Economic Appraisal in Advanced Bridge Management Systems

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ABSTRACT

A combination of factors has helped focus attention on the area of Bridge Management in recent years. Between the most significant ones are the recognition of the important role of bridges in a Highway System under growing stress and of the need of establishing preventive maintenance as a priority to reduce congestion and optimize the use of the existing road system. Reflecting this new disposition, the majority of the research in the area of infrastructure management systems in the last two decades has been focused in the production of increasingly sophisticated tools to manage the maintenance of bridge networks.

The development of improved appraisal mechanisms to increase the quality of decision-making in the establishment of maintenance and repair strategies is a vital step towards the development of more adequate systems for Bridge Management. This work proposes the use of an innovative architecture to create a new generation of systems and support the development of a more sophisticated appraisal model.

INTRODUCTION

The problem of infrastructure conservation and renewal can be considered as being both challenging and timely (*1*). The status of maintenance and repair activities has progressively changed over the last decade with Bridge Management evolving from being a secondary or neglected activity to become a priority on the agenda of the majority of transportation agencies around the world. This shift in importance is a result of the recognition, by the authorities in charge, that the deterioration of existing structures tends to originate serious problems with important and far-reaching implications, both in economic as well as in social and environmental terms. It is also a reflection of the fact that sustainability is gaining increasingly greater emphasis (*2*). It has also been accepted that road space demand can not anymore be attended by road construction and that maximizing the performance of the existing network is critical.

This scenario establishes the claim for the adoption of a rational, structured and comprehensive scheme for the management of Bridge Maintenance. The complexity of the problem offers sustenance to the idea of developing more advanced computer tools to support this effort. These tools should help managers to adequately assess the condition of the bridge network, weigh different courses of action and determine the best strategy to deal with the problems diagnosed during inspection, while at the same time improving the management and control of data and information. The investigation of feasible ways to advance the current standard of these systems was the main motivation for the research undertaken.

JUSTIFYING THE NEED FOR MORE ADVANCED SYSTEMS

Maintenance and repair of infrastructure elements has been widely considered as one of the most appropriate domains in which to apply the concept of computer-based Management Systems (*3*). Infrastructure managers require enormous amounts of data to produce the necessary information for their planning, design and construction activities. This naturally suggests the use of computer assisted methods, specially when dealing with a great number of structures as is generally the case in decision-making problems relating to infrastructure maintenance (*4*).

According to the AASHTO (*5*), the analytical capability of an organisation in charge of Bridge Maintenance could be substantially strengthened by the incorporation of decision support tools designed to aid in Bridge Management. They have suggested that the adoption of specifically conceived systems is vital for adequately dealing with the maintenance needs of the bridge stock. These systems are usually denominated as Bridge Management Systems (BMS). It is useful to analyze how these tools have evolved in order to understand how to produce better systems.

An Evolution Pattern for Bridge Management Systems

Bridge Management Systems have initially evolved by building over the body of knowledge accumulated in the development of other Infrastructure Management Systems, especially Pavement Management Systems. The greater level of complexity of bridge structures, however, posed new challenges. This fact generated some inertia during the initial stages of development of BMSs. During the last decade, however, studies aimed at finding ways to improve some of the capabilities of existing systems were initiated and the evolution of these tools has accelerated. Tracing a parallel to the general theory of Information Systems, a certain evolutionary pattern can be identified in these systems, as seen in Figure 1 and discussed below.

First Generation Systems

Early BMSs consisted of a simple interface that provided access to some kind of data storage structure containing the characteristics of each bridge and the data generated by the inspections. This type of rudimentary database-type system will be designated as First Generation Systems (FG-BMS). Since adequate data management is one of the main building blocks of any effective Information System, even these simple tools were already able to make a positive impact in the process of Bridge Management, because they offered an easy and safe way to store and retrieve data. The prompt availability of data allowed a swifter evaluation of the needs and constraints of a particular situation by the manager and provided the capability of instantaneously verifying the characteristics and condition of each bridge by querying the database.

