MEASURING INFORMATION CONTINUITY IN EVOLVING DECISION SUPPORT SYSTEMS

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ABSTRACT
Public works agencies worldwide develop and refine quantitative databases and analysis models for predicting civil infrastructure system performance and estimating investment needs. Databases and models are refined for a variety of reasons including improved technologies for data collection, storage, management and analysis, and changes in the behavior and expectations of infrastructure users. Both implicitly and explicitly, the objective of these refinements is to improve the quality of information for decision-makers. While each refinement, considered separately, may improve selected attributes of information quality, it may not be clear what is the collective impact of all refinements to a decision support system, between separate instances of information development. This paper addresses the issue of information quality in the context of the evolving infrastructure decision support systems. Specifically, the paper investigates information continuity in the context of evolving analysis models and data. This discussion is potentially useful for public works agencies with an interest monitoring and managing the overall impact of periodic decision support system refinements on the continuity of the resultant information.

Keywords
Evolving Decision Support Systems, Information Continuity

INTRODUCTION

Public works are the physical structures and facilities developed or acquired by public agencies to provide services that facilitate the achievement of common social and economic objectives (Hudson et al. 1997). Examples of public works include facilities that provide water, transportation, waste disposal and power. Infrastructure Management (IM) refers to the systematic planning and programming of investments for the design, construction, maintenance, operation, recycling and disposal of these physical facilities (APWA 1998), with the objective of providing improved facility performance at lower costs. In the past two decades, IM has been adopted as a management tool by a growing number of public works agencies. This change has occurred in the context of aging civil infrastructure and a growing perception of insufficient budgets for achieving infrastructure objectives. For example, the Departments of Transportation of New York, California, Indiana and Florida have developed pavement management systems (PMSs) and bridge management systems (BMSs). These management systems are typically developed as computer-based decision support systems with quantitative databases and analysis models for evaluating investment options. At the federal level, the United States Department of Transportation (USDOT) has also developed and continues to refine quantitative systems to support highway and bridge investment decision-making.

Infrastructure investment analysis approaches typically determine the impacts of the projected demand for facilities (or systems) on the resultant performance of the infrastructure. They then identify deficiencies in the facilities and estimate the costs of improvement actions to bring the facilities above some minimum acceptable levels of performance (i.e., safety, serviceability and/or preservation). For example, the Highway Economic Requirements System (HERS), the national highway investment model, operates as follows: it estimates the impact of the forecasted future travel demand on the physical condition of pavements and the average speeds of links in the highway network. Based on these projections, it identifies deficiencies in the network and selects improvements to bring the system above a minimum acceptable level of performance. Improvement projects are prioritized by their benefit-cost ratios and an overall investment requirement estimate is developed for some minimum acceptable level of performance. Benefits are measured as the reductions in the costs of user travel time, vehicle operations and safety, as well as the residual values of the capital investments at the end of the planning period. Costs are measured as the initial capital costs incurred for the project improvements (USDOT 1998). HERS is an example of a deterministic investment analysis model, meaning that it does not consider causes and effects uncertainty in the analysis.

An infrastructure management system (IMS) typically has the following components:

- Inventory and Attribute Data:
  Inventory data describe the more permanent aspects of facilities or systems, such as the physical location; attribute data describe aspects of facilities or systems that are more readily subject to change e.g., the physical condition.
- Performance Prediction Models:
  Performance prediction models characterize the relationship between the causes and indicators of facility or system deterioration to enable predictions to be made of the future condition of the facility or system. For example, a pavement performance model may link highway usage with the rate of cracking on the surface of the pavement. This way, future projections of

highway demand could be used to estimate the expected cracking on the surface of pavements in different portions of the network, for the purposes of estimating future budgets and prioritizing expenditures.

- Priority Assessment Models:
  Priority assessment models use various criteria to rank or attempt to optimize the impacts of improvement projects under some funding constraints. For example, a pavement-ranking model may rank pavement projects as a function of their project benefit-cost ratios or their life-cycle benefits and costs.
- Validation Procedures:
  Validation procedures are used to monitor and fine-tune the decision support system with respect to the actual infrastructure facility or system being managed.

