iCOMPASS: An Integrated Approach in Performance-based Management of Infrastructures

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ABSTRACT: The Burlington County Bridge Commission (BCBC) has been investing in implementing technology into their operation and management by adding technology as a value added to tradition and culture. Pennoni Associates, the Engineering Program Manager of BCBC, has been helping BCBC with the design of an Integrated Centralized Operation, Management, Performance, and Security System (iCOMPASS). This system encompasses different modules such as Maintenance, Capital Planning, Inspection, Performance Monitoring, Security, and Digital Archive. Each of these components has a role in adding value and improving the safety of the BCBC assets and productivity of the agency in general. This paper briefly describes the design of the system architecture, role of each module, interconnectivity of different modules, and the integration and implementation process of iCOMPASS.

1 INTRODUCTION

Advancement in technology has revolutionized the management of infrastructure, and has helped infrastructure owners increase the safety of their assets and at the same time improve their institutional productivity and reliability. The owners have been also able to reduce the risks associated with their operations through eliminating or reducing the uncertainties, making more educated decisions, and prioritizing their budget on the most critical assets. Consulting firms have been instrumental in helping asset owners reaching these goals.

Multiple publications can be found in literature regarding the application of technology in management of infrastructure (Liu and Itoh, 2001; Deshan and Qiao, 2009). Some agencies have introduced approaches for multi optimization decision models for bridge management (Lounis, 2005; Patidar, 2007). In addition, some integrated approaches for prioritization of bridge maintenance have been proposed (Valenzuela et al., 2010).

Pennoni Associates Inc. has been the Engineering Program Manager of the Burlington County Bridge Commission (BCBC) since 2004 and has been instrumental to the Commission in keeping their bridges safe and functional. The BCBC is a public agency responsible for the operation and maintenance of several bridges in Burlington County, New Jersey across the Delaware River. It now manages eight bridges, including major movable bridges such as the Tacony-Palmyra Bridge (double leaf bascule bridge), the Burlington-Bristol Bridge (vertical lift bridge), and the Riverside-Delanco Bridge (swing bridge). The mission of the Burlington County Bridge Commission is to provide Burlington County’s residents, commuters, and visitors with safe, accessible, and affordable bridges, roads, and facilities.

Through the past couple of years, BCBC has invested in an integrated and centralized management system that brings technology, expert skills, and tradition into one system that can improve the safety and productivity of their assets and the agency in general.

This proposed system has six different components providing information to the overall system. Chief among the enablers of integrated infrastructure management is the development of a centralized interoperable data warehouse to enable more comprehensive and efficient data and information retrieval, interpretation and usage of the data and documents. Such a system that integrates plans, reports, photos, analytical models, as well as images and data from health monitoring systems in a relational database is now feasible. This warehouse would offer access to historic documents and information, help assist bridge inspections and reporting, synchronize inspections with maintenance, repair and retrofit information, scenario analysis and visualization capabilities representing significant near-term benefits for the stakeholders (bridge owners, bridge managers, maintenance managers and staff, financial officers, security managers and officers, resident engineers, program and project managers, etc.) as well
as lay the foundation for a comprehensive, state-of-the-art infrastructure management system in the future.

Over the last few years the Burlington County Bridge Commission (BCBC) has taken on a leadership role in the application of smart technology, especially for structural and operational health management. While this program has paid (and continues to pay) dividends, the development of a centralized management system would enhance its effectiveness and would be a highly synergistic initiative. For example, a comprehensive data warehouse would provide the Commission with the security to archive critical data and information against loss, ability to more effectively interpret and use data (including both legacy and technology-acquired data), capture and maintain institutional knowledge, enhance bridge inspection and maintenance reliability and efficiency, and provide data redundancy. The legacy information may include construction drawings, historic photos, repair documents, contracts, invoices, inspection reports, etc. In addition, by moving forward with this initiative, the Commission would further solidify themselves as a forward-looking agency and would be at the cutting edge of the modern asset management; a paradigm that is the center-piece of the Federal Highway Administration’s (FHWA) five-year strategic plan.

To this end, Pennoni Associates Inc., through its Intelligent Infrastructure Systems (IIS) Division has designed an Integrated Centralized Operational, Management, Performance, and Security System (iCOMPASS) for management of the BCBC assets. This paper describes this system and its components.