Second Generation Systems

Having data about the characteristics and the conditions of the bridge stored in an easily accessible way in a digital media over time instigated the development of procedures to manipulate this data in order to have a better understanding of its meaning (*6*). This made

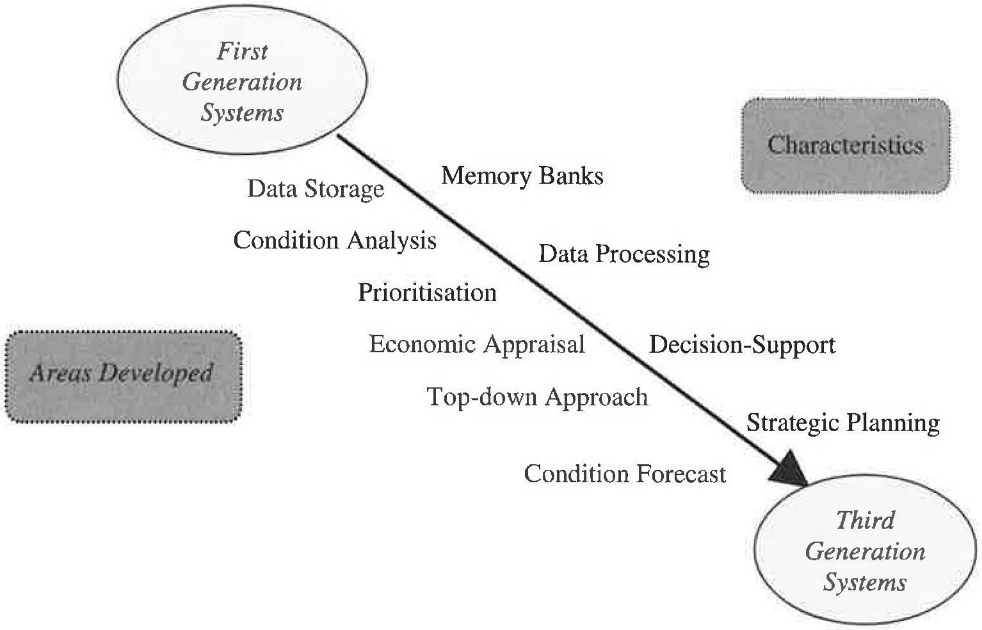

Figure 1: Evolution pattern of bridge management systems.

it possible to automatically produce the information necessary to facilitate the work of the decision-maker, reducing the burden of shifting through a mass of data to make sense of a certain situation. Specialized components were therefore developed to transform and deliver the processed information to the user. Over time, several analytical modules to manipulate data were incorporated, marking the creation of what is defined as Second Generation Systems (SG-BMS). In these systems the data stored was used to determine, generally in a simplified way, a scale of priorities for intervention, using a simple ranking procedure to determine the relative importance of the MRI operations needed in each bridge. This provided an easy-to-use reference to establish network policies.

Better routines were gradually incorporated and systems evolved from being mere database management tools with a ranking procedure attached to become decision-support tools. Even if very limited at first, they already offered a valuable service to the restricted number of authorities that made use of them during the eighties.

Third Generation Systems

Important issues such as the dynamic characteristics of the deterioration processes were not being properly addressed by the second-generation systems and some procedures adopted were very arbitrary and were much criticized. In order to fulfil the potential offered by the sophisticated deterioration models that became available and pressed by the need to deal with the maintenance problems in a more realistic way, a number of countries and organizations have, over the last decade, started to develop more sophisticated systems with improved architectures. The most recent tools produced, such as PONTIS (*7*), have incorporated a series of new and useful features. This marked the emergence of a new generation of systems, that will be denominated as Third Generation Systems (TG-BMS). These can be seen as the current standard but further evolution is necessary.

Examination of the Limitations of the Status Quo

Despite the great evolution of recent years the dissemination of BMSs has frequently been hampered by doubts about their ability to live up to the requirements imposed by real life situations and effectively satisfy users' needs and expectations (*8*). An analysis of the limitations of the status quo was carried out using information available in the literature and obtained through the examination of previous experiences of implementation of systems. Data retrieved by the authors by means of interviews with a group of experts was also used. The main conclusions are reviewed below.

Analysis of the Feedback from Users

One of the most common complaints expressed by users of BMSs is connected with the rigidity inherent in their architecture. Some systems are not capable of performing with enough flexibility to tackle some of the most difficult issues related to the prioritisation and programming of bridge maintenance schemes. This lack of flexibility tends to make systems act in a deterministic and limited way.

Another inhibiting factor is related to the "black-box" syndrome. This is characterized by the inability of some users to identify and understand, in a clear way, the procedures being carried out by the computer. The situation makes users perceive the system as a closed entity over which they have little control and small influence.