Information quality may have different levels of importance in IM depending on a number of factors. Such factors include the level of management of the infrastructure, (i.e., project or network), the types of failure to which the facilities are subject (catastrophic or non-catastrophic), and the level of severity of the funding constraint relative to the minimum acceptable performance for the facility. Van der Pijl (1994) distinguishes between causal and teleological viewpoints of information quality. Causal viewpoints of information quality focus on the processes used for information development. Teleological viewpoints, on the other hand, consider the quality of information as the degree to which information is suited to the purposes for which it is needed. Information quality management must make use of both viewpoints first to define information quality needs for decision support system (DSS) development, and, subsequently, to evaluate the quality of information that is developed using the DSS. This paper focuses on information quality in the context of the main objective of public works analysts and decision-makers, i.e., providing and using information to support improved infrastructure performance,[1] and a key characteristic of associated infrastructure decision support systems: system evolution.[2] From a teleological perspective, the information quality of DSSs is related to the fitness of use of the information for creating higher values of safety, serviceability and performance for facilities and systems. From a causal perspective, the quality of information is defined and constrained by the technical characteristics of the DSS. In this discussion, we are interested in both the causal and teleological aspects of information continuity. In other words, we are interested in measuring the effects of periodic changes in the decision support system on the ability of decision-makers to achieve improved infrastructure system performance using the resultant information.

Civil infrastructure DSSs are continually refined as a function of various factors including improved data collection, storage and management techniques, improved analytical approaches, and changes in the behaviors and expectations of infrastructure system users. As modeling procedures and parameters are changed, and the contents of databases evolve, these changes have impacts on the resultant information generated using decision support systems. Information continuity may be an issue in this context for the following reason. There is an implicit assumption that all planned refinements of

[1] Higher levels of safety, serviceability and preservation (SS&P) of facilities and systems, per unit cost

[2] Periodic refinements related to changes in the technologies for data collection, storage, management and analysis, and the standards of infrastructure performance

DSSs result in improvements to the quality of information. Even in cases where this assumption is true, it is possible that the *combined* effects of changes in the analysis models and databases (between instances of information development) may be different, in comparison with the effects of such changes viewed separately. It is also possible that the collective impacts of such changes may result in relative changes in the trends of system performance as measured by previous instances of the decision support system. In this paper, we explore this issue of information continuity in evolving decision support systems (DSSs). For the purposes of this paper, we define evolving DSSs as decision support systems that have identifiable differences in specific characteristics of the analysis model and database, between different instances of information development. We believe that this issue is worth addressing because several public works agencies periodically refine their databases and analysis models and may benefit from an approach that allows them to track the combined effects of cumulative refinements on decision support systems and the resultant information. This would enable them to assess information continuity between regular instances of information development, and use the results of these assessments to manage future DSS refinements.

Although non-deterministic approaches are increasingly being considered for infrastructure investment analysis, many infrastructure decision support systems still use deterministic procedures. As previously indicated, deterministic analysis approaches do not consider that there are uncertainties associated with either the data or the analysis procedures. The assumptions underlying these decision support systems are that all data inputs are known with certainty and the analyst has complete confidence in the analysis procedures. While the analyst is usually uncertain about some aspects of the data and/or analysis models, this discussion focuses on deterministic decision support systems (DSSs) for two reasons: practical and procedural. First, a notable number of infrastructure investment DSSs used in various public works agencies are deterministic. Second, as the deterministic DSSs may be modified to perform non-deterministic analysis, we view the former as an appropriate point of departure for discussions on the information continuity of decision support systems for civil infrastructure investments. We use the national highway DSS to illustrate the concepts we discuss. In the sections that follow, we discuss how one might measure the impacts of cumulative DSS refinements on information continuity, between various instances of information development.

EVOLVING INFRASTRUCTURE DECISION SUPPORT SYSTEMS

Many decision support systems (DSSs) are not static in the sense that they evolve as a function of time. Often this evolution is overlooked or not formally addressed. Thus, estimates of changes in some measure of performance of an infrastructure system, in specified time intervals, may be premised on two different criteria for performance – related to separate temporal instances of the decision support system. Sometimes, this issue of underlying change may be non-significant. However, we are interested in exploring instances in which this underlying change is significant and the associated implications. Evolving DSSs may be viewed as having different instances of analysis models and databases associated with separate instances of information development. The national highway decision support system (DSS), for example, may be viewed as an evolving DSS. Beginning in 1965, the Federal Highway Agency (FHWA) has been mandated to develop highway investment requirement information for congressional decision-makers, on a biennial basis (United States Code 1965). The FHWA has developed a quantitative DSS for this purpose. This DSS consists of a deterministic analysis model and database that have incrementally been refined, over the past three decades. The first such analysis model was developed in the early 1970s and has evolved in various ways to the present. Table 1 depicts the evolution of the analysis model, database and information product of the national highway decision support system.

