National Database System for Maintenance Actions on Highway Bridges

Paul Thompson, Consultant (corresponding author)
258 Hardwick Ct, Castle Rock, CO 80108
303-681-2425 (phone); 303-265-9694 (fax); pdt@pdth.com

George Hearn, Associate Professor of Civil Engineering
Department of Civil, Environmental, and Architectural Engineering
University of Colorado
428 UCB, Boulder, CO 80309
303-492-6381 (phone); 303-492-7317 (fax); george.hearn@colorado.edu

Bill Hyman, Senior Program Officer
Reliability Focus Area, Strategic Highway Research Program SHRP 2
500 Fifth St NW, Washington, DC 20001
202-334-1914 (phone); whyman@nas.edu

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ABSTRACT

One of the enduring challenges of bridge management has been the need for procedures and technical methods for capturing data on the implementation of bridge maintenance, repair, and rehabilitation work; and using this information to improve forecasting models. Often characterized as the feedback loop of bridge management, such procedures and methods, if they can be developed and implemented, would greatly enhance the potential for long-term success of structure management strategies.

National Cooperative Highway Research Program Project 14-15 has directly addressed this need. The project viewed the problem as capturing data from routine maintenance management processes, and converting them for use in bridge management systems. This conversion required the establishment of an intermediate classification scheme — a bridge maintenance catalog — that is compatible with existing maintenance management systems but also compatible with bridge management systems such as AASHTO's Pontis.

Using work accomplishment data classified according to the standard catalog, conventional cost accounting techniques could be applied to convert measurement units and to relate quantitative condition data and economic inputs, to economic outputs and condition outcomes. A software system using the technologies of Microsoft Excel and Access, Visual Basic, eXtensible Markup Language (XML), and Javascript, was developed to demonstrate the conversion procedures. The software was applied to data from several state Departments of Transportation to compute bridge management system unit costs, action effectiveness measures, and other performance measures useful for bridge management.

BACKGROUND

Definitions of bridge maintenance were collected from AASHTO (1, 2), from published materials of state transportation departments and from NCHRP reports. Bridge maintenance can be defined by at least four means:

- Policy: Descriptive concepts of the kinds of work and outcomes that are maintenance.
- Action: Maintenance denoted by lists of maintenance crew actions and maintenance contract pay items.
- Budgets: Maintenance projects identified by the source of funding and by the kind, if any, of federal participation in funding.
- Data: Maintenance identified, and perhaps limited, by the capabilities of data systems used for maintenance management.

Maintenance Defined By Policy

Policy-level definitions of maintenance were obtained from AASHTO, from FHWA and from nine state transportation agencies.

According to AASHTO's guide to maintenance management systems (2), maintenance is any activity other than new construction. AASHTO's maintenance manual (1) more narrowly defines maintenance as routine upkeep and relatively small repairs that keep bridges in good condition. Maintenance actions include routine cleaning and painting as well as repairs and replacements of components. FHWA (3) recognizes these same activities as maintenance, but identifies routine maintenance by state DOTS as ineligible for HBRRP funds. Indeed, major maintenance can cause a structure that is eligible for Federal HBRRP funding to "drop" off of the eligible list for a period of ten years.

Jorgensen's NCHRP report on budgeting for highway maintenance (4) defines maintenance as actions that preserve assets in their as-constructed condition; a statement that excludes improvements to existing structures as well as new construction. State DOTS often define maintenance in a similar narrow sense: maintenance preserves bridges and can restore bridges to original condition. New construction is excluded. So too are betterments: actions or projects that increase capacity or improve function of bridges.

California DOT (5) states that maintenance does not include reconstruction or improvements. Idaho DOT (6) considers improvements to be part of maintenance. Michigan DOT (7) notes that maintenance projects are of short duration and have little impact on traffic operations. Montana DOT (8) states that maintenance preserves the originally intended use and function of bridges. Ohio DOT (9) states that maintenance aims to keep bridges in original constructed condition. Oregon DOT (10) identifies preserving, repairing and restoring as maintenance. Texas DOT (11) identifies maintenance in three categories: routine, preventive and major. Major maintenance includes bridge replacement and bridge reconstruction. Washington state DOT (12) identifies normal maintenance including cleaning and minor repairs.