A side effect many times associated with the black-box syndrome, but that also appears alone, is the tendency to overestimate the accuracy of the results. This is a consequence of the propensity of certain users to trust implicitly the output from the system just because it is the result of fairly complex mathematical manipulations done by a computer and is presented in an organised and well designed format. The results may be given undue consideration by users that do not fully understand the implications and limitations of the processing, inducing the adoption of false "assumptions."

The perception of lack of control caused by the "black-box" syndrome allied with the inability of some systems to adequately respond to the demands of a dynamic decision-making process due to their rigid architecture has prompted some organisations to undertake steps to reduce the participation of BMSs in their management activities. The use of parallel paper-based processes, which often override computer results and suggestions, is a common stance in these occasions. This is a very ineffective choice because the management work is in effect being carried out twice and there is the added risk of conflicting information being produced and disseminated, causing confusion and generating uncertainties in the organisation. The adoption of less sophisticated systems, resembling earlier generations of BMSs, has been advocated to resolve this impasse (*9*). The reduction of the computer role restores the control of the process to the user but prevents systems from becoming useful tools to support the complex decision-making activities typical of bridge maintenance problems.

Certain systems have also suffered because of the lack of a common architecture between their constituting parts. In some cases, the development of systems was gradual and indigenous and the various Bridge Management functions were automated at different times and treated, at some stage, as independent systems. This means that there is an absence of a common design framework. This kind of fragmented evolution of an information system in an organisation tends to create difficulties to its use. The lack of coordination detracts from the need to have all the information readily available to achieve the best performance during the decision-making process. It also makes the upgrading of the system a complex activity, involving sometimes a complete overhaul of the software structure and of the storage system to accommodate new routines or better models.

Discussion of Expert Opinions

The analysis of expert opinions showed that there is a mixed impression about the importance of BMSs. Practitioners tend to consider BMS tools as interesting tools but they are normally wary of the work involved in setting up and administering a system. All experts interviewed concurred that there is need to improve existing Bridge Management practice and that computer-based systems can play an important part in it. Some have even started developing some in-house tools. Many doubts were, however, expressed about the ideal structure for such tools. Some experts that have had experience with existing commercial systems considered them as inappropriate and in need of change. The analysis of the knowledge elicited about current practice has also highlighted several problems. One of the most important issues is that cost analysis is still being done based on unitary costs. This practice can distort the budget determination and allocation. It was verified also that maintenance selection is being treated in a subjective way that is not considered adequate if structured and well-based decisions are to be taken.

Characterization of the Opportunities for Change

The combination of factors discussed in the previous item justify the idea that further advancements are necessary in the field of BMSs. Fortunately, several factors seem to be combining themselves to support the idea of undertaking changes. In fact, a definite momentum for change can be identified in the area with several factors pushing the development of systems. The inability of existing BMSs to cope with some of the less structured aspects of the problem, as discussed above, is creating dissatisfaction between bridge managers and introducing additional support for change. Meanwhile IT developments are providing opportunities for the creation of a new architecture and the great amount of research dedicated in recent years to the various aspects related to Bridge Management provided a sound basis for other theoretical changes. The experience collected and the examination of the problems faced during the introduction and testing of BMSs in practice have also provided an important feedback. A considerable amount of knowledge has been accumulated and is now available to help find ways to overcome some of the limitations discussed earlier.

Having the desire and the technical capability of producing a more advanced system would not be sufficient if there were no social and political motivation to implement the changes. Opportunely, society is increasingly demanding the establishment of an efficient scheme for Bridge Management because of the importance of maintaining the existing working structure in face of increasing traffic. The rising awareness of people about the importance of externalities means that effects that previously were not considered now have to be taken into account. There is special concern about the environmental impacts of transport (*10*).

DEFINING THE FORMAT OF AN ADVANCED (4th GENERATION) SYSTEM

Given the momentum for change discussed above, the authors sustain the idea that there is a clear opportunity for the creation of new and more developed systems for Bridge Management. The pursuit of improvements in this field is important since the sign of a healthy organisational function such as Bridge Management is that it continually improves over time (*5*). The challenge is to create a computing environment for the bridge community that will alleviate the information management burden and improve the decision-making power (*11*). Not all the problems can be solved without extensive research and testing, but a framework to facilitate the production of enhanced systems was investigated.

