indicators
RSSB	UK Railway Safety and Standards Board
SIMPLE	Sustainable Infrastructure Management Program Learning Environment
WERF	Water Environment Research Foundation

Executive Summary

The MTA NYC Transit (NYCT) has begun an enterprise-wide Asset Management Improvement Program (AMIP). In 2012, NYCT developed an executive-level concept of operations that defined a new asset management framework following a systems engineering approach. NYCT has recognized the need for a fully developed asset hierarchy to enable the evaluation of performance and cost at different levels within the agency. To that end, NYCT has initiated this project as one of the initial steps in better understanding the state of the art in asset management.

This report presents methodologies used for asset registration, asset hierarchy, and criticality and risk assessment, gathered from an extensive literature review and interviews with industry experts. The interviews included companies from the water, oil and gas, and rail industry in the US and UK; however, their names need to remain confidential. In addition, a review of asset management standards is included as an appendix to this document.

1 Introduction

The term “asset management” first appeared in the banking industry to describe an investment practice that builds wealth through investments in different types of financial assets. The principles of asset management are well established in car manufacturing, mining and petrochemical industries. In 1999, the US Department of Transportation defined asset management as a business process and decision-making framework that draws from economics and engineering theory and practice to manage a broad range of assets during an extended time horizon. The approach incorporates the economic assessment of tradeoffs between alternative investment options at both the project level and the network or system level, and uses this information to help agencies make cost-effective investment decisions [1].

Asset management is no longer considered a cost but a value-generating practice that spans over all levels within an organization and links the organization’s mission and long-term investment strategies with the short and medium-term tactical and operational objectives. Organization-wide, systemic and systematic approaches to value-based asset management along with high quality asset information are necessary to guarantee success of asset management projects.

To build and sustain a value-based asset management one must institute business practices and the supporting technology on the basis of flexible asset hierarchy and information quality. Asset hierarchy flexibility is essential for value-based asset management since value recognition is not a one-time shot but rather an evolutionary process requiring machine learning and intelligent tools to grow and to optimize. Flexibility on asset hierarchy granularity is also a fundamental characterization of a value-based asset management system. While it is easy to breakdown assets according to their functions, ownerships and community memberships, it is less obvious to structure them according to technology advances and exogenous market factors. A robust and flexible asset hierarchy must be able to adapt to new hardware and software technology. Moreover, in a dynamic business environment assets generate value as members of community of assets under dynamically changing functional hierarchies and operational conditions. The functional and operational importance of assets partially changes due to their criticality factors. In a value-based asset management environment asset criticality assessment is an ongoing process that provides a criticality ranking list of systems, assets and components, identifying conceivable failure mechanisms underlying the failure rates, likelihood of impact from the failure, and ultimately, identifying the consequences of these failures. Asset criticality can shape and reshape the interaction between assets, thus significantly impacting asset hierarchy. Therefore, asset hierarchy must be adaptable to these interactions and changing dependencies.

Information quality is another major requirement for value-based asset management. It is defined as the fitness for use of the information – but has various dimensions. Research has shown that six dimensions of information quality are critical for effective asset management: accessibility, consistency, validity, timeliness, accuracy, relevance and completeness [43]. High quality asset information is essential from three perspectives: (1) to develop better quality asset management plans (as compared to plans with incomplete or inaccurate data), (2) to minimize the likelihood of incorrect expenditure prioritization, and (3) to avoid unnecessary costs through having to correct the data. For instance, having a complete and accurate record of all the assets, their age, location, function, value, etc. in the asset register is critical for long and medium-term planning of CAPEX and OPEX. Simple and obvious as it may sound, not many organizations can claim to have a good quality asset registry. This brings with it a resulting business risk – unplanned expenses, asset failures and disruption to public (especially in the case of infrastructure systems), etc.

Project Organization

This report presents a review of asset management practices with particular focus on asset hierarchy and asset criticality in asset intensive industries.

Section 2 begins with a summary of the ten-step asset management methodology proposed by the US Environmental Protection Agency (EPA) as it can be used as a general model for any organization's asset management methodology. Two of the ten steps are particularly discussed in this report: 1) Step 1 refers to the development of an asset register, and 2) Step 6 focuses in determining business risk exposure and criticality. These two steps are discussed in detail in section 3 and 4, respectively.

Section 3 starts with a discussion on asset hierarchy and asset hierarchy models. Then it presents the three-phase asset hierarchy development framework developed by the Water Environment Research Foundation (WERF), followed by a four-step asset register development process.

Section 4 discusses risk assessment and criticality analysis. The risk assessment subsection includes steps to estimate risk, quantitative and qualitative methods to assess risk, graphical tools and types for risks. The criticality analysis subsection presents the steps to conduct the analysis which includes asset identification, criteria definition, and scoring.

Project Approach

The Project Team conducted a comprehensive literature review and organized interviews with experts from several domestic and international organizations. Two major types of sources of information have been used for literature review purposes. The first type consists of existing standards, guidelines, and regulatory compliances regarding asset management and enterprise risk management. The second type includes white papers, technical reports, scientific articles, and academic theses and research. This report particularly focuses on practical methodologies and frameworks used in industry. The interviews included domestic and international organizations from the aviation, water, transit, and oil and gas sector. However, name of companies and detailed information cannot be disclosed.

The study is a collaboration between the Center for Advanced Infrastructure and Transportation (CAIT) at Rutgers University and the Institute for Manufacturing (IFM) Distributed Information and Automation Laboratory at Cambridge University – UK. CAIT has partnered with EAM Group to accomplish this effort.

2 Approaches to Asset Management

This section reviews asset management methodologies used by environmental protection, highways and transportation, and power distribution organizations.

US Environmental Protection Agency Asset Management Methodology

A literature review of various asset management methodologies revealed that most industries have accepted the general methodology developed by the United States Environmental Protection Agency (EPA). The methodology consists of five core questions and a ten-step process that helps define asset management plans [2].

The Five Core Questions:

The following five core questions should be clearly answered when implementing an asset management framework [2]:

1. **What is the current state of my assets?**
    - What do I own?
    - Where is it?
    - What condition is it in?
    - What is its remaining useful life?
    - What is its remaining economic value?
2. **What is my required level of service (LOS)?**
    - What is the demand for my services by my stakeholders?
    - What do regulators require?
    - What is my actual performance?
3. **Which assets are critical to sustained performance?**
    - How does it fail? How can it fail?
    - What is the likelihood of failure?
    - What does it cost to repair?
    - What are the consequences of failure?
4. **What are my best O&M and CIP investment strategies?**
    - What alternative management options exist?
    - Which are the most feasible for my organization?
5. **What is my best long-term funding strategy?**

According to Remenyte-Prescott and Andrews [3] from the Nottingham Transportation Engineering Centre at the University of Nottingham in the UK, these five core questions can be used as the foundation of many asset management best practices. Variants of these five core questions are not uncommon. For example, the Port of Seattle uses the following [4]:

1. What do we own and how long do we want it to last?
2. Who is responsible for the maintenance?
3. What is the age, condition, and cost to replace?
4. How long will the assets last based on appropriated maintenance funding?
5. Where do we place strategic priorities?

Implementing a mechanism that enables companies to provide effective responses to these questions is the main objective of enterprise asset management [2].

The Ten-Step Process

To address each of the five core questions, EPA developed the ten-step process illustrated in Figure 1.