TABLE 1: Instances of Information Development for Highway Investment Decision-Making at the Federal Level

Ith* Instance of Information Provision	Year	Information Product	Quantitative Analysis Model (M_i)	Quantitative Database (D_i)
1	1968	1968 National Highway Needs Report	None	None
2	1970	1970 National Highway Needs Report	None	None
3	1972	The 1972 National Highway Needs Report	Highway User Investment Study [Instance 1]	Miscellaneous sources of data from the States [Instance 1]
4	1974	The 1974 National Highway Needs Report	Highway User Investment Study [Instance 2]	Miscellaneous sources of data from the States [Instance 2]
5	1977	The Status of the Nation's Highways: Conditions and Performance [1977]	Highway User Investment Study [Instance 3]	Miscellaneous sources of data from the States [Instance 3]
6	1981	The Status of the Nation's Highways: Conditions and Performance [1981]	HPMS-AP [Instance 1]	HPMS [Instance 1]
7	1983	The Status of the Nation's Highways: Conditions and Performance [1983]	HPMS-AP [Instance 2]	HPMS [Instance 2]
8	1985	The Status of the Nation's Highways: Conditions and Performance [1985]	HPMS-AP [Instance 3]	HPMS [Instance 3]
9	1987	The Status of the Nation's Highways and Bridges: Conditions and Performance [1987]	HPMS-AP [Instance 4]	HPMS [Instance 4]
10	1989	The Status of the Nation's Highways and Bridges: Conditions and Performance and the Highway Bridge Replacement and Rehabilitation Program [1989]	HPMS-AP [Instance 5]	HPMS [Instance 5]
11	1991	The Status of the Nation's Highways and Bridges: Conditions and Performance [1991]	HPMS-AP [Instance 6]	HPMS [Instance 6]
12	1993	The Status of the Nation's Highways, Bridges and Transit: Conditions and Performance [1993]	HPMS-AP [Instance 7]	HPMS [Instance 7]
13	1995	1995 Status of the Nation's Transportation System: Condition and Performance	HERS [Instance 1]	HPMS [Instance 8]
14	1997	1997 Status of the Nation's Transportation System: Condition and Performance	HERS [Instance 2]	HPMS [Instance 9]
15	2000	1999 Status of the Nation's Highways, Bridges and Transit: Condition and Performance	HERS [Instance 3]	HPMS [Instance 10]

i = integer

Temporal changes in the data and model affect highway performance estimates under funds-constrained analyses, or alternatively, they affect the highway investment requirement estimates, under performance-constrained analyses. In the temporal continuum of data and model evolution, we can depict a three-dimensional response surface for highway performance estimates, under similar constraints of funding and time. Our discussion is placed in the context of this three-dimensional space, and focuses on the discrete points in time that correspond with instances of information development for decision-makers. Figure 1 illustrates the hypothetical 3-D space of evolving analysis models, data and infrastructure system performance estimates, under similar constraints of funding and time. This figure illustrates the potential relative impacts of model and data changes on performance estimates. For example, it is clear that, in the i^{th} instance of the analysis model, there is an increase in the estimates of system performance with changing data, over time. In the $(i+1)^{th}$ instance of the analysis model, however, there is a decrease in the system performance estimate, over time. These are potentially possible trends in infrastructure performance estimates as a function of temporal data and modeling changes, and they may be of practical significance. For example, the changes illustrated in Figure 1 could be interpreted as follows: within the data domain under consideration, the criteria for performance evaluation grow relatively less stringent with the i^{th} instance compared with the $(i+1)^{th}$ instance of the model. In the rest of the paper, we discuss and interpret the information continuity significance of combined data and model changes between instances of information development, both from causal and teleological perspectives of information quality.

