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Rational Bridge Maintenance Decisions in Urban Areas

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ABSTRACT: The paper discusses decision-making issues concerning the maintenance of urban bridges based on practical experience from a bridge managing organization. It is described how the specific characteristics of urban bridges influence the way decisions about their maintenance are made. Three illustrative examples highlight opportunities and challenges regarding the use of formal decision analysis in the management of urban bridges. The author advocates the use of Bayesian decision analysis.

1. INTRODUCTION

Bridge owners need to make decisions about their assets at different stages in the bridges' life cycle. Decisions at various project phases are based on different levels of information and degrees of decision model complexity.

In an urban context, the consequences of bridge maintenance interventions often involve large uncertainties due to infrastructure interdependencies, lack of space, parallel development projects, boundaries of ownership and responsibility etc. Furthermore, decisions about bridge reinvestments might need to be made at different organizational levels based on the expected costs of the project and might involve various budgets. The importance and complexity of such aspects might be underestimated.

Maintenance decisions and prioritization of assets is primarily based on their structural condition, expected costs of interventions and their consequences. Regarding consequences, there are aspects that are difficult to assess, such as e.g., accessibility, usability, aesthetics, cultural value etc. However, these relevant characteristics need to be quantified to carry out a formal decision analysis that better represents the real process of decisions.

This contribution discusses and exemplifies some practical decision-making issues based on experience from real cases of urban bridges in Stockholm where formal decision analysis could provide a powerful tool to assist the decision maker.

2. BRIDGE MAINTENANCE DECISIONS

2.1. Theoretical framework

During the service life of a bridge, a number of maintenance-related decisions has to be made, e.g.:

- Should inspected damages be further assessed? If yes, how?
- Should repairs be made or postponed? To which point in time?
- Should certain parts of the bridge be altered? In which way?
- Should traffic on the bridge be restricted? To what level?
- Should the bridge be replaced? When?

These decisions might have various consequences and they could be done in multiple ways. Smaller decisions could be more ad hoc and include subjective elements. Larger, more important decisions require analysis that is more detailed and rational treatment. In any way, decisions are made under somewhat uncertain circumstances. The likelihood of certain events influencing the decision, the outcome of the possible decision alternatives and the consequences of the actions could be subject to significant uncertainty. The decision maker, however, typically has some knowledge about the uncertainties and can assign likelihoods to various events and outcomes. Furthermore, the decision maker is able, to some extent, to evaluate the desirability of the outcome of each decision scenario.

Thus, maintenance decisions can be interpreted as decisions under risk (Luce and Raiffa, 1957). In this context, the utility of each outcome is weighted by its probability of occurrence and the alternative with the highest expected utility is selected as the rational choice. The mathematical framework for making such rational decisions, i.e. statistical decision theory and Bayesian analysis, is described by Raiffa and Schlaifer (1961) in general, and by Benjamin and Cornell (1970) in a civil engineering context.

2.2. Fundamental decision case

The fundamental case of bridge maintenance decisions is presented in Björnsson et al. (2019). The decision problem is illustrated as an influence diagram, shown in Figure 1. The actual condition **state** of the bridge is unknown (however, prior knowledge about the likelihoods of being in specific states typically exist). The decision maker may choose from various **actions** to alter the bridge's condition and the **utility** of the actions depends of the original condition. Before making any action, the decision maker has the possibility to improve their knowledge about the condition of the bridge by carrying out various types of condition **assessments**. These assessments, however, come with certain **costs**, which have a negative effect on the overall utility. Furthermore, the **outcome** of assessments is uncertain.

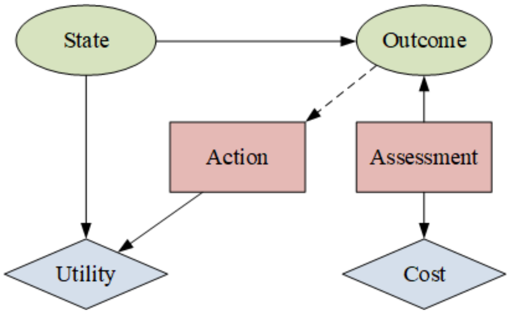

Figure 1: Influence diagram for the fundamental maintenance decision case.

This decision scenario is typical for bridge condition assessments and follow-up actions. However, it is quite simplistic and real decisions may include additional considerations, e.g.: the possibility of applying assessments successively (Honfi et al. 2019; Honfi et al. 2020); uncertainties in the outcome of actions, and their effect on condition state (Honfi, 2019; Larsson Ivanov et al, 2022); temporal aspects, such as e.g. time value of money (Larsson Ivanov et al, 2022).