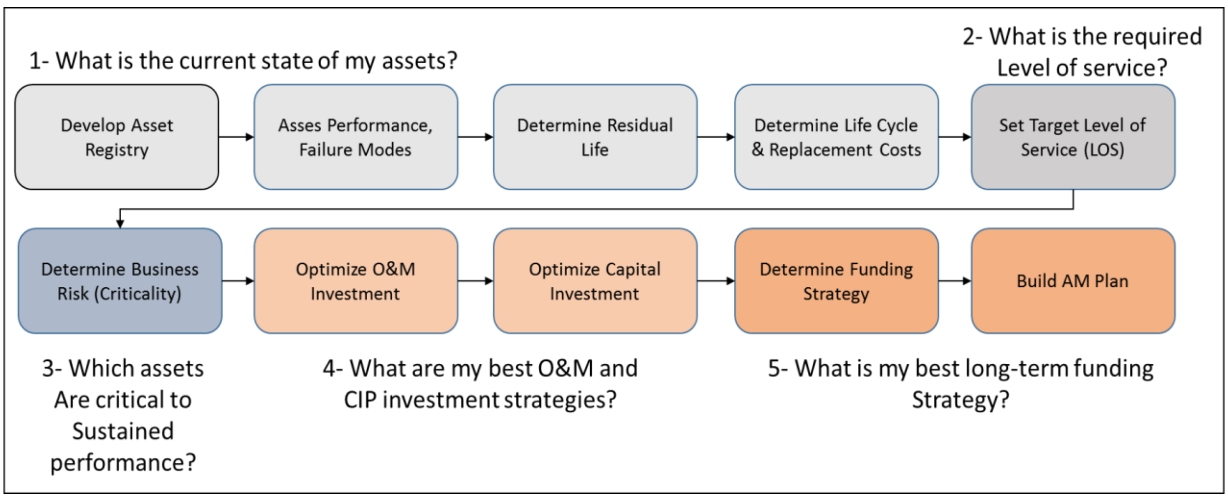

Figure 1 – EPA 10 Step asset management process [5]

<u>Step 1: Develop Asset Registry</u>

In general terms, an asset registry is a database of all assets within an asset group. An asset registry typically follows a hierarchical logic that enables analysts to investigate the effect of asset failure on other assets (asset interconnectivity). In addition, in order to fully understand the total cost of service in asset management planning; a thorough asset registry is essential.

Step 2: Asset Performance and Failure Modes

This step involves evaluating the performance of the assets and identifying major failure modes. Asset functionality, level of service, availability, maintainability, sustainability and reliability are common factors to be considered during the evaluation of asset performance.

Step 3: Determine Residual Life

Residual life is the time left until failure and is particularly important for managing high cost and high risk assets. Residual life is usually specified once the time and likelihood of the impendent failure mode is known. Depending on the type of asset, it will either reach the end of their useful life through amount of use or length of service. The other general factors determining residual life of assets worth mentioning are poor installation, requirement to operate the assets at a level not envisaged during the design phase, defective materials, poor maintenance and operating environment.

Step 4: Determine Lifecycle and Replacement Costs (LCC)

The Asset and Infrastructure Management for Airports – Primer and Guidebook [6] defines lifecycle and replacement costs (LCC) as all costs of owning and operating an asset from planning through retirement or replacement. They calculate these costs as:

LCC = Capital cost + Lifetime operating costs + Lifetime maintenance costs + Disposal Cost – Residual value

The above calculation is based on direct lifecycle cost and economic cost which are two major cost perspectives. Please note that capital cost is a variation of economic costs such as financial cost and triple bottom line.

Step 5: Set Target Levels of Service (LOS)

In general, this step involves establishing target levels of service for each asset, addressing the demand of asset services as well as stakeholder and regulators requirements, and determining the actual performance of the assets. The LOS includes the needs of any technical, managerial or financial components of the system, as long as all regulatory requirements are met. The LOS should be a fundamental part of how the system is operated.

Step 6: Determine Business Risk (Criticality)

Since assets are not equally important to the system’s operation, an organization should identify the assets that are highly critical to its operation. This step specifies those assets that are high cost in detrimental levels of service, and consequences to the level of service at the time of their failure. Organizations should focus investment and attention to the assets within the system that matter the most based on risk calculations. In the literature, many methods are used for evaluating risk exposure associated with the physical failure of assets. In the simplest terms risk is calculated as follows:

Risk exposure = Probability of failure × Consequence of the failure

Step 7: Optimize Operations and Maintenance (O&M) Investment

One of the purposes of identifying critical assets is to allow the agency to make more informed decisions regarding the use of its operation and maintenance budget. It is beneficial to the agency to spend the greatest portion of its operation and maintenance budget on assets that are most critical to the overall operation. As a rule of thumb, planned maintenance costs are about one third less than unplanned maintenance for the same task. This step in general, identifies the best O&M investment strategies, the alternatives and the most feasible options for the agency.

Step 8: Optimize Capital Investment Plan (CIP)

The purpose of this step is to utilize the data and information established through the last seven steps to evaluate the best operation, maintenance and capital investment strategies needed to deliver the required level of service at the best cost and level of risk exposure. Capital investment is made up of two major types of projects: renewal and augmentation. Ideally, capital investment planning should cover a 20 year period. It should be updated each year so that it always shows 20 years of needs. Overall, a cost effective Capital Investment Plan (CIP) is about right solutions at the right time; a combination of balancing and risk consequences.

Step 9: Determine Funding Strategy

At this step, available funding strategies are evaluated for implementation of asset management investment plans developed through all previous steps. Up to this step, all components of the asset management strategy lead a system to discover what actions are most appropriate to manage the system at the desired level of service and at the lowest cost. The last two steps in the asset management methodology determine the best way to fund the operation, maintenance, repair, rehabilitation, and replacement of assets.

Step 10: Build / Document Asset Management Plan

The objective of this step is to prepare an asset management plan that is amenable to all stakeholders within the organization. The asset management plan should be thought of as a strategic and tactical roadmap for the organization. It should be written in a plain language and updated frequently as the system performs its operational duties to determine if the methodology used for all components has changed during time.

These ten steps constitute a useful guide especially for the development of the first asset management plan. As the asset management planning activity becomes embedded in the agency planning processes, the update of the asset management plans focuses on re-running the investment analysis using updated data rather than a full establishment of the state of the assets data and information and constraints, and therefore, involves far fewer resources and time to execute.

American Association of State Highway Asset Management Model

According to the American Association of State Highway and Transportation Officials' (AASHTO) subcommittee on asset management:

> "Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision-making based upon quality information and well-defined objectives."

In the transportation asset management guide, AASHTO defines a business model, a decision support system, and an asset management approach, all linked to the five core questions presented in the EPA methodology. Figure 2 presents AASHTO's asset management model.