2 VISION OF iCOMPASS

Figure 1 shows a simplified illustration of the essence of iCOMPASS. Different knowledge sources (e.g., expert knowledge on the operation and maintenance of infrastructure), information sources (e.g., bridge information model) and data sources (e.g., raw sensor data, images and videos) need to be integrated to support inspection, maintenance, operation, financial decisions, etc. For instance, a user query that requires spatial groupings of repair items to minimize cost may need expert knowledge regarding bridge characteristics, 3D bridge information models containing connectivity information between bridge components, and inspection and sensor data showing the existing conditions of the structural members. At present, supporting such a user query requires significant human technical expertise regardless of the substantial progress that has been made in the area of data collection technologies (e.g., sensors), data processing and visualization techniques.

3 SIX GENERIC STEPS TO PERFORMANCE-BASED ASSET AND RISK MANAGEMENT

3.1 Conceptualize and Model the System

Most infrastructure systems have evolved piecwise over many decades and often centuries, of intersecting and interconnected human, natural and engineered sub-systems. There is seldom a complete systems-diagram indicating all of the sub-systems and the relationship of elements within these multi-domain systems. Human elements may include history, culture and values, economics, politics, public policy, communities, industries, organizations and individuals. Natural elements often include trees, water (aquifer, ground water, river, lake, ocean, etc.), air, soil, environment, climate and wildlife. Engineered elements are typically either manufactured or constructed. The associated human, natural and engineered systems of infrastructures and their intersections and interdependencies are often not completely identified. The first step to asset management is to identify and map the multi-domain system. This is done by a careful inventory of the organizational and engineered assets, revenue and financing mechanisms and interviews with critical individuals. Multi-domain systems are often visualized by using GIS-based tools with a time dimension.
Multi-domain system identification would parallel system-identification by the construction of a systems diagram, and leveraging and integrating various analytical and numerical modeling approaches and tools. For example, organizations may be represented through their organizational structure, decision and communication models. Engineered elements and nature may be modeled based on statistical, probability or physics based approaches. To identify each element and sub-system, an investigation and documentation of history, review of all legacy data and information, and collection of additional data and interviews would be required. The infrastructure system would be structured into asset groups that are likewise human, natural and engineered element groups with similar functions and properties within the system.

3.2 Formulate System Level Performance Criteria

This step requires formulation of criteria for defining infrastructure system performance. It is highly desirable to include the critical stakeholders (that would be identified in Step 1) in this process and to establish measures and their desirable upper-and-lower bounds to designate what constitutes acceptable and not acceptable performance in any of the following categories and sub-categories:

- **Utility and Functionality**
  - Societal and environmental impacts
  - Operational efficiency, safety, impacts on traffic flow, adaptability to change in demands
  - Network/corridor level economic impacts, route redundancy
  - Intersections/interconnections: military, multi-modal, intersections with other infrastructures such as carrying communication, power, water, sewer lines
  - Bascule operations – reliability and risks

- **Safety and Stability of Failure**
  - Performance during hazards, special events with very long return periods
  - Hydraulics, soil, foundation and substructure’s impacts on long-term safety
  - Structural redundancy – multiple load paths for intrinsic and live loads, fatigue redundancy
  - Failure modes – global, member, stability, local capacity/demand, stability of failure

- **Durability and Serviceability**
  - Condition and aging of coatings, membranes, materials, members and connections affecting lifecycle preservation strategies
  - Flexibility, vibrations, cracks, chloride intrusion, rebar cover, coatings, membranes, etc
  - Any structural details requiring NDE inspection (pin-hanger, fatigue-sensitive welds, etc)
  - Bearings, joints, approach slab, runoff/drainage

- Ease and reliability of inspection and maintenance

- **Cost**
  - Finance, revenue and expenditure mechanisms for inspections, maintenance, rehab and retrofit needs over anticipated lifecycle
  - Decision processes impacting in-house and external contract costs of a project

- **Organizational Performance**
  - Dedication to quality and external review (TQM, 6SIGMA, etc)
  - Politics (local/state/federal) and other mechanisms impacting land-use, demand control, sustainability and economic development - organization’s response to politics
  - Organizational vision: policies-strategies-tactics, collective vs. top-down, transparency
  - Organizational structure, decision and information flow (system vs. silos; performance vs. process; concentrated vs. distributed decision-making, empowering personnel as stakeholders)
  - Revenue, finance and expense: decision mechanisms, accountability, transparency
  - Accession planning, recruiting, institutional education and training, incentivizing growth

3.3 Formulate Condition and Performance Metrics for Asset Groups

In the case of a regional highway transportation infrastructure, asset groups would include: (a) users and traffic, (b) safety and information devices; (c) approach roadways, pavements, (d) bridges, and (d) organizational assets including management, security and enforcement personnel, operators, inspectors, maintenance personnel, toll collectors, etc.