Based on stated policies, cleaning and minor repairs are always maintenance. Repairs or replacements of components are often classified as maintenance. Improvements achieved in small projects might be maintenance. Larger projects for improvement, bridge reconstruction, and bridge replacement are not maintenance. New construction is not maintenance.

Maintenance by List of Actions

A review of maintenance actions as presented by AASHTO and by state DOTs reveals seven common operations in bridge maintenance (Table 1).

TABLE 1 Common Operations in Bridge Maintenance

Clean, Clear actions include sweeping, flushing, removal of incompressibles, removal of vegetation, removal of material in channels and all similar operations.
Seal, Paint, Coat actions provide spot, partial or complete application of fluid sealers, paints, coatings or preservatives.
Reset actions include re-positioning, lubrication, tightening (of bolts and rods) and other minor corrective actions.
Repair actions return elements to better condition, and perhaps to as-built condition. Patching is a repair action.
Replace actions are replacement in kind of all or part of elements.
Modify actions are repairs or replacements that alter elements.
Emergency actions are in response to sudden acute problems that must be corrected to restore or continue traffic operations.

Most state DOTs identify maintenance actions in all operations shown in Table 1, though terms vary among DOTs. Some DOTs identify minor repair and major repair rather than Repair and Replace. Some DOTs describe betterments, instead of Modify actions. Some DOTs have separate categories for maintenance of movable spans, of motion equipment, of tunnels and of other structural assets. In general, bridge replacement and reconstruction are excluded from maintenance. Improvements to bridges may be maintenance, if projects are small. Improvements are not maintenance if projects are large. Modify actions, within maintenance programs, can include replacement of obsolete railings, extension to drain outlets, and relocation of bracing in truss portal frames.

Maintenance Defined by Budget

Budgets in transportation departments identify funds for the maintenance division, for contract maintenance, and for equipment and materials used in maintenance tasks. In a simple sense, the actions and projects funded by DOTs as maintenance are strictly maintenance. The federal HBRRP program has an impact here. Bridge replacement or major rehabilitation projects that are eligible for HBRRP funds are not maintenance. At the same time, projects that extend life of bridges are maintenance and can be HBRRP-eligible. These projects usually entail repair, (element) replacement, or minor modification.

From the DOT budget perspective, cleaning and other routine upkeep are always maintenance. Repairs, component replacements and minor modifications are usually maintenance, and may be eligible for HBRRP funds. Bridge replacement and major rehabilitations are not maintenance. Any project that affects HBRRP-eligibility of a structure is not maintenance.

Maintenance Defined by Database

The capabilities of data systems can impose limits on the work that is tracked as maintenance. Maintenance data are the history of maintenance actions executed on individual bridges. Each bridge is presented to the maintenance database as an entity; as a complete set of descriptive and defining data. The bridge is presented as its NBI record, its element-level model, its element-level condition data, etc. Maintenance actions are tied to individual bridges. The existence, and essential immutability, of each bridge and its make-up are necessary attributes. Projects that replace bridges or greatly alter bridges are not maintenance, in this context, because they are not compatible with the basic concept of maintenance data organization.

Maintenance Categories

Maintenance programs consist of two broad categories: cyclic work and singular work. Cyclic work, which includes actions such as deck sweeping, is performed at a set interval. Singular work, such as repair, is performed in response to deficient condition. The categories reveal two distinct origins of maintenance projects. Cyclic work is generated in response to DOT policy. Singular work is generated in response to inputs from bridge inspections and road surveys. A third category, Updating, may be added, though it is not prominent in DOT literature on maintenance. Updating is work to replace obsolete elements such as bridge railings, when the replacement is performed as part of the maintenance program. DOTs use various names for these categories of maintenance. Terminology is addressed in the next section.

Contract Maintenance

For the most part, bridge contract work is let through a standard bidding process. DOTs normally prepare Plans, Specifications, and Estimates (PS&E) for many types of bridge maintenance work. The PS&E, or its equivalent, typically includes pay items for bridge maintenance. The item tabulation for a maintenance contract can include some items that appear only for maintenance work, and other items that appear in new construction as well. Items to patch, to place deck toppings, to perform partial depth demolition are maintenance-related. Items for mobilization, traffic control, furnishing materials among others could appear in contracts for new construction as well as maintenance. Some DOTs identify maintenance contracts as a separate class, and compute distinct values of average unit costs for pay items in these contracts.