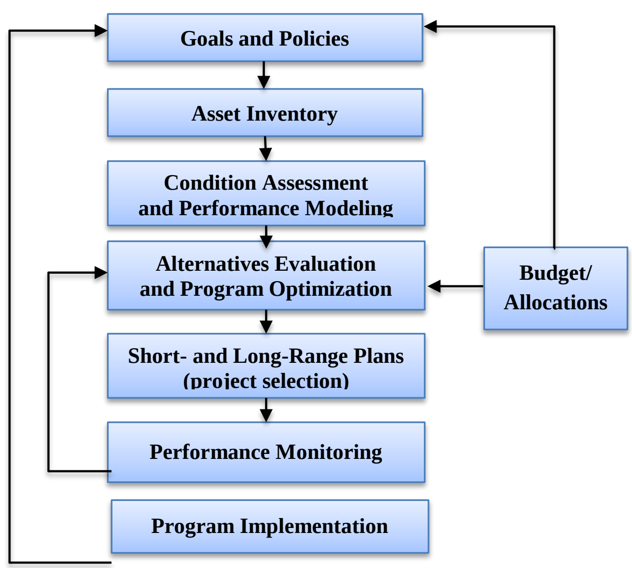

Figure 2 – AASHTO's transportation asset management model [7]

Virginia Department of Transportation Asset Management Methodology

The Virginia Department of Transportation (VDOT) adopted the AASHTO's transportation asset management model and further developed a needs-based budgeting process that systematically identifies maintenance needs based on asset inventory and condition data. The process guides the allocation of available resources across maintenance activities and districts, and helps develop the annual budget request. The needs-based budgeting process includes the following five steps:

1. **Inventory and condition data collection**
   - Annual collection of pavement condition data on 100 percent of interstate and primary and approximately 20 percent of secondary pavements.
   - Biennial collection of bridge condition data on all national bridge inventory structures.
   - Statewide random sampling for selected traffic and drainage assets every two years.
2. **Set goals and apply business rules**
   - Implementation of decision logic for what maintenance treatments should be applied based on asset characteristics and condition to restore serviceability and minimize life cycle costs.
   - Business rules also include deterioration / life cycle and cost models.
3. **Conduct needs analysis**
   - Estimate the current maintenance backlog (total needs) and the cost to maintain assets at their current condition level.
4. **Develop budget requests and resource allocation strategies**
   - Address the identified needs and move towards greater balance in the backlog of maintenance needs across districts over time.
5. **Track and evaluate accomplishments**
   - Provide accountability for expenditures.
   - Build better information over time on asset age, detailed inventory characteristics, and resource use.

EA Technology Asset Management Approach for the Electricity Industry

EA Technology LLC developed an asset management model for the electrical power distribution industry. The six steps in the approach are as follows:

1. Identify asset deficiencies or failures.
2. Find failure processes and identify deterioration that can lead to asset failure.

3. Identify and evaluate component measures. When failure data is available, it is possible to estimate the failure rate which is related to the condition of the item. If failure data is limited, a risk measure can be established through expert engineering judgment and laboratory testing.
4. Format an overall condition measure.
5. Model the degradation process of the condition. Different models have been used in practice to model the deterioration, including regression and Markov models.
6. Evaluate different asset management policies. Effects of asset management actions can be deterministic (i.e., always return the item to its best condition or improve an item's condition rating by a fixed amount), or stochastic (i.e. maintenance may not always be carried out to the same standard). The most suitable, efficient, and cost-effective asset management strategy will be chosen.

The focus of the following sections will be to address the first and sixth steps of the EPA model which refer to the creation of a systematic approach for asset registry and inventory, and the development of a framework for risk definition and classification.

3 Asset Hierarchy and Asset Registration

Developing a well-organized and comprehensive asset hierarchy is a significant step in building an effective asset management program since it helps define overall priorities. Creating an asset hierarchy process is a major step of a higher-level process called Asset Register Development Process. This section defines asset hierarchy and introduces two asset hierarchy models, presents an asset hierarchy development framework, and defines an asset register development process.

Asset Hierarchy

An asset hierarchy is a systematic framework and comprehensive listing of all assets in a logical, clear, holistic and nested order that facilitates locating asset records and the rolling up of data from lower levels to higher or vice versa [8]. It provides a suitable framework for the business to structure data in an information system and facilitates the classification of assets and its relevant information [9, 10]. It also allows companies to track all their assets, through implementing a diagram that projects the relationships between physical locations, functionality, operations, and asset types. These relationships facilitate the process of data collection, monitoring, grouping, as well as identifying the critical assets [11]. An effective asset hierarchy enables companies to build a well-organized data management structure that can be used in prioritizing maintenance and renewal activities [12-14].

At the strategic management level, an asset hierarchy provides the means to identify and plan for replacement or renewal of major systems, organize assets in classes and with similar use and risk, and enable long term financial planning. At the operation and maintenance level, an asset hierarchy provides a tool for process analysis, supporting better decision-making, improving efficiencies and effectiveness of assets, and maintenance and operations staff [15]. Beyond putting assets in different categories, an asset hierarchy is about demonstrating the relationships and the interaction between assets [16].

Asset Hierarchy Models

Different types of asset hierarchies are used in industry; however, the most common type is typically designed in the shape of a family tree structure, built on the parent-child relationships. Such structure enables the user to flow down to additional levels, until the desired level of specificity is reached. Asset hierarchies' structures such as family trees facilitate data collection and are specially useful in building asset registries and inventories. A typical parent-child asset hierarchy level includes "Facilities", "Parent asset", "Asset" and

“Child Asset”. Figure 3 shows a typical asset system hierarchy diagram based on the family tree structure.

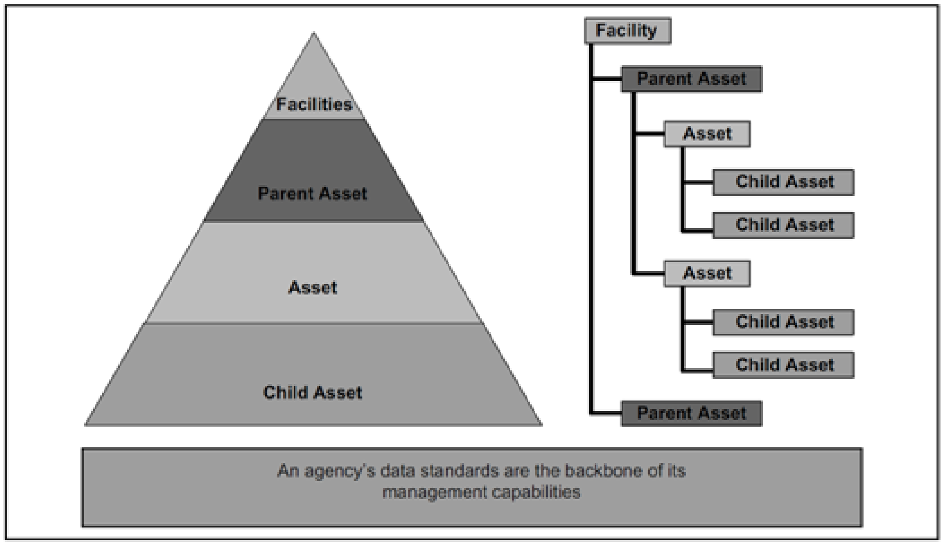

Figure 3 – Generic asset system hierarchy

What follows is a review of two asset hierarchy models. The first one was proposed by the Water Environment Research Foundation (WERF), the second is part of the ISO 14224 standard.

<u>Water Environment Research Foundation Asset Hierarchy Model</u>

The WERF report presents a generic three-level asset hierarchy.

- Level 1 includes major systems (i.e. water treatment, raw water transmission systems).
- Level 2 comprises asset systems and processes (i.e. facility and operating units).
- Level 3 includes maintainable assets.

The report also suggests creating further levels, if more details are required to show the relationships between components. An alternative method for such three-level asset hierarchy is the nine-level hierarchy introduced in ISO 14224.

<u>ISO 14224 Asset Hierarchy Model</u>

The ISO 14224 standard for petroleum, petrochemical and natural gas industries provides a set of guidelines for identifying different asset levels [8]. It suggests a general framework for development of asset hierarchies and classification of relevant data that needs to be collected. The framework is illustrated in Figure 4.