The goal of Step 3 is describing the condition and performance of the elements in each asset group in terms of measures that correctly relate to the utility, serviceability, safety and lifecycle cost of each asset group and of the integrated system as a whole. It is critical that the condition and performance measures and associated metrics for each asset group should not only reflect expected performances of particular asset groups but also how each of the asset groups impact system performance. After all, system performance is based on the performance of the entire set of asset groups successfully working together.

The current practice in highway infrastructure asset management is commonly based on managing pavements, bridges and sometimes traffic and safety assets individually and separately. For example the traffic and safety asset group may include signs, lights, cameras and safety devices such as crash barriers, but the safe and efficient flow of traffic is often neglected although this is a most critical component. Bridge and pavement asset groups are commonly described in terms of measures that are disconnected
from each other, for example, bridges are described in terms of their subjective condition and sufficiency rating while pavements are described in terms of ride quality and skid resistance measures. It follows that the condition measures and performance metrics of asset groups should recognize and account for the interactions and interdependencies between asset groups. For example, an effort to correlate bridge and pavement performance measures in order to explore how they may be managed from a common platform is a critical need. However, formulating common performance measures accounting for the impacts of different asset groups to affect system performance is often hindered by fragmentation between civil engineering sub-disciplines. It is ironic that multi-disciplinary integration remains a most formidable challenge standing in front of formulating and adopting meaningful asset management practices.

3.4 Collection of Data, Information, and Heuristics for Asset Groups

Once the measurable indicators that will describe the condition and performance of each asset group are established, data would be collected to establish the current conditions and performance of each asset group. Designing meta-data so that data will fulfill the objectives of asset management is a critical step; this should be done by technology providers in partnership with the organization. Such data would include all documentation, visual assessment, experimental measurements and especially images, and would be archived and organized in a distributed and smart data-information warehouse. One of the principal objectives of this project is to design the metadata (by defining standards describing types of data, how will it be collected and checked for quality, how will it be processed, integrated, visualized, interpreted and archived) for the assets owned by BCBC. In terms of highway infrastructure there have been a number of experimental techniques used to measure mechanical properties and operational performance of pavements, bridges and traffic. These are simply not yet adopted by many state DOT’s and other infrastructure owners. Additional technologies are being developed at a fast pace. Given how IT has changed the productivity of the corporate world, it should not be impossible to improve productivity and performance by leveraging IT in state and local government agencies. The critical issue in this step is overcoming the communication barriers between engineers of various bureaus and services with backgrounds from different sub-disciplines (bridge, pavement, geotechnical, hydraulic, traffic, materials, design, maintenance, etc), and agree on the performance measures and asset condition data that will objectively relate to asset group and system performance. The more sensitive an indicator that directly relates to condition and performance is utilized, the more definitive and objective a measure of condition and performance may be established. The key is to formulate such indicators given the specifics of the system and asset groups.

3.5 Optimizing System Condition and Performance

Once Steps 1-4 are accomplished, the remaining challenge is to understand the sensitivity of system performance to various limit-state performances of different asset groups by observation, image and data collection, and sometimes by making minor perturbations to the system (e.g. varying lane configurations, rigorously and conspicuously enforcing size and weight restrictions, etc). These efforts may be more effective if the models constructed in relation to Step 4 can be leveraged for scenario analyses.

Once the most critical asset group attributes that impact system performance under different demand scenarios are established, the goal would be to optimize system performance given the asset conditions, available financing and revenue resources and repair, retrofit and other methods that may be leveraged for eliminating current or probable future performance deficiency of assets that have the greatest impact on system performance. The most common approach in seeking optimal solutions would be through minimizing lifecycle cost together with constraints related to sustainability and other constraints associated with politics, finance, organizational resources, etc that have to be established during Steps 1-4.