Summary on Bridge Maintenance

Bridge maintenance can be defined in terms of policy statements, lists of actions, budget status and the capabilities of maintenance data systems. US DOTs all recognize maintenance as distinct from construction; where construction includes new structures, replacement of structures and major rehabilitation of structures. Cleaning, painting and minor repairs are always maintenance. Replacement or modification of portions of bridges may be maintenance if projects are small and have short duration. Larger projects are construction, rather than maintenance. Emergency work, usually in response to accidents or extreme weather, is classified as maintenance, and can enter significant, temporary modifications of bridges.

MAINTENANCE CATALOG

Maintenance actions are identified by item numbers. The numbering system employs as many as three, two-digit fields; one field for each among bridge component, maintenance operation and maintenance action. Numbering for bridge components and maintenance operations are shown in Table 2.

TABLE 2 Numbering for Bridge Components and Maintenance Operations

	Component
1	Deck
2	Joints
3	Drains
4	Railings, etc.
5	Bearings
6	Superstructure
7	Substructure
8	Appr., Embk.
9	Channel
10	Culvert
11	Bridge
12	Movable Bridge

	Operation
1	Clean/clear
2	Reset
3	Coat
4	Repair
5	Replace
6	Modify
7	Emergency

In its most general version, numbering for maintenance actions uses two fields, identifying, in order, a component and an operation (see FIGURE 1).

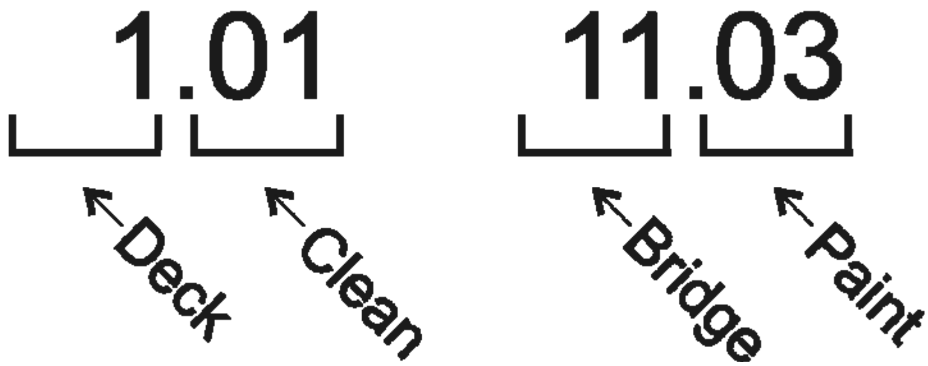

FIGURE 1 Basic Numbering for Maintenance Actions

Actions can be used with maintenance operations to provide more detail on the work performed. Numbering for actions is shown in Table 3.

TABLE 3 Numbering for Maintenance Actions

	Clean/Clear
1	Wash
2	Zone wash
3	Sweep
4	Flush
5	Unclog / cleanouts
6	Graffiti
7	Vegetation / trees
8	Debris / Drift

	Reset
1	Consumable
2	Tighten
3	Caulk
4	Lubricate
5	Reposition
6	Gates/signals
7	Mechanical equip
8	Electrical equip

	Coat/Paint
1	Paint
2	Spot paint
3	Seal surface
4	Seal cracks
5	Chemical treatments
6	Surface prep

	Repair
1	Patch
2	Re-attach / Re-anchor
3	Straighten
4	Jack / Align
5	Reinforce / Strengthen
6	Dredge / Grade

	Replace
1	Individual
2	Section
3	Complete
4	Span

	Modify
1	Geometry
2	Protection
3	Vulnerability
4	Strength/capacity
5	Function
6	Assembly

	Emergency
1	Post
2	Shore
3	Closure, full
4	Closure, partial
5	Detour
6	Temporary bridge

When actions are used, numbering for maintenance items has three fields, identifying in order, a component, an operation and an action (see FIGURE 2).

