Framework for a Web-based Intelligent Infrastructure Asset Management System

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Abstract. Pavement Management Systems (PMS) provided the framework for the development of infrastructure management systems. Under the leadership of the Federal Highway Administration (FHWA), infrastructure management has further evolved into asset management, adding two new dimensions to the traditional approach: integration and business-like objectives. The paper makes the case that systematic asset management is today's best approach for balancing growing demands, aging infrastructure, and constrained resources, and that asset management can greatly benefit from the application of novel artificial intelligence and information technologies. Some of the information management and analysis tools that have enabled the developments in infrastructure management are discussed. The incorporation of these technologies into the decision-making process of how to maintain our transportation infrastructure systems is expected to provide a more efficient method for their intelligent renewal, which is instrumental in accommodating for the increasing demands of the next century. The framework for developing and implementing Web-based intelligent infrastructure asset management systems is presented.

INTRODUCTION

Efficient and well-maintained infrastructure systems are essential for societal stability and for promoting economic growth and environmental sustainability. Queiroz and Gautam (1) identified a very strong association between economic development, measured as per capita gross national product (GNP), and road infrastructure. Furthermore, the World Bank's (2) research showed that the economic development of nations correlates to a high extent with the countries’ infrastructure systems. Sound public infrastructure plays a vital role in encouraging more productive and competitive national economies.
Infrastructure Deterioration

The U.S. is served by some of the best transportation infrastructure systems in the world. The value of the total infrastructure assets in the U.S. is estimated at $20 trillion dollars (3). The U.S. transportation system includes nearly 6.3 million kilometers of street, roads, and highways; more than 570,000 bridges, 230,000 kilometers of railroads, 41,000 kilometers of navigable channels, 2.4 million kilometers of oil and gas pipelines, 200 large ports; and more than 18,000 airports (4). However, many of the current systems are reaching the end of their service lives. They have deteriorated due to environmental action, use, and/or misuse. For example, in a recent survey conducted by the American Society of Civil Engineers (5), America’s roads only received a D+ grade and America’s bridges received a C grade. This deterioration represents an important problem because the deteriorated infrastructure systems cannot simply be replaced. Consequently, there has to be a paradigm shift from construction to maintenance and rehabilitation of the existing infrastructure systems. The emphasis should be on the "intelligent" maintenance and renewal of our infrastructure. Management decisions on what assets to maintain and when to maintain them should be based on infrastructure asset management systems. These integrated decision support systems help decision-makers find the optimum distribution of resources for cost-effectively maintaining the infrastructure systems in the best possible condition.

Infrastructure Management

Infrastructure management has existed for as long as we have had infrastructure. Public and private agencies have always tried to maintain their infrastructure assets in good and serviceable condition at a minimum cost. However, the focus on using automated systems to manage a systematic approach to infrastructure management started with the early pavement management systems. Pavement management systems provided the framework for the use of systems concepts to integrate the planning, design, maintenance, rehabilitation, and management of the pavement component of the transportation infrastructure. They provided the foundation for the development of bridge management systems first, and infrastructure management systems second. The similarities encountered in the bridge and pavement management processes suggested the feasibility of defining a common framework for infrastructure management systems (6). An infrastructure management system has been defined as the operational package that enables the systematic, coordinated planning and programming of investments or expenditures, design, construction, maintenance, rehabilitation and renovation, operation, and in-service evaluation of physical facilities (7). This operational package is composed of a series of "generic" tools, procedures, and methods to manage different types of infrastructure assets or facilities independently or as part of an integrated system.

Integrated Infrastructure Management Systems

Sinha and Fwa (8) first outlined the concept of a total highway management system for a state highway agency. Based on a comprehensive review of the state-of-the-art in highway infrastructure management systems, Markow identified a clear tendency towards integrated, flexible, and distributed systems (9). Zhang and Hudson (10) demonstrated that the concept of generic systems is practical for developing decision support systems for infrastructure management. They developed a GIS-based, multimedia, integrated infrastructure management system that can be used to manage a wide variety of infrastructure data. There are many
advantages to these integrated systems including better flow of information among subsystems, elimination of redundant data, reduction in system development and maintenance, and better and more consistent optimized maintenance and rehabilitation programs for the various infrastructure types. The use of generic models, which can be customized by the user to fit local conditions and experience, reduces the implementation efforts and allows for the exchange of experiences among infrastructure types. Integrated infrastructure management systems have been developed and implemented at the national (11), state (12), and municipal (13, 14, 15, 16) levels.