Another consideration relates to the intersections and interdependencies between different infrastructures that virtually or physically intersect in a geographic region. Especially valid for dense urban areas, the challenges that are caused by the failure of one infrastructure on the others are significant and cannot be ignored in asset management.

3.6 Closing the Loop

The final step in asset management is to “close the loop” by monitoring condition and performance along time using objective measures and metrics as described above and continuously improving each of the products discussed above in relation to conceptualizing and modeling the system, system and asset group performance and condition measures and metrics, meta-data design, data collection and enhancing and optimizing the system performance. This step is where technology may be utilized to its full potential – imaging and sensing systems for health and performance monitoring, leveraging IT and expert input for effective inspections, leveraging a smart data-information system for integrating and following up with inspection and monitoring results, and generating various expenditure options based on system conditions and performance enhancement by leveraging optimization based on lifecycle cost (applied systems analysis) are all useful technology applications if integrated and applied prudently. Technology
promises to greatly improve infrastructure management - however reaping the benefits and positive impacts of technology requires us to modify and change the societal and organizational cultures to understand and embrace technology with a full understanding of the paradigms such as performance-based engineering, health monitoring and management and asset management that help us to optimally leverage technology.

4 ARCHITECTURE OF iCOMPASS

4.1 System Design

The design of iCOMPASS has been based on the standard V Diagram approach, commonly seen in systems engineering, in which feasibility studies are performed and Concept of Operations (ConOps) is developed and approved by the stakeholders. A concept of operations is a document describing the characteristics of a proposed system from the viewpoint of an individual who will use that system. It is used to communicate the quantitative and qualitative system characteristics to all stakeholders. Then the high level requirements are determined based on which high level design is done by the system engineer consultant and approved by the stakeholders. Detailed design of the system will be done next by a programming consultant. After detailed design of the system is done, required hardware will be procured and installed in the field (site) and the system will be deployed. The task of integrating the various subsystems and corresponding communication protocols follows the implementation phase. During this phase all the units, devices, subsystems and the entire system is verified and the system will be fully implemented. Figure 2 illustrated this procedure, known as V Diagram.

4.2 Modules of iCOMPASS

During the feasibility studies and concept explorations for iCOMPASS, five separate modules were determined that serve the stakeholders to meet their organizational needs. These modules are: Capital Planning and Management (CPM), Maintenance Management (MM), Inspection Information Management (IIM), Performance and Health Monitoring System (PHMS), and Physical Security Information Management (PSIM). These modules are each connected to a centralized Digital Archive (DA) server, which controls all communications between various modules. Figure 3 shows these components and their connections. The following sections briefly describe each of these modules and their functionalities.

4.2.1 Inspection Information Management (IIM)

The Inspection Information Management (IIM) module of iCOMPASS will manage the information collected during bridge inspection activities. Currently the inspectors are still using the traditional inspection tools and forms in the field which limits their capability to access the information related to each structural member or connection, as well as other necessary information such as the past inspection reports and photos, drawings, past maintenance/repair tasks, etc. With advancements of technology, especially the smart tablets and applications, it is envisioned that inspectors can get live access to all of the information from the field and take advantage of this access to improve and facilitate the inspection tasks. With appropriate implementation of this technology, the inspection tasks can be more efficient and can be completed with higher quality.

The IIM application is being developed to have multiple levels of access for different users. These may include the commissioners, bridge managers, maintenance managers, inspectors, resident engineers, security personnel, etc. In the proposed operations for the IIM system it is assumed that the other modules of iCOMPASS will be involved in providing information for the users of the IIM system. The IIM system is going to be an integral part of the MM system by generating maintenance needs automatically during the inspection with immediate notification to the maintenance manager. This system, teamed with the MM and the DA will aid the bridge owners in their overall CPM.
The IIM will be comprised mainly of two components: the application in conjunction with the DA and the handheld tablets the field inspection will utilize. The inspectors will carry the handheld tablets which will wirelessly connect to the central IIM system. The tablets will be used to collect information about the condition of the bridge including all the standard forms, photo logs, consultant forms, sketches, etc. In cases where the specific structural component is instrumented or finite element analysis (FEA) results exist, the inspectors will have access to the FEA results, real time or stored data from sensors, etc. to help them better identify the critical elements.