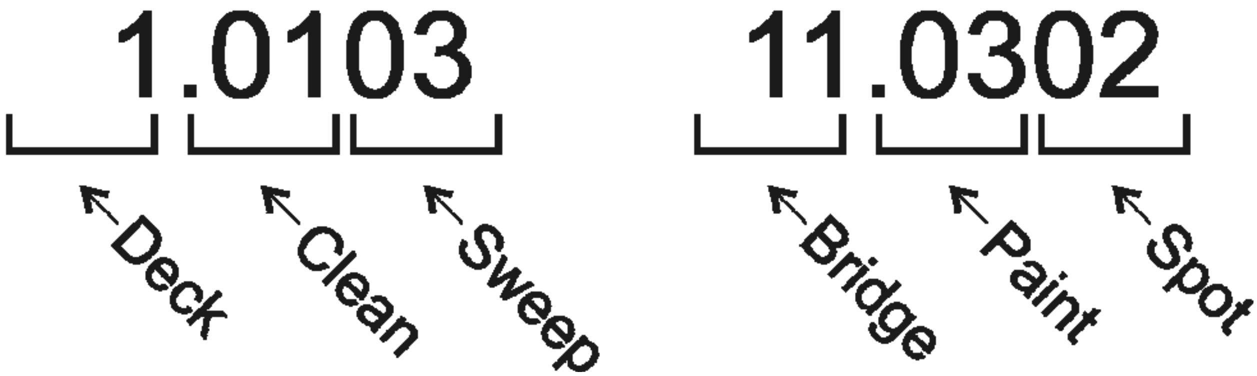

FIGURE 2 Numbering for Maintenance Items Using Actions

The numbering system easily rolls up from its more detailed implementation to more terse. The numbering system allows simple collection of maintenance data by bridge component or by maintenance operation.

ANALYSIS PROCEDURES

Figure 3 shows the conceptual framework for the cost analysis, which comes in four phases:

- Recognition of condition deficiencies, from bridge inspection. When planning future bridge maintenance, the quantity of deterioration is usually the only quantity known with any degree of confidence. Thus, the analysis starts here.
- Economic inputs. These are the resources that are put into a maintenance activity. Such resources typically include labor, materials, equipment, and contract pay items. In most agencies, these inputs can be tracked in maintenance and financial management systems. Usually the inputs that are trackable do not include indirect costs such as engineering, mobilization, and maintenance of traffic.
- Economic outputs. Measured separately from inputs, this is a description of work completed in maintenance activities. For example, if a crew painted 5000 sq.m of steel, that would be considered an output. If the crew used 10 gallons of paint and 8 hours of time, those are inputs. Outputs typically use different units of measure than inputs. Output costs are often computed in the headquarters office using cost allocation procedures, rather than in the maintenance yard. They typically include indirect costs, especially if the work is done by contractors.
- Outcomes. Typically, the purpose of maintenance activity is to change a deteriorated condition into a better condition. The amount of change is called the outcome. Like the initial condition, outcome is generally measured by bridge inspection, usually the next regular inspection after the work is done.

Both cost and quantity of both inputs and outputs are used in the analysis. If any are missing, the analysis can still work without them. But then, of course, the results will be less complete.

Rollup Procedures

Costs and quantities can be “rolled up” (i.e. summed) to any level of aggregation where it makes sense. Input costs are rolled up to the level of resource definitions, and then to the level of component/ operation/ action for the whole database. If several states or time periods are in the same database, they are rolled up together. However, they can be configured to roll up separately as well. Output costs are rolled up to the same levels as inputs, but are also allocated to structures and their elements, and from there to the level of elements and actions for the whole database.

Quantities are not necessarily rolled up to the same levels as cost, because of the need for compatibility of measurement units. It’s the “apples and oranges” problem that resource quantities measured in gallons shouldn’t be added to resource quantities measured in hours. Yet, the database is structured to allow valid rollups of the most important quantities.

The analysis computes unit costs and performance measures from this information. Table 4 describes the statistics that are computed.