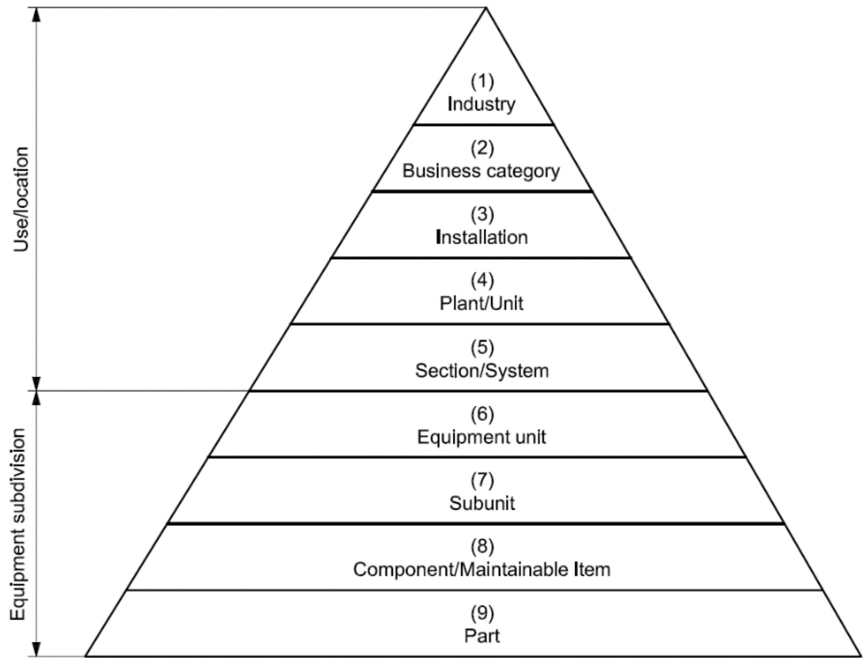

Figure 4 – ISO 14224 framework for asset hierarchy

This hierarchy performs efficiently when the company provides a clear definition of each level or decreases number of levels to match the company's available assets and equipment. Different organizations customize the ISO 14224 framework based on their own characteristics or functionalities. The hierarchy can be built based on spatial/geographical relationship between assets, business unit operations, and responsibilities, facility types or a combination of these characteristics. ISO 14224 provides a best practice for oil and petrochemical companies, any deviation from this framework is possible but needs to be specified.

In Figure 4, Levels 1 through 5 present a high-level categorization related to industry and plant applications regardless of equipment units. Equipment units are located in Level 6. ISO 14224 explains that this is because particular equipment may be used in multiple industries and for reliability purposes it is necessary to have further operating and technical details of equipment. In addition, Level 6 through 9 are related to inventory (equipment unit) with the subdivision in lower indenture levels corresponding to a parent-child relationship.

ISO 14224 directly focuses on Level 6 for the collection, recording and monitoring of reliability and maintenance data. It also provides a supplementary reliability and maintenance parameters in relation to each lower level of the taxonomy. Although the table was created for the petrochemical and oil industries, it can be a good example for other industries including the MTA.

Asset Hierarchy Development Framework

The Water Environment Research Foundation designed a three-step framework for planning a well-constructed asset hierarchy and register [5]. The process is part of an intuitive and user-friendly set of online guidelines, templates, and decision support tools called SIMPLE (Sustainable Infrastructure Management Program Learning Environment). SIMPLE facilitates the development of consistent total asset management and provides effective implementation guidelines for organizations to continuously measure their improvements in asset management. Figure 5 presents the three-step framework to implement the asset hierarchy. Further details can be found in [8].

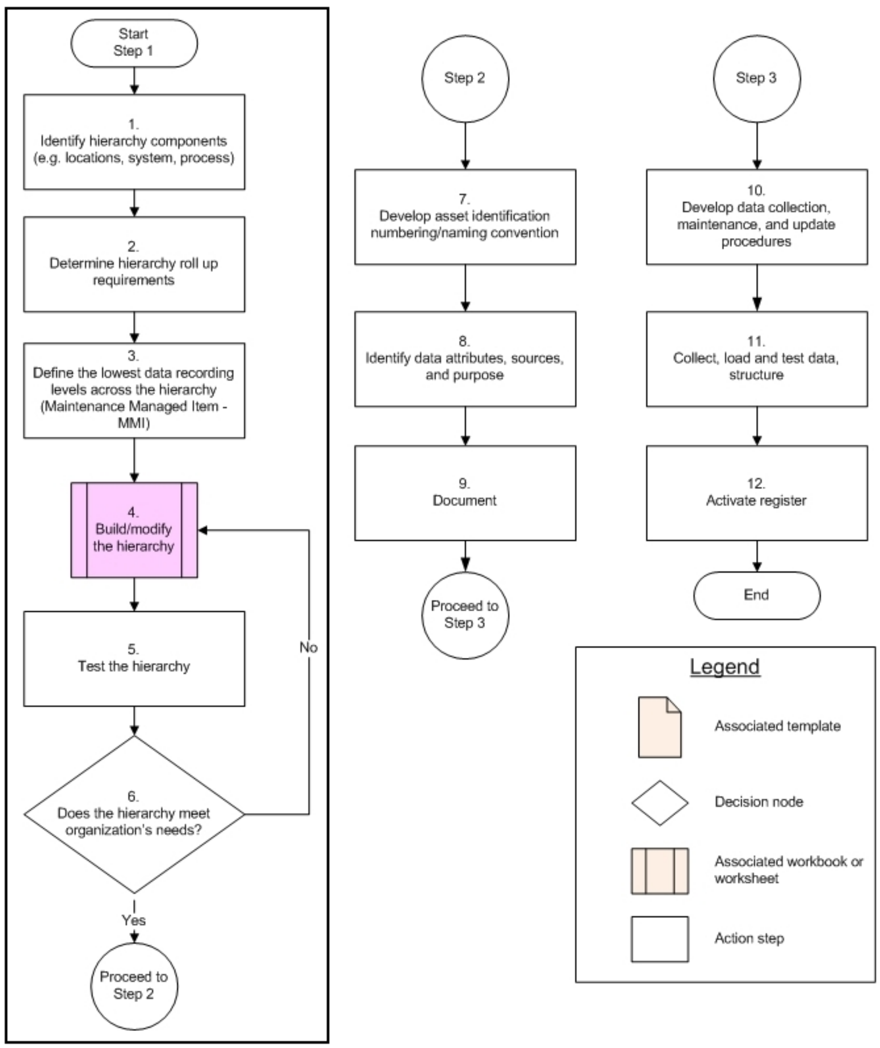

Figure 5 – SIMPLE's approach to Asset Hierarchy [8]

In addition, WERF suggests the following recommendations for establishing the asset hierarchy:

1. Start with a simple hierarchy model or an existing hierarchy from a vulnerability assessment, asset ledger, or GIS breakdown.
2. Compare to maps or as-built drawings of your assets.
3. Remove any assets that are not applicable.
4. If more than one level 1 asset exists, use separate steps for each asset.
5. Add any unique or system-specific assets. Modify the asset descriptions, if appropriate, to match specific conditions.
6. Develop a final asset inventory but design it in such a way that additions and subtractions can be made.

Figure 6 – Recommendations for development of an asset hierarchy and asset register [17]

The WERF report also provides a list of information that must be collected at each level of the asset hierarchy. The information includes specifications such as asset name, definition, components, performance indicator, and relationship diagram [18]. In addition, the report suggests two formats for asset hierarchy, both illustrated in Figure 7. For each format, the report provides a list of potential assets / components that should be added to the hierarchy.