Guidelines

The first step in the process of outlining a framework for change involved the definition of a series of guidelines to shape the expected behaviour of advanced systems. The development of any software should follow the generic design principles of software engineering but a set of additional development principles was established to help guide the transition from the actual state of development towards the emergence of an Advanced Bridge Management System. These guidelines include:

Flexibility
This is the main idea from which the whole concept of advanced systems derives. The principle states that advanced systems should be designed having in mind that the necessities of a bridge manager are complex and dynamic. As long as feasible, no strict and rigid path of calculation should be enforced and no unique format for the presentation of results should be adopted. Instead, mechanisms should be created to allow greater freedom for the user to choose the best way to manipulate the software. A basic requirement embodied in the principle is that the type and scope of the information produced should be open to changes through customization. The user must have the possibility of establishing different policy scenarios and altering the prevalent system of values instead of accepting a standard set of static policies and values.

Openness
The world is becoming increasingly networked and connected. Recent IT developments are allowing people to communicate more easily and efficiently. Advanced BMSs must be aware of this reality and adopt an open architecture that would enable them to communicate with other software or share information seamlessly, therefore adopting a distributed architecture. The principle of openness implies that an advanced system should have informal boundaries. The idea of a singular and self-containing whole should be abandoned in favor of a more modern and decentralized structure. It is expected that advanced systems will evolve towards a virtual structure, where a user-friendly coordinated interface hides an extensive and loose conjunction of modules with different and complementary functions (see modularity) that can even be physically located in different places.

Adaptability

The principle of adaptability suggests that advanced systems should always be able to make use of the existing data to produce some kind of result, no matter its precision or completeness. Different behaviors might have to be adopted depending on the amount and quality of data available. If detailed data is available, the software should use it to produce more precise information and deliver the best possible results. If the more strict data requirements are not fulfilled, the system should still be able to produce an acceptable output, recurring to previously stored average values or "default" values or, in their absence, inferring the necessary information from the incomplete data, using sensible reasoning mechanisms. This principle is vital due to the high cost of producing, maintaining and updating data about a great number of bridges.

Transparency

It is important to ensure that the user understands the models that compose a system, not just how to use them, but also the basic assumptions on which they are based (*12*). The principle of transparency implies that advanced systems should enable the user to verify all the assumptions adopted during processing and override them. This extended control over the computing effort can lead to a better understanding of the problems and induce a more critical view of the results.

Progressiveness

Because there are serious problems associated with installing a new system (resistance to innovation, training, etc.), the software design must encompass the possibility of a partial and progressive installation of its components, while preserving its capacity for delivering valid results. This is an especially important factor because some of the specific components that would probably be part of the structure of advanced systems, like congestion management modules or environmental restriction thematic maps, are not usually available for an immediate incorporation into the system. It is expected that initiatives of this nature will be develop in the next years, so the system must be able to smoothly change from a more limited and simple state to more complex ones, without demanding strenuous efforts to ensure that things are running accordingly.

Interactivity

Management Information Systems should be an amalgam of human and computer-based activities. Man and machine have different but complementary roles to play to achieve the successful operation of a system. The principle of interactivity states that the software design should create frequent opportunities for the user to interact with the computer, guiding the processing efforts according to the real needs of the problem and directing the establishment of solutions using engineering sense. The user is seen in this view as a moderating influence on the process.

Technical Changes in Advanced Systems

Changes are inevitable to bring Bridge Management in line with an increasingly wired and dynamic world. There are various emerging IT and AI technologies that could be useful in developing a more advanced architecture for advanced BMSs. Numerous alternatives for improvement have been suggested in the literature but the potential benefits to be accrued in adopting each of them are not accurately known. It is vital however to investigate how to harness the power of recent developments to create opportunities in areas still largely untapped in the domain of Bridge Management. The collection of possible enhancements considered ranged from the development of better data storage facilities to the introduction of new and spatially oriented user interfaces. The main ones and their approval level according to experts are shown in Figure 2.

Procedural Changes

The improvements discussed in the previous section are of a structural nature and demand the introduction of new technologies. They change the way that a system is structured and behaves. The adoption of such changes will ultimately result in the development of a new system architecture. While not directly impacting the procedures embedded that are the real core of a Bridge Management System, they will force their reorganization and provide a new basis for the development of improved methods for their implementation.