An issue with making the decision model more complex is that it requires substantially more input, and more time for consideration and analysis. The quantification of the required inputs and the interpretation of the analysis results might be difficult and not necessarily increase the confidence in the decision, especially if the uncertainties are large.

Furthermore, maintenance decisions are typically not made in isolation. A bridge that needs to be repaired often has several defects that might be worth to fix simultaneously to avoid recurring traffic disturbances. Some repair works might be carried out most effectively if coordinated with the repair needs of other bridges in the surroundings. In other cases, repair works needs to be distributed in time due to budgetary constraints or to avoid continuous traffic congestions in a certain area. These are typical considerations for urban bridges, which are often difficult to quantify.

3. MANAGEMENT OF URBAN BRIDGES

3.1. Urban bridges

The most fundamental function of bridges is to provide passage over a terrain obstacle. However, for bridges in cities additional functions might also be pronounced compared to their rural counterparts.

According to Salamak and Fross (2016) the main functions of urban bridges are to: 1) provide transport link between separated urban areas (i.e., facilitate urban development); 2) create an attractive exterior (i.e., add to the city's visual identity); 3) demonstrate technical capabilities; 4) construct a user-friendly structure; and 5) eventually have a symbolic connotation (e.g., link divided groups of the society). Thus, these aspects need to be addressed when new bridges are built in urban areas or significant changes are made to existing ones.

Stockholm is a city built on 14 islands connected by 57 bridges. Thus, bridges often connect separated areas and facilitate urban development. The total number of bridges in Stockholm is, however, much higher. The municipality alone owns more than 900 bridges.

Some bridges are city landmarks and can be viewed as an indicator of technological and economic progress of a certain historical period and the present. When Västerbron (The Western Bridge), see Figure 2, in Stockholm was inaugurated in 1935, it was the largest steel arch bridge ever built in Sweden. The bridge had several contributions to the development of bridge design and construction, including calculations methods for large-span arch bridges, building technology innovations, large-scale application of welded steel and spray painting. The bridge is a good example of how urban bridges contribute to history, culture and the daily life of the inhabitants of the city. It offers a panoramic view to the old town and the City Hall, includes an iconic part of the annual Stockholm Marathon, and is a popular spot for watching fireworks.

Figure 2: Västerbron, the largest bridge in Stockholm.

Urban bridges can make a large impact on the perception of a city and result in substantial changes to landscape. This is illustrated on two images of Kungsbron (The King's Bridge) in Figure 3. The reconstruction of the bridge in 1944 and the developments in the surrounding area resulted in a completely different visual experience.

Figure 3: Image of Kungsbron in 1896 (above, source: Stockholm City Museum) and 2023 (below).

3.2. Tight places, complex infrastructure

Urban bridges are often built in tight places and are physically interconnected with other types of infrastructure or similar infrastructure operated by others. This interconnection and resulting interdependency might increase as the municipality evolves and the infrastructure becomes more interwoven.

Infrastructure complexity poses a challenge to maintenance interventions, as they might be more disturbing than thought, and include risks of cascading consequences. They might also require more careful planning due to the large number of stakeholders, which in turn might lead to increased lead times for construction and maintenance projects.

A prominent example is the ongoing reconstruction of Slussen, the sluice area, a major transport hub in central Stockholm, connecting two islands, and separating Lake Mälaren from the Baltic Sea by locks. The project is perhaps the most complex transport infrastructure reconstruction in Stockholm's history, affecting the maintenance plans of several bridges in the surroundings. The total surface area to be constructed equals approximately 100 new bridges that will need to be maintained.

4. MUNICIPAL DECISION-MAKING PROCESSES

4.1. Prioritization of maintenance actions

Due to limited resources, the need for high availability and accessibility of the municipal transport system, and a good collaboration with relevant stakeholders, maintenance actions require careful planning including prioritization of actions.

Management of bridge stocks primarily follows condition-based maintenance planning strategies and allocation of the available resources. Other aspects are often not considered in a structured manner. Instead, subjective, somewhat ad hoc decisions are made based on information obtained by various organizational channels. This makes it difficult to facilitate a rational and highly automated decision-making process. Furthermore, various decision levels and procedures might exist in an organization managing transport infrastructure assets. For instance, at the Transport Department of the City of Stockholm the way decisions are made depends on the nature and the estimated total costs of the maintenance activities for the considered asset. Smaller interventions that does not require complex planning are referred to as routine maintenance and carried out continuously. Maintenance activities that are more complex, costly and increase the value of an asset are called reinvestments.