- Level 1 asset
  - Level 2 asset
    - Level 3 asset
    - Level 3 asset
  - Level 2 asset
    - Level 3 asset
    - Level 3 asset

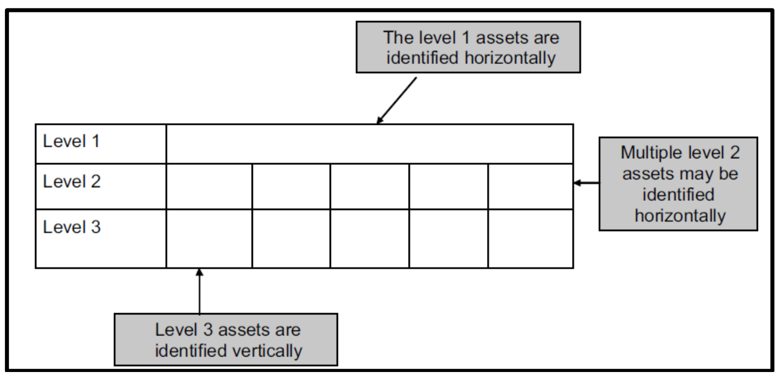

Figure 7 – Two formats for developing asset hierarchy [18]

Attributes for each asset should be collected in a way that supports management and operation functions. There are several categories of attributes data that could be collected regarding each asset. Identification, physical description, location, risk analysis, asset groups, performance etc. are different categories of attributes.

Asset Register Development Process

Asset registers are defined as "listings of information relating to various aspects of an asset portfolio, in a way that allows data to be cross-referenced and retrieved as required" [19]. The asset register development process consists of four specific steps as shown in Figure 8.

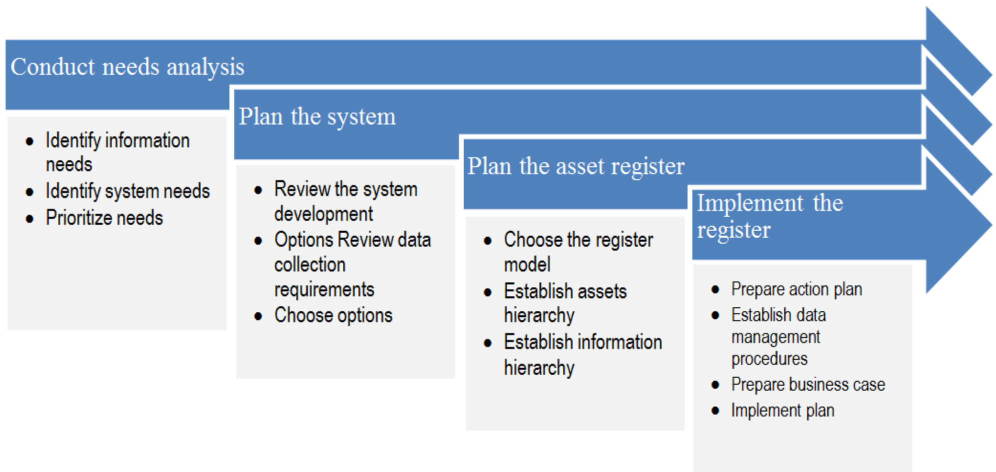

Figure 8 – Four-step asset register development process [19]

Conduct Needs Analysis

In the first step, the asset management team must provide a list of requirements for the asset register process. This list includes all required, planning information needs, management reporting needs, as well as system needs. Then, based on multiple criteria, the data needs are prioritized. Some criteria examples are: accessibility of data, flexibility, ease of updating, cost, security of data, connectivity, reliability of the system, relevance of the data and so on. The New South Wales Treasury's guideline [19] emphasizes that "the best practice approach might be to rank potential improvements by assessing them against these criteria on a scale of one to five." In addition, several "Multi-Attribute Decision Making (MADM)" techniques can be alternatively used[1].

Plan the System

In order to develop a well-established asset management system, organizations should create a plan for their asset register system. In this plan, they must define the software and

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[1]- Multi-Attribute Decision Making (MADM) techniques— a subset of MCDA approach—can be implemented to address the problems of ranking and selection. In particular, when ranking and prioritizing should be conducted with multiple decision makers such as process owners, managers and asset management analysts. For further information see [18, 19, 20, 21]

hardware structure and methods they plan to use. They also need to identify how to establish an asset management database system and reporting for different operational levels and management levels [19]. In this step it is also necessary to identify which technologies are the most appropriate regarding the organization’s functionalities, constraints, and objectives. To do so, it is necessary to evaluate different data collection systems including: Geographical Information System (GIS), Global Positioning System (GPS), data loggers, compact disk technologies, etc. Then the operational requirements of data collection are defined and the data sources are determined. As-constructed drawings, work orders, and reports including maintenance reports, condition audit and monitoring reports, call reports etc. are the main sources of data [5].

Plan the Asset Register

In this step organizations must determine a model hierarchy that can be matched with their management and operation structure [20]. The International Infrastructure Management Manual classifies assets by either their functionalities, types or both. The New South Wales Treasury introduces three types of models for classifying assets [19]. Figure 9 provides conceptual presentations regarding each model [21]. The Unified Composite Model is often proposed for small and focused organizations (e.g. libraries, hospitals) or for organizations with identical geographical divisions but centralized management structure (local authorities, education, polices). The Segment Autonomous model is appropriate for large organizations with separate business centers such as the state transit authorities. The Umbrella Integrated model can be employed for organizations with multiple responsibilities and common funding sources. Further details about characteristics of each model can be found in reference [22].

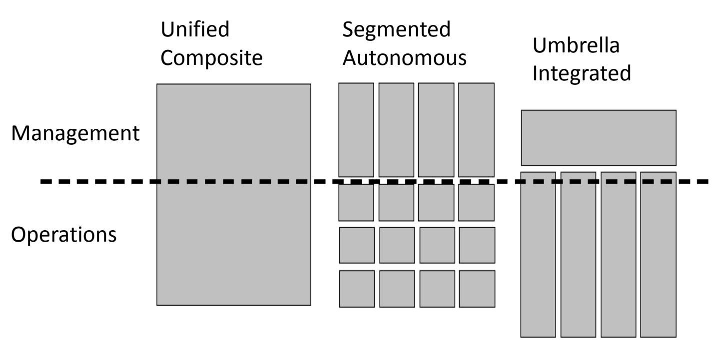

Figure 9 – Three different types of asset register models [19]

Implement the Register

The last step is to prepare for implementing the asset register. In this phase, an action plan should be provided in a measured, step by step approach with the most priority on collecting data with the greatest outcomes [19]. In the action plan, the significant milestones should be identified. Moreover, a data management procedure should be established and data collection schedules should be identified. Best practice principles for gathering efficient data, identifying assets, their attributes, and performance indicators, are presented in the WERF report previously discussed [19]. The final section of this step is to provide an Asset Register Business Case incorporating all the data, information and planning recommendation that have been identified in the development process. It includes a cost/benefit analysis that allows organizations to conduct a quantitative comparison between alternatives. Once a plan is selected and budgets are approved, all the steps planned should be implemented. Some data may be transferred from existing databases and some should be created manually. A business case template can be found in [19].

4 Risk Assessment and Criticality Analysis

Risk is a function of the probability of an incident and its likely consequences. Risks assessments are conducted to identify assets that are most likely to cause great impact to the business should an incident occur. Common types of risk include: health, safety, financial, performance, public image, and environmental risks. These types of risks are highly correlated to the criteria that affect criticality. Asset criticality is a structured methodology that identifies the assets whose failures have the highest potential impact on business goals [23]. It can be used to determine maintenance strategies, investment strategies, and growth plans, to help organizations prioritize expenditures on assets that are critical according to predefined business criteria. This section presents steps, criteria and methodologies for assessing risk and criticality.