This module of the iCOMPASS system will provide all stakeholders with an efficient tool which will ultimately manage all the components of the bridge inspection and maintain the assets effectively.

### 4.2.2 Maintenance Management (MM)

The Maintenance Management module of iCOMPASS is designed to issue, track and record all the routine and repair maintenance task orders that exist at the BCBC for maintaining their assets. These task orders include (but are not limited to) roadway condition and de-icing, routine maintenance of drainage systems, routine maintenance of vehicles and trucks, routine maintenance of the mechanical and electrical systems, daily and weekly operations checklists, annual state reports, as well as all the repair tasks that are done in-house.

The system will be able to issue the task orders, assign the task orders to personnel, track them, and record them on the Digital Archive. In addition, MM system tracks and manages human and financial resources for the maintenance department.

### 4.2.3 Capital Planning and Management (CPM)

This module is designed to track all the contracts, projects, bids, invoices and market prices for the contracts done by outside contractors. The system is capable of defining new projects, estimate the project cost, define new contracts under each project, receive and track bids from contractors, receive and track invoices for each contract, and track market prices for commodities that are commonly used in the construction projects.

In addition, the system can track the cash flow and move, postpone and plan different projects in order to equally distribute the required annual budget between future fiscal years. This system is interconnected with MM and IIM system and shares documents and information with these systems as well as DA.

### 4.2.4 Performance and Health Monitoring System (PHMS)

The fourth module of the iCOMPASS system consists of the Performance and Health Monitoring System. The fundamental objectives of this module are to track not only key structural responses over time to ensure they are consistent with expected values, but to also monitor and track key performance metrics to ensure that the movable components of the structures are operating as expected.

To address the stakeholder’s requirements developed during concept explorations, a set of targeted monitoring systems were designed in conjunction with a vast fiber optic communications network. One of these requirements consists of a PHMS which has the ability to track measures of dead load distribution in addition to the deformations and displacements of the sub- and super-structure due to ambient temperature variations over daily and seasonal time periods to provide a baseline for future comparison and development of automated alerts.

A derivative benefit of the PHMS is the ability to transform the structures into a scale for measuring traffic loads. Typically this is done by instrumenting redundant members with high speed strain gages and monitoring the strain level measured for a passing vehicle in comparison to that measured with a vehicle of known weight.

In addition to these functionalities, the PHMS will include cameras and sensors that assist the operators and the engineers monitor the movable bridges during opening and closing to ensure proper operation of mechanical and electrical systems and determine if any immediate intervention is required. The PHMS communicates directly with MM, IIM and DA modules. In addition, the PHMS shares alerts
and notifications with the PSIM, to be explained below.

4.2.5 Physical Security Information Management (PSIM)

This module monitors the physical security and safety of the assets and consists of closed circuit cameras (CCTV), image analysis software, display walls, and an alert analysis system. This system filters and generates alerts based on the information provided by CCTVs and image analysis software as well as alerts received from PHMS, MM, and IIM modules.

4.2.6 Digital Archive (DA)

The Digital Archive (DA) module acts as a centralized storage for all the legacy documents as well as the documents generated by different modules of iCOMPASS after implementation of the system that include all the technology acquired data as well. Different modules connect with the DA to store and retrieve data, and the DA will have its own interface with upload, download, search, and archival functionalities.

4.3 Information Flow

As described in the previous section, different modules of iCOMPASS interact with each other and with the Digital Archive. The design of this communications network and information sharing depends on the Concept of Operations (ConOps), high-level requirements, and high-level design criteria developed earlier in the project. The level of access to other modules for each user also depends on the criteria and access requirements defined and approved by the stakeholders based on the organizational chart of the client. As an example of how the modules will communicate with each can be envisioned as the sharing of maintenance task orders between MM and IIM modules, and sharing of measured data between the PHMS, MM and IIM modules. Figure 4 shows an example of information flow between the DA, PHMS and IIM modules.

4.4 Integration of iCOMPASS

After all of the individual modules are operational, the functional integration and implementation of iCOMPASS will take place. This integration will be based on the ConOps and high-level requirements developed earlier in the project. Frequent meetings with the stakeholders, consultants and other end-users, getting the client’s approval at different phases as the project and implementation is moving forward, and receiving and providing feedback to all the parties involved are crucial for designing a complicated system such as iCOMPASS.

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REFERENCES