Asset Management

In the private sector, industry leaders develop tailored asset management systems that let them monitor and assess the status and condition of their assets (real estate, physical plants, inventories, and investments) individually and collectively. These systems give them the information and tools they need to retain their competitiveness. Similarly, public sector officials responsible for the nation's infrastructure have to maintain, replace, and preserve these assets. They have to make the best use of limited resources and have to ensure accountability to the public service. In addition, the need for more “business-like” practices has been accentuated due to the recent trend towards privatization of some of the government infrastructure development and maintenance activities.

Following the example from the private sector and under the leadership of the Federal Highway Administration (FHWA), infrastructure management has evolved into asset management (17). The proposed generic scheme for an asset management system is presented in Figure 1. Other national and international organizations are sponsoring focused efforts on infrastructure asset management. For example, the Organization for Economic Co-operation and Development is conducting a study to evaluate the state of asset management systems implementation, identify their benefits, and examine implementation challenges. Similarly, but at the national level, the American Public Works Association (APWA) has recently formed a task force to impress on its members the merits of asset management (18).

FIGURE 1 Generic Asset Management Framework (19).
Asset management combines engineering principles with sound business practice and economic theory. An asset management system is mission-driven, has explicit goals for asset performance, and is customer-focused, flexible, accessible, and user-friendly. Asset management adds two new dimensions to infrastructure management: integration and business-like objectives. Systematic infrastructure asset management is today’s best approach for balancing growing demands, aging infrastructure, and constrained resources.

TRANSPORTATION INFRASTRUCTURE MANAGEMENT TOOLS

The development of infrastructure asset management systems has been made possible due to the information technology advances of the past decades. Some of the information management and analysis tools that have enabled the developments in infrastructure management are discussed in the following paragraphs.

Information Technologies

Geographic Information Systems

All transportation management problems are, to different degrees, geographical because they involve the relations between objects and events located in different spatial positions. Since the data required always has a spatial component, the more rational way to store and relate this information is through a spatial consistent referencing system such as a Geographical Information System (GIS). Furthermore, GIS can play an important role in enhancing the analysis of several infrastructure-related issues. Therefore, a GIS platform appears to be a logical choice for the manipulation and analysis of transportation infrastructure information. The spatial component added by these systems can improve the quality of the decision-making process. Successful experience with linking transportation infrastructure management and GIS has been reported by Petzold and Freud (20), Shahin et al. (21), Osman and Hayashi (22), Cheetham and Beck (23), and Medina et al. (24), among others. The benefits from using a GIS platform include facilitating the preparation, analysis, display, integration, and management of geographical infrastructure data to support the decision-making process. Furthermore, spatial considerations can also vastly improve the quality of the decision-making process by allowing better coordination of maintenance and rehabilitation activities of different infrastructure assets.

World-Wide-Web

The distributed nature of the infrastructure asset also makes infrastructure management an excellent ground for the use of emerging Web-based information technologies. These technologies allow efficient inputting, accessing, and analyzing of information remotely from geographically distant locations. Prototype web-based infrastructure management systems have been developed for managing coastal infrastructure (25), military facilities (26), and university buildings (27). Rojas and Songer conceived a computer-aided facility inspection system that integrates several information technologies with pen-based computers in a Web-centric client/server application. This application uses dynamic 2D vector graphics to navigate the Web. It has integrated a database of CAD drawings, a C++ application, and several Web technologies such as CGI Scripts, SQL Statements, and Java Applets and Scripts. A pilot implementation of the system on six buildings of the Boulder campus of The University of Colorado indicated a 20% reduction in inspection cost (27). This suggests that the savings could be even more
significant in more extended infrastructure systems such as water-distribution networks or highway systems.

**Data Warehousing**

Data warehousing refers to the implementation of an intelligent data abstraction scheme of field processes and/or raw data for future analysis. Data warehousing is an intermediate and critical step in the modeling efforts of an integrated infrastructure management system. There are several types of database models that have been employed with success in large projects. These include standard Relational Database Managers (RDBMS) and Object-Oriented Databases (OODB). Object-oriented databases store the information as objects and can make reference to the objects through an immutable object identity. This facilitates the development of the generic models and process required for the development of generic infrastructure asset management systems. However, the recent migration of current database engines to modern programming language architectures makes this distinction nearly irrelevant. Current data warehousing engines can handle both relational and object-oriented databases, thus simplifying the database warehousing procedure.