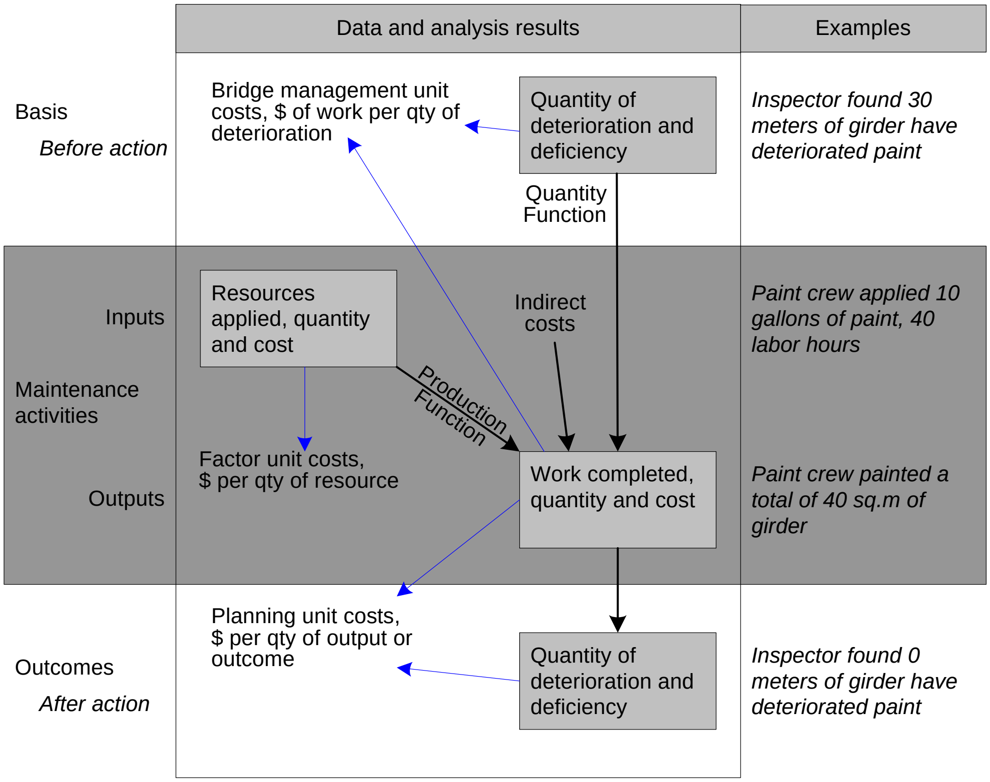

FIGURE 3 Conceptual Framework of Cost Analysis

TABLE 4 Statistics Computed by the Analysis System

Variable name	Description
qty_def	Quantity of defects, computed as the element quantity in condition state 2 or below for any element.
qty_inp	Quantity of input resources, from the event_resource table.
qty_out	Quantity of output, from the event_activity table.
qty_res	Quantity of resulting defects, an outcome measure determined by qty_def for the following element inspection.
cost_inp	Cost of input resources, from the event_resource table.
cost_out	Cost of output work accomplished, from the event_activity table.
ucost_def	Unit output cost relative to initial defects, computed as cost_out ÷ qty_def. This is the Pontis (13) total MR&R action unit cost.
ucost_inp	Unit cost of inputs, computed as cost_inp ÷ qty_inp.
ucost_out	Unit cost of outputs, computed as cost_out ÷ qty_out.
ucost_res	Unit cost relative to resulting condition, computed as cost_out ÷ qty_res.
eff_func	Effectiveness function, computed as qty_res ÷ qty_def, or outcome ÷ initial condition, a measure of the effectiveness of a treatment in correcting the original problem.
qty_func	Quantity function, computed as qty_out ÷ qty_def, or work quantity divided by defect quantity. This is useful in project planning for determining the quantity of work required in response to inspection data.
prod_func	Production function, cost_inp ÷ cost_out, a measure of the amount of a given input required in order to achieve a desired output.
prob1 .. prob5	Pontis action effectiveness probabilities.

All of these are descriptive and not normative statistics. That is, they describe what the agency has been doing in the past and not how operations might be improved in the future.

Cost allocation

All cost data originate with costs gathered in the agency's maintenance management process. Each activity is identified using the maintenance catalog with component, operation, and action. This makes it straight-forward to roll up total costs for a database as a whole, in the same categories of component, operation, and action.

A more complicated problem is the association of work accomplishments with the original deterioration that likely motivated the work. The database provides a capability to directly enter, for each activity, the bridge element to which the action was applied. However, as found in NCHRP Synthesis 227 (14) this is not within the capabilities of most agencies at this time.