Risk Assessment

Several approaches have been implemented by different organizations to calculate risk. Such approaches often include the same two key elements: likelihood of failure and consequence of failure, which can be estimated using either qualitative or quantitative methods.

Steps to Estimate Risk

The steps to estimate risk are as follows [24]:

1. Consider each asset in its operating context – what it does and where is it?
2. Develop an equipment failure description – i.e. how can it fail?
3. Estimate the consequences of each failure – i.e. what happens when it fails?
4. Determine likelihood of each failure – i.e. how often is it likely to happen?
5. Calculate the risk from the likelihood and consequences.
6. Sort the risk scores in decreasing order of importance.
7. Map the maximum risk score for the unit onto a selected scale (optional).

Note that when several types of risks are assessed, assets can have more than one risk ranking.

Risk Elements

Risk is most commonly calculated as a function of two elements: frequency or likelihood of failure (f_r) and business consequences (B_c).

$$Risk = F_r \times B_c$$

Alternatively, organizations may include additional elements into the equation (e.g. vulnerability, threat, impact, etc.) to provide a more accurate measure of risk depending on the organization's functionalities, types of failures or losses, business goals and policies. For instance, a generalized form of risk calculation is as follows:

$$Risk = F_r \times V_u \times I_m \times B_c$$

Where:

- F_r represents frequency of asset loss or service interruption due to failure, fault, planned or unplanned stoppages, rare events such as natural disasters, human induced events, etc.
- V_u denotes vulnerability, which indicates the degree of susceptibility a system has to any form of harm, as well as its overall level of protection. Vulnerability can also be defined as a combination of the attractiveness of a system or asset as a target and the level of deterrence and / or defense provided by the existing countermeasures [25].
- I_m indicates impact caused by asset loss or service interruption. It is a function of capacity, reliability or efficiency loss. For instance, capacity loss accounts for impact amount and duration. It allows comparing different impacts. For example: 50% capacity loss with duration measured in minutes, or 10% capacity loss with duration measured in days.
- B_c represents business consequences. This is measured in short-term and long-term scales. The impact and business consequences are not necessarily proportional. Depending on the type of impact, the short-term and long-term business consequences could range from negligible to very severe.

Quantitative Methods

In the quantitative methods used to assess risk, the risk elements are calculated by directly using quantitative measures usually gathered from historical data [26, 27]. For example, frequency can be calculated by using historical records of failures categorized by type and severity. Net present values of loss, total profit loss, total replacement and repair costs, number of defective products, etc. are examples of quantitative business consequences. The advantage of using quantitative measures is that these are tangible and make sense to managers. The quantitative measures are usually universal regardless of types of assets and functionality, and are often connected to business performance indicators. The main disadvantage of using quantitative methods is that the data required to calculate risk does not necessarily exist. Even if it exists, it may not be properly gathered and recorded. In addition, in some cases, the consequence of an event cannot be easily quantified using historical data.

Qualitative Methods

When using a quantitative approach to calculate risk is unsuitable, it is necessary to apply a qualitative method. In these methods, engineers, technical staffs, managers and other key stakeholders, define the elements needed to estimate risk (i.e. failure frequency, vulnerability, impact, business consequences), and develop tables to quantify these elements based on their expertise, the organization's background, asset criticality criteria, etc. The values assigned to these elements are then used to obtain the risk value.

An example of a qualitative method is Failure Mode and Effect Analysis (FMEA). It is a systematic approach to quantify frequency of failure, consequences and impact, also used to prioritize critical assets by ranking the risk associated to each potential failure [34, 29]. Tables 1 – 3 show examples of ranking of frequency, consequences, and probability of detection, the associated scores, and technical descriptions [33].

Table 1 – Frequency of occurrence [28]

Score	Description
1-2	**An unlikely probability of occurrence** during the operating time interval. Unlikely probability is defined as a single failure mode probability < 0.001 of the overall probability of failure during the operating time interval.
3-5	**A remote probability of occurrence** during the operating time interval (i.e. once every two months). Remote probability is defined as a single failure mode probability > 0.001 but < 0.01 of the overall probability of failure during the item operating time interval.
6-7	**An occasional probability of occurrence** during the operating time interval (i.e. once a month). Occasional probability is defined as a single failure mode probability > 0.01 but < 0.10 of the overall probability of failure during the operating time interval.
8-9	**A moderate probability of occurrence** during the operating time interval (i.e. once every two weeks). Moderate probability is defined as a single failure mode probability > 0.10 but < 0.20 of the overall probability of failure during the operating time interval.
10	**A high probability of occurrence** during the operating time interval (i.e. once a week). High probability is defined as a single failure mode probability > 0.20 of the overall probability of failure during the operating interval.

Table 2 – Consequences [33]

Score	Description
1-2	Failure is of such minor nature that asset will probably function with a minor problem.
3-5	Failure will result in slight deterioration of part or asset performance.
6-7	Failure will result in deterioration of part or asset performance.
8-9	Failure will result in high degree of customer dissatisfaction and cause non-functionality of asset.
10	Failure will cause non-system operation or non-compliance with government regulations.

Table 3 – Detection [33]

Score	Description
1-2	Very high probability: verification and/or controls will almost certainly detect the existence of a deficiency or failure.
3-5	High probability: verification and/or controls have a good chance of detecting the existence of a deficiency or failure.
6-7	Moderate probability: verification and/or controls are likely to detect the existence of a deficiency or failure.
8-9	Low probability: verification and/or controls not likely to detect the existence of a deficiency or defect.
10	Very low (or zero) probability: verification and/or controls will not or cannot detect the existence of a deficiency or defect.

Types of Risks

Risks are broadly classified in four types:

<u>Health and Safety (H&S) Risks</u>

Major asset failures could result in injuries needing first aid treatment, hospital treatment, restricted ability to work, loss of limb, and in the worst case scenario, fatalities. To assess H&S risks, companies investigate the possible H&S consequences of asset failure and classify them into different categories and increasing order of seriousness. For example, in the O&G industry, health and safety risks are classified into four categories, ranging from minor injuries at the lower end of the scale to fatalities at the higher end of the scale. In the UK, the Railway Safety and Standards Board (RSSB) collects safety records for the rail network and provides guidance on safety risks [29]. Inspection and maintenance standards put in place by the companies ensure that safety risks are minimized, if not eliminated.

Performance and Financial Risks

Asset failure and underperformance could lead to financial consequences. Fundamental to the rail sector is the ability of the infrastructure to provide the capability to run trains considering key performance factors such as specified line speeds and schedules. In the UK, contractual arrangements put in place impose penalties on infrastructure management companies for delays resulting from asset failures. In addition to the financial risks due to loss of function or performance, there is a direct cost related to maintenance and repairs. These involve costs of personnel, equipment, replacement assets or components, logistics, etc. However, in practice, the direct cost of maintenance often pales in comparison with the costs incurred due to loss of production – in the case of O&G industry – or penalties – in the case of rail in the UK. It is to be noted that in the UK rail sector, performance risks and maintenance costs are also part of the criticality criteria.