Data warehousing has become very popular with government and private organizations as it allows them to perform sophisticated analyses of large amount of data. In particular, the information architecture needed for infrastructure management must be flexible, adaptable, and dynamic, and allow for collaborative input from diverse stakeholders. Although most existing databases still rely on RDBMS, internet-based, object-oriented distributed architectures are expected to support the enterprises and (infrastructure) organizations of the twenty-first century (28). The advantages of these applications are that they provide maximum flexibility, scalability, and support of evolutionary growth.

**Artificial Intelligence**

Artificial Intelligence is a discipline that attempts to represent and manipulate knowledge to automatically solve problems that before were only solved by humans. Artificial Intelligence techniques have proven to be useful tools in the infrastructure management process. In particular, artificial neural networks, expert systems, and fuzzy logic have been used for several of the functions conducted by infrastructure management systems. Other techniques, such as machine learning, genetic algorithms, and case-based reasoning, also have significant potential.

**Artificial Neural Networks**

Artificial neural networks are models structured upon the organization of a human brain that can learn if provided with a range of examples, deduce their own rules for solving problems, and produce valid answers from noisy data (29). Their architecture, as shown in Figure 2, is characterized by a large number of simple neuron-like processing units interconnected by a large number of connections. These artificial neurons are capable of simple computations: they receive input from their neighbors, modify their state of activation \(a_i\), compute an output \(o_i\), and send that output to their neighbors. The main characteristic of artificial neural networks is that they are capable of self-organizing and learning. They are not programmed in the classical sense, but rather they are "trained." The pattern of connectivity among the processing units and the strength of the connections encode the knowledge of a network.
Artificial neural networks are particularly appropriate in solving associative-type problems in which there are a large number of examples over a wide range of input variables. Neural networks have been used for asset condition assessment (30, 31, 32, 33), performance prediction (34, 35), project selection (36, 37), prioritization (38), and resource optimization (39). These experiences show the potential for the use of neural networks in infrastructure management. All of them used feedforward neural networks that received supervised training before implementation. Due to the dynamic nature of the infrastructure management process, an adaptive neural network, capable of updating its knowledge as it is used, is expected to perform significantly better.

**Expert Systems**

Expert systems are rule-based programs, usually confined to a specific field, that attempt to emulate the behavior of human “experts” (40). One of the unique characteristics of expert systems is their ability to explain their logic and reasoning to reach conclusions through an explanation subsystem. There have been several applications of expert systems in the infrastructure management field. Ritchie et al. (41), Lee and Gadiero (42), Hajek et al. (43), and Ross et al. (44) used knowledge-based expert systems for selecting and planning pavement rehabilitation strategies. Harper and Majidzadeh (45) presented an expert system that recommends feasible maintenance plans be used as the input for an optimization process. Clark and Mehta (46) used expert systems to develop an integrated multimedia-based building management system. However, there is no strong evidence confirming the advantages of expert systems against a traditional rule-based decision tree. A hybrid system that combines expert systems with other artificial intelligence techniques may perform better.
**Fuzzy Logic**

Fuzzy sets (47) allow the use of subjective information, such as expert opinions, rules of thumb, and other "non-quantifiable" but significant information, in the decision process. Infrastructure management decisions usually involve handling and processing subjective information. This process generally induces uncertainties. If these uncertainties are of an ambiguous rather than a random nature, the use of fuzzy set theory rather than probabilistic theory is more appropriate. Fuzzy systems efficiently handle fuzzy rules and explain the reasoning used to reach a solution. However, they do not incorporate formal learning algorithms to extract information from existing data. Fuzzy systems have been used for computing asset condition indices (48, 49, 50, 51), structuring the decision process in preserving civil infrastructure facilities (52), and network optimization (53).

**Soft computing and Hybrid Systems**

Each of the discussed techniques (expert systems, neural networks, and fuzzy logic) has its own strengths and weaknesses. In order to develop high-quality practical intelligent systems, it is necessary to integrate these and other technologies, such as machine learning and genetic algorithms, in a hybrid system that cleverly combines the best of all worlds. For example, a hybrid neuro-fuzzy system can be created or improved automatically by means of neural network methods, and can explain its reasoning in terms of fuzzy if-then rules (54). For that reason, techniques such as neuro-computing (neural networks), fuzzy logic, genetic computing, and probabilistic reasoning have been grouped under the umbrella of soft computing (55). Soft computing tolerates imprecision, uncertainty, and partial truth to achieve tractability, robustness, low solution cost, and better rapport with reality.