Below a certain cost, the responsible unit initiates and carries out reinvestment projects within a previously allocated, recurring yearly budget. However, for larger reinvestments approval from higher organizational levels is required at each project stage. Thus, the uncertainties in larger projects increase especially concerning time schedules.

To carry out an infrastructure reinvestment project three main decisions are required:

1. Investigation decision, to analyze and evaluate various alternatives, their costs and benefits, i.e. initiate a conceptual planning.
2. Policy decision, where it is decided to establish a project with a more detailed cost assessment.
3. Implementation decision, which is about to carry out the project plan, i.e. perform the maintenance actions drawn up in the plan.

In the first step, i.e. at the investigation phase, a formal decision analysis can be carried out. However, the uncertainties are often large regarding the condition state, but also the costs and benefits of various actions. These uncertainties, however, can be systematically reduced during the process.

4.2. Large reinvestments

For large reinvestments projects, the aforementioned decisions are made at the Transport committee's or the Municipal council's level. To initiate such decisions an internal prioritization approach is followed focusing on the following aspects:

- Asset condition, which indicates the time priority of the project, i.e. the urgency of interventions.
- Operational consequences, i.e. how the planned project would influence the overall maintenance needs in the future.
- Relative social benefits, i.e. how much value the project provides in relation to the estimated expenditure.
- Risks and uncertainties, i.e. the overall project risks and complexity.
- Political priority, i.e. how the project relates to the municipality's overall goals and strategies or other higher-level policies.

The prioritization is essential since decisions need to be made between project proposals of different nature, e.g. renovation of a bridge, refurbishment of a square or replacement of noise barriers. In a Bayesian decision-making approach these aspects needs to be considered in the utility functions.

4.3. Smaller reinvestments

For smaller reinvestments the procedure is similar, however, less bureaucratic and all decisions are made within the department. Furthermore, there are dedicated multi-year programs allowing for a more flexible working process.

The prioritization is primarily based on the structural condition and the estimated costs of the maintenance actions. The starting point is the Swedish Transport Administration's framework (Trafikverket, 2021). If maintenance is needed within six years (the typical interval between major inspections), several possible strategies are considered and the one that is judged most beneficial is chosen as the main strategy (S1). Besides the main strategy, there is an alternative strategy (S2). S2 describes the consequences that follow if the S1-strategy is not carried out before its validity "expires". The budget is then allocated with the aim to maximize the overall benefits of the combination of S1 and S2 strategies for the assets that require actions within the planning period.

In an urban context the application of the prioritization framework is somewhat challenging due to two main reasons. First, the assessment of costs and benefits is often difficult without more detailed planning. Second, the scheduling of the projects could depend on (unforeseen) other projects due to infrastructure interconnectedness.

To facilitate a more comprehensive prioritization, an approach proposed by Ritzmo and Pihlsgård (2022) is adopted. Three categories are used as the basis of prioritization: condition (severity of damages, deterioration, age etc.), sensitivity (direct consequences of improper maintenance) and criticality (indirect consequences, i.e. possible traffic disturbances, social and environmental aspects) of the assets.

Due to a more structured working process, decisions about small reinvestments are more suited for a rational decision-making using Bayesian decision analysis. However, the optimal decision should be made considering the entire bridge stock and the available yearly budget.

5. ILLUSTRATIVE EXAMPLES

5.1. Uncertainties in costs estimates

Estimation of reinvestment costs might be very difficult at an early stage in a project. The accuracy depends on the time and resources available for the initial investigation. For example, for the renovation of Västerbron (Figure 2), the estimations during the investigation phase have roughly changed as follows (Trafikkontoret, 2018 and 2020):

- 2018-19: estimated costs for assessment, 5 million Swedish Kronor (MSEK); estimated costs for renovation, unknown; estimated costs for replacement, 1000-1500 MSEK
- 2020-21: estimated costs for continued assessment, 20-25 MSEK; estimated costs for renovation, highly uncertain (perhaps around 900 MSEK); estimated costs for replacement of the bridge, 1000-1500 MSEK
- 2022-23: estimated costs for renovation, <500 MSEK; estimated costs for replacement of the bridge, >2000 MSEK

The case is studied using a modified version of the influence diagram in Figure 1, where the utility node (the estimated investment costs) depends on the assessment outcome, rather than on the condition state. The state of the bridge {'good', 'satisfactory', 'sufficient, 'insufficient'} is largely unknown and there are two main actions to choose from {'renovate', 'replace'}. It is possible to carry out an assessment, which gives more certainty about the condition state. A more detailed assessment reduces uncertainty, but comes with additional costs.