Various procedural changes have also been identified as necessary and several possibilities for improvement were considered. It is necessary to address the rigidity of compliance criteria, the imprecision of the techniques for the assessment of the condition state and the forecast of its evolution, the lack of relationship between reliability and deterioration indexes, the inadequate mechanisms for the selection of maintenance strategies, the need for better work packaging and feedback methods, between others.

Having reviewed a great number of developments, the main changes suggested involve:

- the development of inspection expert modules based on KBS technology;
- the introduction of the concept of defects for condition assessment;

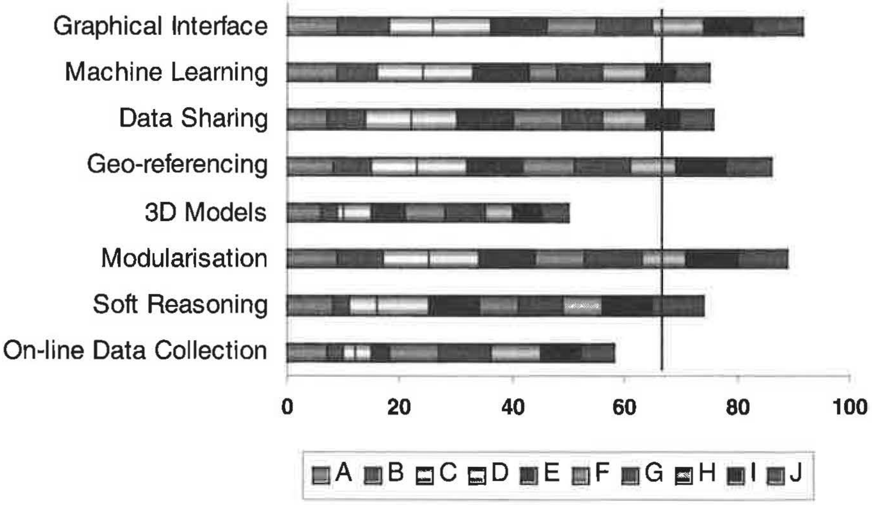

Figure 2: Expert assessment of the suitability of various proposed changes.

- the correlation between risk and condition state;
- the development of more accurate techniques for deterioration forecast;
- the widening of the scope of the economic appraisal;
- the development of modules for assessing the condition state and forecast needs.

A lot of research already is being dedicated to the study of deterioration forecasting using probabilistic or deterministic methods. In addition,

- the decision-making step is the one where the most important management activities are carried out;
- BMSs are essentiality decision support tools;
- Value for Money is an increasingly accepted policy for Public Investment Appraisal but there is not yet a clear definition of Maintenance value;
- Economic analysis is the focus of the DM process;
- Economic analyses needed to subsidise a social appraisal of MRI strategies must be more far reaching than the one undertaken in existing systems;
- The preferred technique for economic analysis is Benefit-Cost ratio;
- The scope of costs associated with a maintenance operation or the deterioration of a bridge is much more ample and has much wider consequences than just the monetary cost of the repair and the user cost.

The authors therefore concluded that the investigation of an improved appraisal model should be one of the main characteristics of an advanced system and this constitutes the major interest of this work. The remaining parts of this paper discuss the development of a new appraisal model for advanced systems.

ECONOMIC APPRAISAL IN ADVANCED SYSTEMS

The panorama of constrained resources and the adoption of Value for Money policies for guiding public investment are placing economic analysis as the main tool for the appraisal of different work strategies. The prospect of change discussed before is fostering the development of a series of new assessment methods to allow the quantification and consideration of such factors. It is not enough anymore just to make technical considerations or consider agency costs. It is necessary to consider the whole of the impacts of bridge deterioration and discuss the destination of money considering all social needs and expectancies. It is also necessary to define how to structure the appraisal of MRI alternatives.

Definition of Appraisal Technique

Several techniques could be used to undertake the Economic Appraisal necessary to subsidise the selection and prioritisation of MRI actions. The choice of the best one to adopt will ultimately be based on the objectives of the decision-maker. In some cases, the objective could be to determine the combination of actions that would minimise the public expenditure in the short or long term, without considering the amount of benefits accrued or assuming that all alternatives would produce similar outputs. In these cases, a cost minimisation technique (*13*) could be used. This approach is sometimes adopted in Bridge Management to determine the minimum level of investment necessary to maintain the condition of the network.