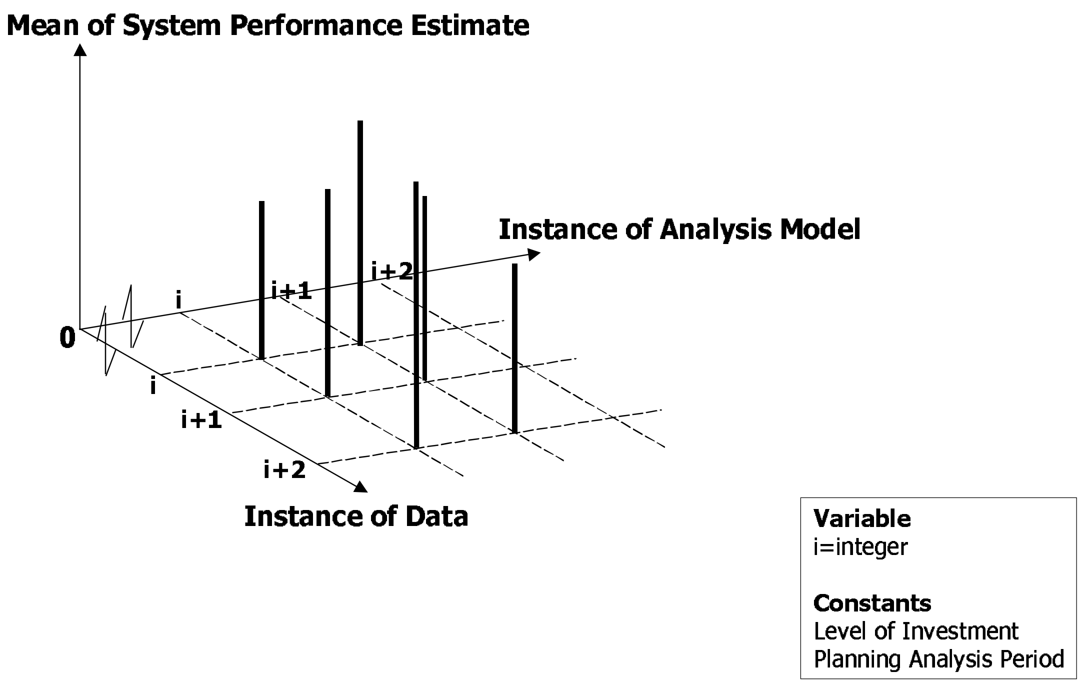

Figure 1: Three Dimensional Space of Evolving Models, Data and System Performance as a Function of Time

In the sections that follow, we characterize the possible changes in infrastructure performance estimates between separate instances of information development, under funds-constrained and time-constrained analyses. We interpret these changes with respect to the continuity of the evolving decision support system and information. Finally, we summarize the potential usefulness of this framework for guiding public works agencies in monitoring and managing the impact of cumulative refinements in decision support systems.

ANALYZING INFORMATION CONTINUITY IN EVOLVING DECISION SUPPORT SYSTEMS

This section develops measures for monitoring information continuity between separate instances of information development. The measures are useful for *ex post* rather than *ex ante* evaluation of the decision support system meaning that they are useful for assessing the continuity of information and the DSS *subsequent* rather than *prior* to information development. The results of this assessment could then be used as inputs to manage cumulative model and database refinements in the future. The discussion focuses on changes in the estimates of highway performance under a given funding constraint, in relation to changes in the actual performance of the highway system as would be obtained from actual data collected from the system. Using the Highway Economic Requirements System (HERS) as an example, one could envisage a funds-constraint analysis in which the analyst estimates the impact of a certain level of investment, **Y**, on the average roughness **X** of the highway system. The approach HERS would use for this analysis is to identify pavement deficiencies and select project improvements. Under the given funding constraint, HERS would prioritize the project improvements as a function of their marginal benefit-cost ratios and select the projects that have the highest economic efficiencies. HERS would then calculate a new average of pavement roughness for the network. Thus, different highway performance estimates, such as the average roughness of pavements, could be plotted as a function of the evolving model and data, as shown in Figure 1, for identical initial conditions and planning periods.