The prior likelihoods concerning condition can be based on the overall condition of the bridge stock, and could be further refined based on certain characteristics of the bridge (age, size, type, materials, etc.). For the different assessment options, conditional probability tables (CPT) are determined to express the analyst's beliefs on how well the results represent reality. The assessment's outcome, thus, indicates the perceived condition state. Expert judgement and historical data is used to determine intervention costs based on the perceived condition.

Bayesian reasoning thus might include subjective elements. However, it helps to structure thinking, analyse various realistic yet uncertain scenarios and the most critical decision factors. The decision maker, thus, comes to a more informed decision and a more informed estimation about the costs, and the likelihoods of which alterative to be preferred.

The final selection of the most appropriate action (a set of various technical solutions) is then based on a utility function, which includes considerations of constructability, construction time, structural performance, maintenance needs and durability, traffic impact, social aspects, health and safety aspects, environmental impacts, initial costs, life-cycle costs, aesthetics.

5.2. Risk acceptance

Using high-strength steel (HSS) bridge bearings bearing) were popular in Sweden between the 50ies and the 70ies. The main advantage of this type of bearing was that they could be made much smaller than traditional roller bearings. However, several HSS bearings have failed in the recent years both in Sweden and in other countries.

There are 10 bridges in central Stockholm with a total 115 HSS bearings. The concerned bridges were built in the 60ies and their expected remaining service life is around 30-40 years. None of the bearings has failed so far or shown any cracks that might potentially lead to failure in the near future. Several maintenance alternatives can be considered for the bearings, such as:

1. No extraordinary interventions,
2. Replacement of the bearings,
3. Auxiliary shoring.

The first option, i.e. no action is made (besides ordinary maintenance), does not lead to any additional costs. However, the risk of failure is not mitigated. If one or several bearings fail, the bridge would probably need to be closed down until replacement of the broken bearing(s). The closure might be longer than for a well-planned replacement and the related traffic consequences might be more severe. Furthermore, there would be a higher risk to injuries, should failure happen during traffic.

From a safety perspective, replacement is the most satisfying option. However, it has the highest costs. It is estimated that replacement of all bearings would cost around 74 million MSEK. To put this is context; this is more than the overall yearly budget assigned to smaller reinvestments for the entire bridge stock. Another issue with this option is that it would require approximately 3 years carrying out the job leading to significant traffic disturbances in the middle of the city.

The third option, auxiliary shoring, is a backup system to be built next to the existing bearing that would take over its function in the event of failure. This would significantly reduce the failure consequences as immediate bridge closure could be avoided. However, the estimated investment costs are relatively high.

The decision problem is again represented by the fundamental case (Figure 1), this time without considering the assessment option. The starting point is that the probability of failure corresponds to the code specified target reliability, or could be some order lower due to deterioration. Different values are tested e.g. between 10^{-6} and 10^{-3}. When considering consequences of failure, it should be noted that failure of a single bearing would not be catastrophic for the bridges in question (and the probability that several bearings fail simultaneously is very low). With the Bayesian approach, the rational choice is studied from an economic perspective considering various levels of failure probability and failure consequences. With reasonable assumptions the rational choice would be the first alternative, i.e. ’do nothing’, as it would lead to the lowest expected losses (based on the information that is currently available).

From a reliability perspective a fundamental question is that the first alternative could be accepted, i.e. a substandard failure probability. The practical decision could be to start a program where the bearings are shored/replaced systematically over a course of years.

5.3. Timing of reinvestments

A major challenge with reinvestment planning is that the maintenance activities suggested in condition assessments might be too expensive to carry out. Thus, it needs to be investigated if maintenance could be postponed and with a new decision to be made in the next inspection interval, based on the updated inspection reports.

The decision making process is illustrated through the double bridge of Kungsbron (Figure 3). Based on the inspection reports and an assessment made in 2020, the remaining service life of the structures is estimated to be around 20-25 years, while the waterproofing layer (which was changed in 1986) is expected to function approximately 6-10 years more. Suggested repairs include replacement of expansion joints, blasting and painting of shear keys and crossbeams, impregnation and coating of edge beams, supports and arches, and concrete repairs. Roughly, the following scenarios were considered to select the most appropriate maintenance strategy:

- Alt. 1: Replacement of the bridges in ~25 years, repairs and change of waterproofing asap (~30 MSEK)
- Alt. 2: Replacement of the bridge in ~25 years, change of waterproofing in ~10 years (~20 MSEK), repairs asap (~15 MSEK)
- Alt. 3. Replacement of the bridges in ~10 years, repairs asap (~15 MSEK)
- Alt. 4. Replacement asap (175-200 MSEK)

With a simplified net present value analysis, the first two options seems most reasonable from an economic perspective, i.e. to postpone the replacement of the bridge as much as possible. However, as illustrated in the first example, the costs of repairs is highly uncertain as it depends on the depth of the investigation and related planning. As more knowledge is obtained about the structural condition and other relevant circumstances, the uncertainty about the expected costs can be reduced.