Soft computing techniques are rapidly gaining ground within the infrastructure management field because infrastructure management decisions involve handling and processing subjective and sometimes ambiguous information. Hybrid systems have been used for automatic analysis of digital images of pavement (56) and sewer pipelines (57), maintenance treatment selection (58), and interpretation of the results of nondestructive techniques to evaluate infrastructure condition (59).

**FRAMEWORK**

Although there have been significant advances in the infrastructure management field in the past few years, additional improvement is needed. At the Second International Conference on Managing Pavements, Hudson and Haas (60) identified the need for flexible, high-risk, medium- and long-term strategic research to produce the significant advances necessary to face the infrastructure management challenges of the twenty-first century. Although significant progress has been made, there is still a long way to go. Areas such as automatic condition assessment, performance prediction, life-cycle analysis, and network-level resource optimization can definitively benefit from the use of state-of-the-art artificial intelligence and information technologies.

The incorporation of novel technologies into the infrastructure asset management process can be instrumental for the intelligent renewal of our infrastructure to accommodate the increasing demands of the next century. Recent advances in areas such as information decision systems, artificial intelligence, web-centric technologies, remote sensing, and simulation models will facilitate the development of the next generation of more “intelligent” infrastructure asset.
management systems. In particular, the use of artificial intelligence computational algorithms will allow the development of intelligent systems capable of acquiring knowledge and improving their performance as they are used. Furthermore, web-savvy technologies offer great opportunities to decentralize the data input and processing processes. The widespread use of these technologies will definitively impact the efficiency and reliability of the infrastructure management decision-making process.

The general framework for an intelligent infrastructure asset management system is presented in Figure 3. This framework builds upon one proposed by the FHWA that is currently being revised as part of a National Cooperative Highway Research Program (NCHRP) research effort. The foundation of the system is an integrated, object-oriented data warehouse, which handles both inventory information and condition measurements for any type of infrastructure. It also contains usage information as well as a user-defined library of maintenance strategies. Since all infrastructure systems are geographically distributed, the users will be able to input, access, modify, and analyze information using web-centric GIS technology.

The analysis component consists of a series of modular applications to predict asset performance, identify appropriate maintenance strategies for each asset, and determine network needs by selecting the most promising strategy for each individual asset using unconstrained life cycle cost analysis. The system can also optimize the resource allocation to maximize the benefits of the overall system under a constrained scenario, in which the user can provide budget caps and minimum performance requirements. One important feature of the system, which is discussed in detail in the following section, is its ability to acquire knowledge by making use of the hybrid soft computing agents.

FIGURE 3 Intelligent Infrastructure Asset Management System Framework.

The TRB Committee AFD10 on Pavement Management Systems is providing the information contained herein for use by individual practitioners in state and local transportation agencies, researchers in academic institutions, and other members of the transportation research community. The information in this paper was taken directly from the submission of the author(s).
The infrastructure management cycle continues with the detailed design of the projects included in the work program and the execution of the specified work. These two activities are usually conducted exogenously to the system by different sections of the agency. Changes in the infrastructure assets as a result of the work conducted, as well as normal deterioration, are periodically monitored and the information collected is used to update the databases. Inventory information is updated based on construction reports.

SOFTWARE STRUCTURE

The general framework presented in Figure 3 can be implemented in a user-friendly, object-oriented, open-architecture, infrastructure asset management systems software package (Figure 4). This package can be organized in modules (i.e., Installation, Database Management, and Analysis) for easier modification and integration. Each module should be composed of several stand-alone tools. State-of-the-art GUI's facilitate the day-to-day operation of the system, reduce the time required to learn its operation, and increase the chance for a successful implementation.

Installation tools

During Installation, the system allows customization of the package to handle one infrastructure component, or several components in an integrated decision support system. The installation module is needed because of the generic nature of the models, but it is also a very important training tool. During the installation, the software guides the user through the steps necessary for defining the structure and scope of the management system to "tailor" the system to the specific agency needs. The user must define the elements defined in the bottom-left block in Figure 4.
**Data Warehouse**

The infrastructure data warehouse, which stores inventory information, condition measurements, and user-defined library of maintenance strategies, must ensure data integrity, accessibility and compatibility, and facilitate periodic updating of information. The data warehouse can be efficiently developed with off-the-shelf or model specific Spatial Database Engines (SDE). An off-the-shelf GIS package with data warehousing and mining capabilities is probably the most effective alternative.