The inability to directly record which elements are affected by a maintenance event, complicates the analysis. Each element definition is uniquely identified with one bridge component, and each BMS action is identified with one component, operation, and action. The reverse is not true, however: each combination of component, operation, and action may be associated with multiple BMS actions. In fact, nearly every combination of component, operation, and action that corresponds to a bridge management action as defined in the AASHTO CoRe elements (15), corresponds to more than one of them. Maintenance action 1.04.01, deck repair/patch, matches 46 different AASHTO CoRe element actions for different elements and condition states.

When a maintenance activity occurs and is recorded in the database, it is required to be identified with a component, operation, and action. If an element is not identified, then there is a strong possibility that more than one element might be affected. For example, a painting action might affect both the girders and stringers. The cost allocation procedure resolves this issue. Here's how it works.

Step 1: Definition preprocessing

A pre-processing algorithm analyzes the bridge management system definitions to index all the correspondences between BMS actions and MMS actions. It identifies the cases where a unique match can be made, and keeps track of the measurement units used, since allocation of work quantities must not mix quantities measured in incompatible units.

Step 2: Event processing, stage 1

The first processing step on maintenance events is to add up the costs over all activities and resources in an event to get the event's input and output cost totals.

Step 3: Structure processing

The algorithm completes the analysis of all maintenance events on each structure before proceeding to the next structure. It associates each element inspection on a structure with the next element inspection after it. It asks the question, "if we ended up working on this element, how did it turn out?"

Step 4: Event processing, stage 2

Next each event affecting the structure is processed. On the first pass, each event is tagged with the identifier of the last element inspection before the event, and the first one after. It is possible that there might not be an inspection before or after, and it is possible for there to be multiple events between inspections. So these possibilities are all accounted for. At this point it becomes possible to allocate event costs to inspections. This addresses the question, "how much did we spend because of the findings of this inspection?"

Step 5: Activity processing, identifying affected elements

Now each activity is associated with element inspections, for the inspection that occurred most recently before the activity. Pontis (13) allows an element to appear more than once in an inspection, for different structure units or environments. So it is first necessary to aggregate the separate instances of the same element.

A maintenance activity can affect multiple elements, and an element can be affected by multiple activities. We can narrow the list of possible associations in this many-to-many relationship by using the results of step 1 to identify just the relevant elements on the structure, the types of elements to which the activity is generally applicable. Often more than one element qualifies.

When more than one element might have been affected, it is valid to allocate the output costs among elements on the basis of quantity of improved condition, or by quantity of total deterioration if none showed improvement. To allocate costs on the basis of quantity, however, it is necessary to make sure all elements so allocated use the same measurement units of quantity. This provides a basis for further elimination of elements from the allocation process, if measurement units are incompatible with most of the elements that were likely affected.

If any of the elements on the structure improved in condition, which is usually the case after a maintenance event, we can narrow the list even further by eliminating elements that did not improve. If no elements improved, but any were deteriorated before the event, we can eliminate elements that were in perfect condition before the event.

Step 6: Allocation of cost and quantity of output, and Pontis unit costs

Finally, after all possible eliminations, we may still have more than one element on the structure that may have been affected by the maintenance activity. When this happens, costs and quantities are allocated between them, by quantity of improvement if possible, or by total quantity of element if necessary. Users of the software developed in the project, can easily view all the inspections that likely motivated the maintenance activity.

After this allocation of costs to elements, it becomes possible to roll up allocated output costs by type of element, giving the average unit cost of each element.

For the purpose of Pontis unit costs, it is necessary to take one further step, since Pontis costs are expressed at the level of element, condition state, and action. We allocate costs not just between elements, but also between condition states. This is obviously based on condition. Within a condition state, costs are not allocated between feasible actions because such actions are considered to be mutually-exclusive alternatives within the theoretical framework of Pontis. So output costs are fully assigned to each BMS action that was not previously eliminated for each condition state.

Step 7: Quantity metrics

Since each combination of BMS element, state, and action uniquely identifies a specific combination of MMS component, operation, and action, it is possible to uniquely determine the measurement units of output. Thus, quantities of output, not just costs, can be allocated to BMS actions. This makes it possible to calculate the quantity function, which directly relates quantities of work, in output units, to quantities of deterioration, in bridge inspection units. For example, we can calculate the average square meters of painting required to respond to each linear meter of deteriorated girder. This information will be very helpful in the future for improving bridge management predictive models.