The scope of this discussion is limited to the combined influences of model and data changes on the highway performance estimates. In other words, we only consider full transitions between consecutive decision support system states, where temporal changes in both the data and analysis models have occurred, and do not distinguish between the separate effects of data and model changes on the performance estimates. To simplify the discussion, let us use the following notation:

$\mathbf{X^e_i}$ – Estimated average performance of highway system at instance *i* of information development;

$\mathbf{X^e_{i+1}}$ – Estimated average performance of highway system at instance *i+1* of information development;

$\mathbf{X^m_i}$ – Measured average performance of highway system at instance *i* of information development;

$\mathbf{X^m_{i+1}}$ – Measured average performance of highway system at instance *i+1* of information development.

Merriam-Webster (1999) defines continuity as a 'course maintained without interruption.' From a causal perspective, a decision support system may be viewed as continuous to the extent that it can adequately capture the trends in infrastructure performance over an extended period of time. Therefore, between any two consecutive instances of information development, we may assess the scope and directionality of change in the measures of infrastructure performance of interest. For any measure of performance of interest, if $|\mathbf{X^e_{i+1} - X^e_i}|$ is closer in value to $|\mathbf{X^m_{i+1} - X^m_i}|$, then we may infer that the relative change in the performance estimate captures better the actual change in the estimates. We may view these quantities as measures of scope of change. For any measure of performance of interest, if the measures $\mathbf{(X^e_{i+1} - X^e_i)}$ and $\mathbf{(X^m_{i+1} - X^m_i)}$ have the same signage, we may infer that the relative change in the performance estimates captures better the actual change in the estimates. We may view these quantities as measures of the direction of change. We could describe DSS and information changes as having a higher level of continuity in those cases where $|\mathbf{X^e_{i+1} - X^e_i}|$ is closer in value to $|\mathbf{X^m_{i+1} - X^m_i}|$, and $\mathbf{(X^e_{i+1} - X^e_i)}$ and $\mathbf{(X^m_{i+1} - X^m_i)}$ have the same signage – in comparison with prior changes in the DSS. In other words, decision support system and information continuity can be said to be achieved as: (I) the estimated and measured scopes of performance change grow closer in value, and (II) there is a similar direction of change in the estimates and measurements of highway system performance.

Using these ideas, how would a public works agency check for continuity of its decision support system and information as a function of time? For a set of performance measures of interest (X_i . . . X_n), an agency may collect data on the estimated and measured values of performance as a function of selected instances of information development. For each quantity of interest, the objective would be to evaluate the scope and directionality of change in the estimated and measured quantity, as a function of the time periods of interest. Estimated quantities that reflect closer measures of change and identical directionality with measured quantities, would indicate that the decision support system (DSS) has increased information continuity as a function of time, with respect to those quantities. In the ideal situation, the DSS would be determined to have increased information continuity as a function of time, for all the performance measures contained in the DSS or of interest to the analyst. In the extreme opposite of the ideal situation, a contrary determination would be made in which the DSS would have decreased information continuity as a function of time, for all the measures contained in the DSS or of interest to the analyst. In intervening situations, a subset of the measures of performance would indicate increased information continuity as a function of time. A public works agency could use the results of such an *ex post* analysis to identify measures of performance whose data collection and/or analysis procedures need to be reviewed, using teleological aspects of the DSS to guide decisions on refinements of the causal aspects of the decision support system.

CONCLUDING REMARKS

Public works agencies worldwide develop and refine quantitative databases and analysis models for predicting civil infrastructure system performance and estimating investment needs. Databases and models are purposefully refined for various reasons including improved technologies for data collection, storage management and analysis, and higher standards for infrastructure performance. Implicitly and explicitly, the objective of these refinements is to improve the quality of information for decision-makers. While each refinement, considered separately, may improve selected attributes or dimensions of information quality, it is not entirely clear what is the collective impact of all refinements to a decision support system, as a function of time. In this paper, we discuss the issue of information continuity in evolving decision support systems. We present ideas for evaluating the continuity of information as a function of various measures of performance in the decision support system and explain how public works agencies may use this information to guide their refinements of the underlying decision support system. Public works agencies may use this framework for evaluating the collective impact of refinements to the continuity of their decision support systems, and for planning future refinements that will result in improved continuity of their DSSs, to the extent possible. Potentially useful directions for this work in the future include investigations of the separate and relative impacts of data and analysis model changes on information and DSS continuity.

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