Another possibility would be to find the actions that would bring the greatest benefit, no matter the cost. If the benefits considered in this case were just related to the improvement of the condition of the bridge, this strategy would be reduced to a "do worst first". However, this would imply a very narrow interpretation of value and goes against the recommendations in the ICE report on value management (*2*), which suggests that the scope of the value characteristics considered should be as broad as possible. Another problem with both the "cost minimisation" and the "worst first" strategies is that they do not establish a relationship between the expenditure and the expected return in terms of beneficial impacts. Consequently, they are not efficient in asserting the achievement of Value for Money nor adequate to take into consideration the variations in Public Welfare. To do that, it is necessary to compare costs and benefits and determine if the budget is being spent in the wisest way.

There are various ways to compare cost and benefits, depending on how the benefits are measured. When the consequence is the same but the cost varies in magnitude between alternatives Cost Effectiveness Analysis (CEA) can be used. If the project effects are expressed using a subjective value function, a Cost-Utility Analysis (CUA) is more adequate. The problem is that these two alternatives can just assess the effectiveness of the expenditure but are not able to assess the social relevance of the project. If the social worthiness of the project must be assessed, it is necessary to compare benefit and costs on the same basis. The most common reference for the analysis of the impacts of an MRI strategy is the monetary one. When cost and benefits are compared in monetary terms, the analysis is reduced to a Cost-Benefit Analysis (CBA). In strict terms, the term CBA would be designating an analysis referring to any private entity. However, in public decision-making it is necessary to consider the question from a wider point of view, trying to include all possible effects (*14*). This means that, in the case of Bridge Maintenance provision, it would not be enough to make a pure financial appraisal from the point of view of the maintenance agency, but that it would also be necessary to consider the impacts on users, the environment and society (*15*).

In the UK, CBA has long been applied to the domain of transportation, starting with the evaluation of the M1 motorway project in 1960 (*16*). Since then it has been routinely recommended by the Department of Transport for the evaluation of investments in transport. In the early 1970s a formal procedure to evaluate trunk roads schemes using the technique, denominated COBA (*17*), was introduced. The trend towards using CBA in public decision-making is reinforced in guidance notes from the Treasury (*18*).

All these facts support the suggestion that social CBA should be the preferred technique for appraising MRI actions. The new system proposed will therefore be based on a new appraisal method based on an improved cost-benefit analysis, as follows.

DEVELOPMENT OF THE APPRAISAL MODEL

A new appraisal model based on the notion of value is being proposed. It reorganizes the traditional CBA formulation as follows:

$$V(MAI_X) = (VBU + VRC - OCI - ECI) / MCI \qquad \text{(Eq. 1)}$$

where: VBU is the monetary expression of the variation in bridge utility; ECI is the monetary expression of the external cost of the MRI intervention;OCI is the opportunity cost of the investment in the period; MCI is the expenditure incurred by the agency during the MRI intervention; VRC is the variation in the discounted replacement cost.

The interpretation of cost and benefits in the improved model must be wider than the one used in current systems. The assessment of impacts must follow the idea of utility and the cost structure must be reviewed to eliminate the use of fixed unitary costs, as discussed below.

Proposing a New Cost Structure

Maintenance expenditure is frequently estimated using average values. This practice can induce serious errors because it does not consider that many costs are related to the physical and functional characteristics of the bridge. The use of average values increases the uncertainty and should be avoided. The proposal is to use a more sophisticated definition of costs and rely upon previous experiences and logical reasoning to estimate a particular cost for each bridge.

It is necessary to this end to understand how specific physical and functional characteristics of a bridge can affect the work to be undertaken and, consequently, reflect on the expenditure. The new structure for costs proposed is based on the division of costs in three great groups: direct, related, and indirect costs. The inspiration for the new classification of agency expenditure came from the notion that it is adequate to isolate the main expenditure from the right-of-way mobilisation and other costs less directly associated with the work.

Direct Costs

A direct cost is the basic cost of performing the activity. It will depend just on the type of activity being performed and the element affected. Being by definition insensitive to the shape, location or importance of the structure, the Direct Cost will be influenced just by the characteristics of the action being considered, by the type of element on which the activity will be performed and by the amount of work required.

Related Costs

A related cost is composed of the costs incurred to support the execution of the MRI activity in a particular bridge. It will include the expenditure with things such as providing special access equipment to allow the activity to be undertaken and establishing temporary light and water connections.