Pontis action effectiveness

After completion of the cost allocation procedure on each structure, one further computation yields Pontis action effectiveness probabilities. In Pontis, the condition of an element following an MR&R action, is forecast using a vector of transition probabilities, representing the likelihood of each possible condition state after the action These probabilities are memory-less; that is, they don’t depend on the condition before the action.

To perform this computation, first each event is associated with the inspection following the event. This is different from the cost allocation procedure, which relates each event to the inspection before it. An unweighted average is computed; first for all elements of the same type on the structure; then to the level of elements, states, and actions for the whole database. These results are directly usable in Pontis.

Limitations of the analysis

It is clearly valuable to have a rigorous procedure to estimate bridge management planning metrics. The process described here makes the most of the available data, and is far better than any other automated process developed thus far for this purpose. However, the limitations of the analysis must be recognized:

- Even in a large database, many structural elements might not have received any maintenance work. No results will be generated for such elements.
- The methodology is sensitive to the agency's procedures for estimating the output cost of maintenance activities, which are not always as rigorous.
- There can be great variations from one project to another. More in-depth research using the research products, may uncover and quantify the factors that cause variation, making application of the results more precise.
- When combining data from multiple agencies, there can be differences in element definition and accounting procedures that cause the unit costs and productivity measures to vary. For example, a box girder in California is likely to be a large single-unit box with high costs per linear foot; while in Colorado the same element is more likely to be a small precast box beam placed adjacent to several others, counted separately in length.

In a Florida DOT study of Pontis unit costs (16), a rigorous statistical method was followed to estimate the costs from a very complete database of in-house and contract maintenance events. The results were then put before a panel of expert estimators. It was found that 55% of the unit cost values required significant adjustment by expert review.

SOFTWARE SYSTEM

The National Bridge Maintenance Database (NMDB) is a combination of tools that support various parts of an ongoing process as shown in Figure 4. These tools make best use of generic technologies for each phase of the data life cycle. The most significant tools are these:

- A generic bridge maintenance database, delivered in XML format. XML is a data standard that is specifically intended to be open, human-readable, generic, and vendor-neutral. The XML database follows a specific structure, called a schema, that determines what kinds of data may be included in the database.
- An Excel workbook file called The Organizer. This file contains procedures for importing, converting, organizing, and editing the XML database. The organizer can import data from an agency maintenance management database provided the database meets certain standards. It can also import from Pontis and from other XML databases using the NMDB schema. The Organizer handles data validation and the cost analysis.
- A Web Site (Figure 5), which gives a very user-friendly and flexible interface for browsing through a database and accessing the most significant analysis results. This site consists of a collection of files in HTML, XML, Javascript, and graphic formats. All executable code in the web site operates in the user's browser. This makes the system generic and is most compatible with agency data security standards. The web site can be customized on an agency's web server, or it can be downloaded and run entirely on a desktop computer, local area network, or intranet.
- An output database, which can be used for any analyses that are not provided by the Organizer or Web Site. The XML database is designed to be directly importable into common database management systems such as Microsoft Access.

All of these components are supplied with the project deliverables. The content of the databases consist of sample data from ten agencies, that each agency can use in combination with its own data for development of bridge management inputs and metrics. A variety of standard reports (Figure 6) present various stages of the analysis from maintenance management inputs to bridge management results.