Public Impact Risks

These risks involve impact of asset failures to members of the general public, and second-order effects resulting from media coverage and damage to company reputation. In the O&G sector, this ranges from minor consequences such as public complaints with no ensuing media coverage, to large-scale evacuations and major road closures with ensuing extended national and international media coverage. In the transit sector, impact of asset failure to the public is measured by estimating Lost Customer Hours (LCH). LCH represents the average time a customer loses due to delays and disruptions. It is calculated for each segment of the track between two stations, for every type of disruption (e.g. temporary speed restrictions, line suspensions, line closures), and depending on whether the disruption is planned or unplanned. Planned disruptions, for instance, can be carefully managed by providing advance warning to customers and by deploying replacement bus services. Other criteria include cleanliness, ambience, etc.

Environmental Risks

This type of risk involves environmental damage caused by asset failures. This is of major concern in the O&G sector, with risks ranging from environmental damage limited to the site, to widespread damage requiring extended cleanup, government fines, resulting media coverage, and damage to reputation [30]. The environmental risks in the rail sector are considered to be minimal, and do not play a huge part in criticality assessment. However, as regulations tighten up due to global concerns of climate change, these are expected to play a more important role in the transportation sector.

Graphical Tools

Risk Matrix

A risk matrix is a two-dimensional table used to define various levels of risk of an asset. One dimension represents frequency or likelihood of failure, and the other dimension represents consequences. The matrix can be used as a visual tool for both qualitative and quantitative risk assessment. When quantitative measures are used, the axis can have continuous values. Figure 10 shows an example of a criticality matrix used by an O&G company. Tables 4 and 5 provide details regarding the rows and columns of the matrix.

CONSEQUENCE \ PROBABILITY	A	B	C	D	E
I	1	1	1	2	3
II	1	1	2	3	4
III	2	2	3	4	4
IV	3	4	4	4	4

Figure 10 – Example of risk matrix used in an O&G company

The lower Arabic numbers show the higher risk values. In this example A1, B1, C1, A2 and B2 represent the highest risk.

Table 4 – Probability of Failure

Probability Category	Corporate Risk Matrix Definition	Qualitative Interpretation Guidance	Quantitative Interpretation Guidance
A	Possibility of repeated incidents	**Very Likely** Similar event may occur at sites every 0-10 years. Has happened several times at the site or many times in the Company	0.1 to 1 Nominally 0.3
B	Possibility of isolated incidents	**Somewhat Likely** Similar event may occur at site every 10-40 years. Has happened once before at site or several times in the Company.	0.01 to 0.1 Nominally 0.03
C	Possibility of occurring sometime	**Unlikely** Similar event may occur every 10-40 years at one of 10 company sites. Has not happened before at site, or has happened a few times in the Company.	0.001 to 0.01 Nominally 0.003
D	Not likely to occur	**Very Unlikely** Similar event may occur once in 40-100 years at one of 10 Company sites. Have been isolated occurrences in Company or has happened several times in industry.	0.0001 to 0.001 Nominally 0.0003
E	Practically impossible	**Practically Impossible** Has happened once or not at all in the Company. Has happened a few times or not at all in industry.	< 0.0001

Table 5 – Level of consequences

Consequence Category	Health / Safety	Environmental	Public Impact	Financial
I	Fatality(ies); Serious Injury requiring Medical Treatment to members of Public	Potential Widespread, Long Term, Significant Adverse Effects; Major Emergency Response; Long Term Cleanup	Significant Public Disruption, Extended National or International Media Coverage; Large Community Impact; Large Scale Evacuation; Major Road Closure > 24 hours	Corporate > $10M
II	Serious or Lost Time Injury / Illness	Potential Localised, Medium Term, Significant Adverse Effects; Intermediate Emergency Response; Weeks/Months Cleanup	Small Public Disruption, One-Time National or Extended Local Media Coverage; Medium Community Impact; Small Scale Evacuation; Major Road Closure < 24 hours	Business $1M - $10M
III	Restricted Work or Medical Treatment	Potential Short Term, Minor, Adverse Effects. Local Emergency Response; Days/Weeks Cleanup	Public Complaints, One Time Local Media Coverage Small Community Impact; Secondary Road Closure < 24 hours	Site $100k - $1M
IV	First Aid / Minor Injury	Inconsequential or No Adverse Impacts Confined to Site or Close Proximity	Public Complaint, No Media Coverage Temporary Closure of Side Road; Minor Inconvenience	Other < $100k

Based on the information received by the team during interviews with an organization from the O&G sector, the most critical assets typically account for less than 1% of the total available assets. Based on a review of industry practices, no evidence was found on an approach that gives different weightings to each individual risk. On the contrary, each risk is treated equally, and the consequences are classified in a normalized scale, which allows different risks to be compared to each other as shown in Table 5. If an asset ranks as "very critical" in one risk type, and less critical in another risk category, the final risk score is "very critical".

<u>Risk Graph</u>

Another visual tool for quantitative and qualitative risk assessment is risk graphs. Figure 11 shows an example from the water industry used for qualitative purposes. Different zones are highlighted with different colors showing different levels of risk. The small red dots represent different assets, thus allowing the organization to compare multiple assets/infrastructures using a single table. It shows that any asset with a risk value greater than 50 (any multiplication of frequency and consequence that results in a risk value > 50) is located in Zone 1 (orange zone) which represents most intolerable risk. Zones can be defined by organizations based on their policies and strategies. More advanced plots and maps have also been used particularly when the geographical positions of the assets are important (e.g. train stations and oil/water pipe networks).

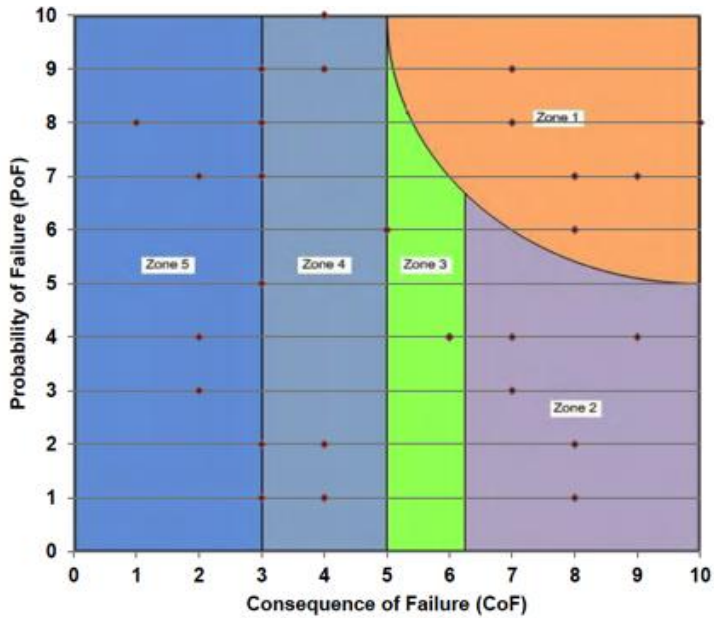

Figure 11 – A general risk graph [5]

Both, risk matrices and risk graphs help agencies understand risk and impact and allow them to prioritize security operations so that the most important infrastructure assets are protected and disastrous situations are prevented – or their consequences mitigated.

In order to inform decision-making and to facilitate the preparation of a business case, all the companies reviewed use a conversion factor for converting non-financial risks into monetary figures (e.g., average hourly salary is used to convert Lost Customer Hours to GBP). In the rail sector, the practice is similar. However, there is often a single risk that dominates due to the fact that sufficient risk control measures are put in place to mitigate other risks. For example, safety risks, on the other hand are considered negligible as inspection and maintenance standards specified either by regulatory bodies or by the companies take a risk adverse perspective to safety, and safety related incidents are avoided at all costs.

Criticality Analysis

The important steps required to determine criticality include: asset identification, criteria definition, and scoring.