To further study the decision problem at Kungsbron an influence diagram is made as shown in Figure 4.

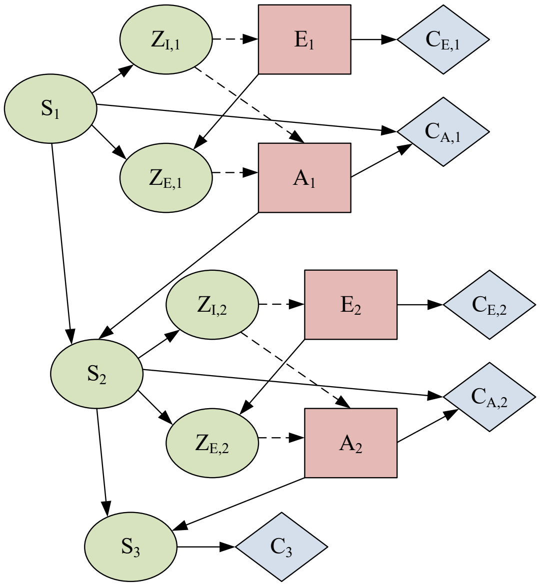

Figure 4: Influence diagram for the case study.

It considers the (unknown) condition state of the bridge (S_i = {'good', 'satisfactory', 'sufficient', 'insufficient'}) at time t_i, when a decision needs to be made. Actions (A_i = {'do nothing', 'renovate', 'replace'}) could be selected based the available (generally uncertain) inspection information ($Z_{I,i}$ = {'severely damaged', 'moderately damaged', 'slightly damaged', 'practically undamaged'}) or an additional assessment (E_i = {'no assessment', 'assessment'}) could be made. The outcome of the assessment ($Z_{E,i}$ = {'safe', 'unsafe', 'no result'}) is uncertain and depends on S_i. The assessment (if carried out) has a certain cost ($C_{E,i}$), such as the chosen action ($C_{A,i}$). The value of $C_{A,i}$ depends on S_i, i.e. the worse the condition state, the more the renovation of the bridge would cost.

In the study, t_1 represents the time at the latest major inspection and t_2 is the time at the next major inspection (6 years after the t_1). At t_2 new information about the structure will be obtained and a new planning period begins, i.e. a new decision has to be made. It should be noted that there are no costs associated to the inspections here, as they need to be made anyway. It is assumed that the bridge will be replaced after 24 years (four inspection periods) at t_3, if the bridge is not in good condition (i.e. not replaced earlier).

The inputs are defined based on available data where possible. For instance, the prior probabilities being in a given condition states are based on the overall distribution of damage condition classes from the bridge management system (BMS). The sensitivity/specificity of the assessment methods, efficiency of repairs, and the degradation of the condition state between two different time instances is based on expert judgement and expressed with CPTs between the respective nodes of the influence diagrams.

The result of the analysis indicates if further assessments should be carried out or not, based on the results of the inspections, and if a subsequent interventions should follow. Furthermore, it helps to investigate the possible consequences if the primary strategy is not followed.

6. CONCLUSIONS

Even though important decisions about bridge maintenance are made on a regular basis by public authorities, local and regional governments, formal decision analyses are rarely carried out.

The theoretical framework, i.e. Bayesian decision theory, for rational decision-making is available. However, appropriate formulation of the relevant decision problem and the related analysis model requires experience. Furthermore, the information to be used in relatively complex models might not be readily available (even if it exists). In overall, the amount of missing information is enormous and the stored data often contain errors (e.g. incorrect records in BMS). Thus, better information needs to be collected and analyzed. This requires resources and governance.

The promise of the Bayesian approach is that it results in decisions that are more informed and facilitate a more efficient and sustainable management of transport infrastructure. It also improves transparency, which is essential for public organizations. Thus, Bayesian decision analysis is a useful, if not necessary, approach for the decision-making process in the management of municipal bridges. Its use is strongly suggested, especially if the application of data-driven approaches becomes more widespread.

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