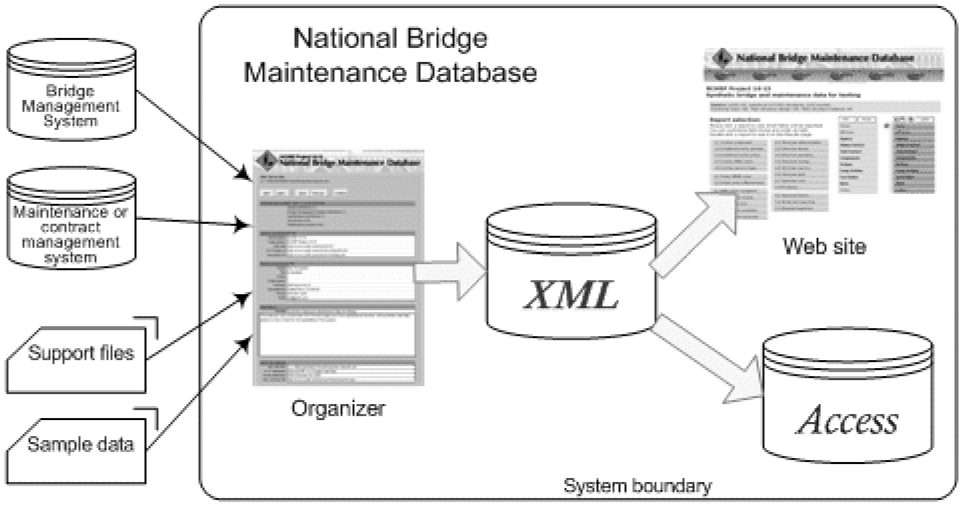

FIGURE 4 Data Flows in the National Bridge Maintenance Database

MRR Actions (946)

Item	Element	Element	State	Action	Description	Qty-Def	Cost-Out	UCost-Def	BMS-Units	Comp/Action	Activities
1	12	Bare Concrete Deck	1	1	Add a protective sys	0	0	0.00	sq.m	1.0602	Activities
2	12	Bare Concrete Deck	1	2	Miscellaneous Maint	0	0	0.00	sq.m	1.0000	Activities
3	12	Bare Concrete Deck	2	1	Repair spalled/delam	9,997	7,923,922	792.63	sq.m	1.0401	Activities
4	12	Bare Concrete Deck	2	2	Add a protective sys	9,997	7,923,922	792.63	sq.m	1.0602	Activities
5	12	Bare Concrete Deck	3	1	Repair spalled areas	0	0	0.00	sq.m	1.0401	Activities
6	12	Bare Concrete Deck	3	2	Rep spall & add prot	0	0	0.00	sq.m	1.0602	Activities
7	12	Bare Concrete Deck	4	1	Repair spalled areas	0	0	0.00	sq.m	1.0401	Activities
8	12	Bare Concrete Deck	4	2	Rep spall & add prot	0	0	0.00	sq.m	1.0602	Activities
9	12	Bare Concrete Deck	5	1	Repair spalled areas	0	0	0.00	sq.m	1.0401	Activities
10	12	Bare Concrete Deck	5	2	Replace deck	0	0	0.00	sq.m	1.0503	Activities
11	13	Unp Conc Deck/AC Ovl	1	1	Miscellaneous Maint	0	0	0.00	sq.m	1.0000	Activities
12	13	Unp Conc Deck/AC Ovl	2	1	Repair potholes and	0	0	0.00	sq.m	1.0401	Activities
13	13	Unp Conc Deck/AC Ovl	3	1	Repair potholes and	0	0	0.00	sq.m	1.0401	Activities

FIGURE 5 Example Report of Pontis Unit Cost Data

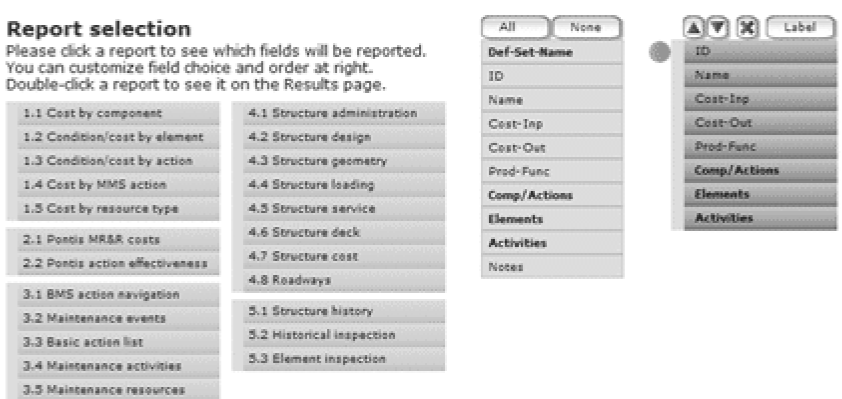

FIGURE 6 Menu of Standard Reports from the Web Interface

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The opinions and conclusions expressed or implied are those of the authors, and not necessarily those of the Transportation Research Board or the National Academies.

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