The related cost has a close relationship to the type of activity being performed and will therefore be partially dependent on the amount of work being carried out but will also be influenced by the characteristics of the bridge. The most common related cost is the access cost, which is composed of the expenditure incurred to provide vertical or horizontal access to the bridge. To calculate the access cost, information about the available plant and the bridge physical characteristics is used to check which kind of access equipment would be necessary. The related cost would then be the sum of installing or procuring the equipment plus the cost of operating the equipment plus the increase in the cost of performing the activity due to the reduction in productivity caused by the use of the equipment.

To appropriate the related costs a linear model consisting of two parcels was proposed. The first parcel of the model (α) will be a lump sum representing the expenditure incurred to set up the support for the MRI activity. The second parcel (β) is formed by the unitary cost of operating the support equipment plus the extra expenditure due to the reduction in productivity caused by the use of the equipment.

Indirect Costs

An indirect cost is one incurred to make the work on the bridge viable. It includes expenditures with environmental protection, traffic management and other disturbance minimisation measures. They will be represented by a Lump Sum but can also have a time-dependent component. For example, the expenditure with traffic management can consist of an initial cost of installing the signalling system plus a time-dependent value of operating it. Indirect costs will therefore have a similar structure as the related costs.

Scope of Effects to Consider

The main reason for investing in maintenance is because it brings benefits. Benefits can be defined as the positive impacts of an action (*19*). Achieving a meaningful definition of these impacts in monetary terms is one of the crucial factors in making an accurate economic appraisal of MRI alternatives. The authors argue that it is necessary to establish more objective criteria for the assessment of the effects of MRI interventions, based on the notion of value maximization. To undertake this it is necessary to broaden the scope of impacts assessed today, since many authorities do not yet consistently consider user and environmental costs.

The Notion of Utility

An innovative way to assess the impact of MRI actions based on the notion that a benefit (or disbenefit) can be ultimately understood as an increase (or reduction) in utility is proposed.

Since they increase the chance of failure and impose extra costs on users and the environment, deterioration and inadequacies will be seen as reducing utility. Conversely, MRI interventions will improve utility by increasing the possibility of survival and reducing the disbenefits forced upon users and the environment. To determine the monetary expression of the change in bridge utility caused by a MRI intervention a *Bridge Utility Function* is defined. This function expresses how the utility varies with changes in the condition of structure. Based on discussions with experts, it is proposed that the utility of a bridge could be suitably expressed by the aggregation of the following factors: Structural Soundness (SS), Functional Importance (FI), Strategic Importance (SI), Environmental Impact (EI) and Historical Importance (HI):

$$BU = w_s SS + w_f FI + w_{st} SI + w_e EI + w_h HI \qquad \text{(Eq. 2)}$$

More factors could be added to the equation if desired, but the ones represented above cover all the relevant aspects elicited from the group of experts interviewed and are seen as a fair expression of the various aspects that determine the usefulness attributed by society to a certain bridge. While some of these components are subjective and cannot be precisely determined, all of them play some part in the decision-making process and can influence the decisions taken. Advanced systems should be able to cope with them if prompted by the user and therefore the utility function proposed should encompass all these different dimensions. As indicated by the presence of weight factors, the user could give different importance to each of the different utility components.

The value of the components of bridge utility will normally vary over time due to changes in the characteristics of the bridge or its role in the network. For example, if a new crossing over a river is created near an old crossing, the strategic importance of the existing bridge will probably be affected. These types of change do not depend on bridge deterioration or MRI operations and will therefore not be significant for the purposes of this thesis. The main factor that affects the bridge utility and is relevant to this work is the change in Condition State of the bridge elements.

A bridge in perfect condition would be at the maximum utility given its current role. Deterioration or inadequacies would introduce negative effects and detract from the total utility. Structural problems lead to an increase in the risk of collapse while the deterioration of the carriageway can affect the level of service and the development of substandard conditions might force authorities to restrict access to the structure, for example. The compromise of either the functional or the structural performance of the bridge expresses itself through several deleterious effects that range from increased congestion to higher emissions of pollutants and increased personal risk to users. Inadequacies in the structure can cause similar problems with an increase in the risk of accidents or the need to restrict access to the bridge.