**Information Management**

The information management module records, modifies, organizes, updates, and reports the inventory and condition information stored in the data warehouse using both traditional and Web-base applications. The package must handle spatial, attribute, and multimedia data. The basic management units will be generic objects, depicted in Figure 5, which will have a few basic required attributes as well as a set of basic virtual functions to provide the required functionality. Appropriate data structure architectures can be inherited from these basic objects to archive information for different types of transportation infrastructure assets. The database system envisioned consists of data abstractions representing infrastructure entities of interest (e.g., pavement distress, rutting, etc.) and data abstractions representing relationships among these real-world entities.

**Analysis Tools**

The analysis module provides tools for resource allocation and asset management. The unique characteristic of the envisioned system is that it provides intelligent alternatives to the traditional analysis tools. Soft computing-based tools can be used to provide intelligent alternatives for knowledge-demanding tasks, such as condition assessment, performance prediction, and project selection. Although soft computing tools have been used in these areas, the applications developed so far have been limited by the fact that they have only used the knowledge available at the time of development of the system. Once implemented, the knowledge remains unchanged. This is a serious problem in infrastructure management systems because, unless the agency has been keeping records of the performance of its assets and maintenance policies, the
amount of information available when the system is developed and implemented is usually limited. Infrastructure management is a dynamic process where feedback is a major component. The envisioned intelligent tools will continue to learn automatically as part of the feedback process. This is very important because data collection efforts are very time- and resource-intensive, and the assets are in service for a long period of time.

The dynamic learning capability may be achieved, for example, by using an adaptive neuro-fuzzy system. A hybrid neuro-fuzzy system can be created or improved automatically by means of neural network methods, and can explain its reasoning in terms of fuzzy if-then rules. It can be interpreted as a system of linguistic rules, and can learn from the successes and failures of the criteria used to select projects. This approach allows for the combination of expert knowledge and knowledge acquired from examples using neural network algorithms. The artificial neural networks will bring to the table excellent pattern recognition capabilities. Fuzzy systems will contribute their capacity to efficiently handle fuzzy rules and explain their conclusions. The evolutionary self-learning capabilities can be implemented by developing a retraining algorithm. Machine learning algorithms may help with the interpretation of the feedback information and adjustment of the system with time.

IMPLEMENTATION

The initial training and testing of the intelligent tools require a large amount of information related to infrastructure performance, maintenance and rehabilitation strategies, and criteria applied for their selection. Therefore, the intelligent tools should be provided as alternatives to the traditional analysis tools in the core software package. It is expected that when the system is implemented, the user will probably feel more comfortable using more traditional, proven analysis tools. In addition, the intelligent tools may not be fully calibrated to the local conditions at that time. However, as the system is used, the intelligent alternatives will improve their performance and the user will become more acquainted with the technologies. At this point in time, the user will start to test the new technologies and then adopt them if they prove to be more effective than the traditional tools for a particular application.

One of the more important issues in the development of new technology is its acceptance among practitioners. The best technology will not produce any benefits unless it is effectively applied. Education and training are essential elements in the renewal of our transportation infrastructure. Therefore, the implementation efforts should include a significant technology transfer and training component. This component is necessary to make civil engineers fully aware of the importance and significance of efficiently managing our transportation infrastructure systems. They will bring infrastructure management into the next century.

SUMMARY AND CONCLUSIONS

This paper presented a “generic” framework for developing and implementing web-based intelligent infrastructure asset management systems. The envisioned “intelligent” tools are expected to allow decision-makers to make better use of the resources available for maintaining our civil infrastructure systems. The use of the Internet as the communication mechanism may enhance and reduce the costs of the data collection and processing operations. Furthermore, it is important to define a common framework for infrastructure asset management. Efforts are currently undergoing in the U.S. and Europe to achieve this. A suitable framework for integrating tools and knowledge modules will provide a common platform for the testing and...
evaluation of other infrastructure management methods and tools. This may promote the networking between transportation industry, academia, and government. It may also represent a step toward the establishment of standards within the field. If the intelligent systems help manage infrastructure assets more efficiently, the result would be the provision of a more reliable infrastructure at a lower cost. The improved infrastructure systems will serve the public efficiently, enhance quality of life, and promote sustainable development.

REFERENCES