Asset Identification

This step consists on developing a method to identify existing assets. To do this, the best alternative is to establish an asset hierarchy, assign assets into specific asset categories, and collect all the required information regarding each asset. This will enable ranking of assets within specific categories.

In the rail industry, an initial prioritization is performed to identify those assets that have historically attracted high expenditure. These high priority assets are decomposed down to the component level, and each component is assigned a criticality score.

Alternatively, another approach predominantly done for strategic planning consists on assessing route criticality by segmenting the rail network into manageable sections. For instance, in the United Kingdom the network is segmented into ten operational routes. These routes are further subdivided into strategic route sections that have broadly homogenous traffic levels and infrastructure type. A similar practice involves segmenting the routes into four quadrants based on: (1) the cost impact an incident would have in terms of safety, performance and maintenance, and (2) frequency of incidents [31].

Criteria Definition

The criteria that affect asset criticality vary from one organization to another. These will significantly depend on the types of assets as well as the organization's policies. Criteria normally used across different types of industries include [34-36]:

- Reliability – asset damage, malfunction, depreciation, degradation, life cycle, etc.
- Cost Factor – loss of income, repair costs, and other costs related to the assets.
- Efficiency – loss of service, loss of production, etc.
- Brand – loss of image
- Compliance – regulations and law enforcements, failure to meet statutory requirements.
- Safety – loss of life or injury
- Security – asset location
- Environmental Impact / Sustainability – effect of environment on asset deterioration.

Additional criteria can include [35, 36]:

- Damage to property
- Third party losses
- Loss of company image
- Functionality, maintainability, or reparability.
- Asset condition

Route Criticality can be assessed based on the costs per incident compared to the national average.

Scoring

A common practice is setting an arbitrary scale (i.e. 1 to 10) for scoring the assets against each decision criterion. Lower scores indicate lower criticality. The scoring guide and definition of asset state for each score should be developed by experts and technical staff. The total criticality score can be calculated either by using the average of all scores, or the weighted average provided that the relative importance of each criterion has been predetermined. Scores and final results should be collected in tables for later reference.

The organizations examined from the Oil and Gas (O&G) sector use a three-point scale criticality scoring. The scores indicate asset failure is Very Critical, Critical, or Not Critical in relation to the defined criterion. Similarly, in the rail industry, the scores used are High, Medium or Low.

Conclusions

This project focused on collecting best industry practices from different types of industries in the US and UK. The ten-step asset management process proposed by the US Environmental Protection Agency (EPA) provides a platform for developing initial asset management plans, and systematically improving asset management practices. As the asset management planning activities become embedded in the agency's planning processes, the amount of effort put into updating asset management plans should decrease since it would mostly entail updating the plans based on most recent data.

This report focused only on the first and sixth step of the ten-step process. The first step indicates the development of an asset registry that follows a hierarchical structure is essential to link asset performance to planning functions. The Water Environment Research Foundation (WERF) provides an asset hierarchy development model that can be generalized to transit organizations. The WERF model lays out the steps to define the asset hierarchy, identify data attributes, define data collection procedures, load asset information, and implement the asset register.

For the development of the asset hierarchy, the project team identified the ISO 14224 model developed for the oil and gas industry as the recommended hierarchy model for NYCT. The ISO 14224 standard has been used in many private and public organizations across different types of industries around the world. It presents a well-organized taxonomy to classify assets considering user, location and asset structure. It proposes a reliability and maintenance based asset hierarchy that aligns performance of asset parts at the bottom of the hierarchy with performance outputs at the top of the organization.

The sixth step in the ten-step EPA process focuses on determining business risks and criticality. There is a wide variety of criteria used to assess risk and criticality, however, the most common criteria includes: reliability, costs, efficiency, brand, compliance, safety, security, and environmental impact. There are two types of methods to assess risk. The quantitative methods are mostly based on estimation of risk using historical data as well as statistical tools. The qualitative methods rely on expert knowledge.

Glossary

AASHTO Transportation Asset Management Guide – analyzed the DOT business processes and strategic approach to managing transportation infrastructure assets.

Asset – Hardware, software, procedure etc. used to provide a valued function.

Asset Management as defined by PAS 55 – systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their lifecycles for the purposes of achieving its organizational strategic plan.

Asset Management Plan – document that identifies the short- and long-term service delivery requirements of the portfolio of assets belonging to an organization. It provides a framework for managing an asset, or group of assets, from within the asset portfolio.

Asset Management Policy – sets the framework for the management of airport infrastructure and assets. Most policies include

- Organizational context and importance of asset management,
- Overall vision and goals of the organization and supporting asset management vision and goals,
- Executive and key position roles and responsibilities, and
- Audit and review procedures.

Asset Management Framework – system of processes, procedures, practices, support systems, organizational roles and responsibilities, and policies used to enable sound management decisions for the optimal management of physical assets.

Asset Management Strategy – strategy for asset management covering the development and implementation of plans and programs for asset creation, operation, maintenance, rehabilitation/ replacement, disposal, and performance monitoring to ensure that the desired levels of service and other operational objectives are achieved at optimum cost.

Asset Performance – measurement of the achievement of predetermined outputs arising from the existence and operation of assets using a range of performance targets that measure the individual and collective contribution an asset makes toward service delivery and/or business outputs.

Asset Registry – a record of asset information considered worthy of separate identification including inventory, historical, financial, condition, construction, technical, and financial information about each.

Attributes – a data item related to an asset.

Business Risk Exposure – a metric to expresses risk. Business Risk Exposure is determined as the product of the probability of failure and the consequence of failure.

Critical Assets – assets for which the financial, business, or service-level consequences of failure are sufficiently severe to justify proactive inspection and rehabilitation. Critical assets have a lower threshold for action than non-critical assets.

Condition Assessment – technical assessment of an asset based on a physical inspection, for the purpose of determining its condition and remaining useful life relative to a defined standard.

Decision Support Tools – used by asset managers to determine the best alternative among a set of feasible alternatives. The alternatives may be potential solutions to a range of questions related to strategic planning, airport development, outsourcing, and asset renewal or replacement.

Effectiveness – Relates to how well outcomes meet objectives. It concerns the immediate characteristics of an entity's outputs, and the degree to which an asset contributes to achieving specified outcomes. Entities should ensure that an asset is suitable to the nature of their business and supports the delivery of budget funded entity outcomes.

Efficiency – Relates to the productivity of Commonwealth resources used to conduct an activity in order to achieve the maximum value for those resources.

Functionality – Functionality is 'fitness for purpose'. It describes how well a current asset matches the activities that it supports.

Infrastructure Management – the discipline of managing infrastructure assets that underpin an economy, such as roads, water supply, wastewater, storm water, power supply, flood management, recreational and other assets.

Inventories – Inventories are assets:
- Held for sale in the ordinary course of business;
- In the process of production for such sale; or
- In the form of materials or supplies to be consumed in the production process or in the rendering of services.

Lifecycle Costing – sum of all recurring and onetime costs over the full lifespan or a specified period of an asset under consideration.

Priority – Dynamic assessment of activity importance. Priority varies for each task to be carried out on equipment regardless of the criticality of that equipment.

Risk Management – Risk is part of the environment in which entities operate. Risk management involves the systematic identification, analysis, treatment and allocation of risks. The extent of risk management required will vary depending on the potential impact of the risks.

Useful Life – Useful life is the period over which an asset is expected to be available for use by an entity, or the number of production or similar units expected to be obtained from the asset by an entity. The useful life of an asset may be different to the period of its physical life.

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