The various consequences can be reduced to certain basic effects: time losses, increase in accidents, more emissions, loss of the bridge and additional travel expenses. These in turn can be associated with each of the utility components, which will be the result of the monetary expression of these basic factors. For example, the structural soundness can be modelled as the financial value of the structure at risk, which is represented by the Asset Value (AV) multiplied by the variation of the probability of survival in the interval, minus the potential user cost at collapse (UCC):

$$\Delta BU_{SS} = \Delta P_{surv} * AV - \Delta UCC \qquad \text{(Eq. 3)}$$

The functional importance meanwhile will be the result of the functional value (FV) at risk minus the variation in user costs (UC) during the interval of the analysis ($t_1 - t_0$):

$$\Delta BU_{FR} = \Delta P_{surv} * FV - \Delta UC(t_1 - t_0) \qquad \text{(Eq. 4)}$$

The historic and strategic components will be an expression of the historic and strategic values at risk:

$$\Delta BU_{HI} = \Delta P_{surv} * HV \qquad \text{(Eq. 5)}$$

$$\Delta BU_{SI} = \Delta P_{surv} * SV \qquad \text{(Eq. 6)}$$

Finally, the environmental impact component will be:

$$\Delta BU_{EI} = \Sigma^{n}[\Delta R_{emm}(n) * C_{emm}(n)] + \Delta N_{emm} * C_{nemm} \qquad \text{(Eq. 7)}$$

where $\Delta R_{emm}(n)$ is the variation in the rate of atmospheric emission n, C_{emm} is the monetary expression of the effect of that emission in the welfare of society, ΔN_{emm} is the variation in noise emission and C_{nemm} is the monetary expression of the societal willingness to reduce noise emission.

If there is no detailed data about each of its components, the environmental impact could also be expressed as a generic variation in environmental quality (ΔEQ) multiplied by a certain monetary coefficient that expresses the willingness to pay to avoid the generic degradation in environmental quality (C_{ED}):

$$\Delta BU_{EI} = \Delta EQ * C_{ED} \qquad \text{(Eq. 8)}$$

Considering the factors above, the variation in bridge utility ΔBU could be defined as:

$$\begin{aligned}\Delta BU = {} & w_{SS}[\Delta P_{surv} * AV - \Delta UCC] + w_{FI}[\Delta P_{surv} * FV - (\Delta UC)] + w_{ST}[\Delta P_{surv} * SV] \\ & + w_{EI}[-(\Delta EQ * EC)] + w_{HI}[\Delta P_{surv} * HV] \qquad \text{(Eq. 9)}\end{aligned}$$

Reorganising the elements of the equation:

$$\begin{aligned}\Delta BU = {} & \Delta P_{surv}[w_{SS} * AV + w_{FI} * FV + w_{ST} * SV + w_{HI} * HV] \\ & - [w_{SS} * \Delta UCC + w_{FI}\Delta UC + w_{EI} * \Delta EQ * EC] \qquad \text{(Eq. 10)}\end{aligned}$$

The variation in utility could therefore be seen as consisting of the intrinsic value at risk of the bridge less the sum of negative effects affecting its role. If the sum of negative effects is represented by a factor designated as disutility D, the net variation in utility of a bridge in Condition State CS_0 (at time t_0) at any point t in time to condition State CS_n at time t_n could be modelled as:

$$\Delta BU_x(t_0, t_n) = \Sigma_t[\Delta P_{surv}(CS_t) * BV_x(t) - \Delta D_x(CS_t)] \qquad \text{(Eq. 11)}$$

It is necessary to forecast the Condition State at time t and then calculate the Bridge Value and the Disutility at that moment and in those conditions. The total variation in utility will be the sum of the variations for each period of time t (which will normally correspond to the time between transitions in condition state). The Bridge Value is multiplied by the probability of survival P_{surv} to express the fact that the utility will depend upon the continued existence of the bridge. This formulation implies that, if the bridge fails, the utility is immediately reduced to a value equal to or less than zero, which is considered adequate.

APPLICATION OF THE CONCEPT

Exercises carried out by the authors have shown (*8*) that the use of the new appraisal method can have a strong impact in terms of the cost-benefit (or value) ratio obtained. This would in turn influence the prioritization of activities not just between bridges but also in comparison with other possibilities of public investment. It is considered that this wider analysis, taking into account environmental cost and externalities, must be adopted if Bridge Management is to be carried out in a responsible and structured way.

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