PROBABILITY AND DETERMINISM IN BRIDGE MANAGEMENT

VEROVATNOĆA I DETERMINIZAM U UPRAVLJANJU MOSTOVIMA

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1 INTRODUCTION: THE LIMITS OF CERTAINTY

A fundamental notion governing scientific research since antiquity was stated by Pierre-Simon, marquis de Laplace (1749 - 1827) in his *Theorie Analytique des Probabilités* as follows:

"Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective positions of the beings which compose it... nothing would be uncertain..." Probability therefore compensated for a lack of knowledge.

In his *Discours sur la Methode*, Rene Descartes (1596 - 1650) judged philosophy by the same standard of ultimate determinacy. "I shall say nothing of philosophy, except that it has been cultivated by the most excellent minds that ever lived over the centuries, and that there still remains to be found something that is not disputed, and consequently doubtful." Descartes found people's opinions diverse "not because some are more reasonable than others, but only because their thinking follows different routes and does not consider the same things". A rigorous deductive method would avoid errors and he developed it.

Opinions continued to diverge however. Blaise Pascal (1623 - 1662) found the Cartesian method "largely true", but "useless and uncertain", "mechanical", and "painful". He cautioned that "the heart has reasons that reason knows not". Gottfried Wilhelm Leibnitz (1646 - 1716) estimated that analytic geometry owed more to the genius of Descartes than to his method. Leonard Euler (1707 - 1783) distanced himself from absolute certainty by classifying it into perceptual, demonstrative and moral.

Whereas the assumptions of causality, determinacy and certainty governed the model of nature, they clearly did not apply to human transactions and games of chance. Beginning with Pascal and Pierre de Fermat (1601? - 1665), the list of illustrious mathematicians investigating problems with uncertain outcomes includes Christiaan Huygens (1629 - 1695), Jacob Bernoulli (1654 - 1705), Abraham de Moivre (1667 - 1754), Laplace, Thomas Bayes (1701 - 1761), Carl Friedrich Gauss (1777 - 1855), Andrey Markov (1856 - 1922), and Andrey Kolmogorov (1903 - 1987), among others. The many diverse and brilliant contributions formed the branch of mathematics loosely known as "probability". In lieu of definition, Bruno de Finetti (1906 - 1985) began his comprehensive text on the subject with the following sentence in capitals: "PROBABILITY DOES NOT EXIST."

The numerous definitions and interpretations of the "non-existent" probability converge into two main schools. *Objectivists* or *frequentists* equate the probability of a random occurrence with the relative frequency of outcomes over a large sample. A special case is the "propensity" of occurrence, given a single event. *Subjectivists*, including Bayes and de Finetti, treat probability as a "degree of belief", based on expert knowledge which begins with a prior probability distribution and results in a posterior one. As in the case of determinism, both methods benefit from the accrual of unbiased information. Rather than tending to certainty however, their results approach likelihoods of occurrence. For the purposes of economics, Von Neumann and Morgenstern developed a Theory of Games [1].

While mathematics was refining its treatment of uncertainty, thermodynamics and quantum mechanics observed phenomena with random and indeterminate outcomes untreatable by deterministic models. In nature, as in society, certainty and determinism had revealed their limit.

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2 UNCERTAINTIES IN ENGINEERING

The International Organisation of Standardization (ISO) has identified the following three types of uncertainty in engineering products and processes:

2.1 Randomness

Natural phenomena are random. Extreme events, such as atmospheric, seismic and hydraulic disturbances are inherently unstable. Their characteristics are indeterminate, as are live loads on structures. Material properties, such as yield, ultimate strength, fracture toughness, chemical resistance are not constants.

Randomness lends itself to stochastic analysis. *The random causes for bridge deterioration and accidents can be modelled statistically, given ample data* (Ph. 1). Since that is never the case, stochastic analysis must take into account the deterministic assessments based on phenomenological models.

2.2 Ignorance

All information is incomplete. Many of the quantitative parameters describing the “as built” and extant states of a structure cannot be fully known. Measurements of structural and material behaviour are often absent, inaccurate or irrelevant. Data are insufficient for an adequate stochastic analysis of, for example, vulnerabilities, potential hazards, material properties, amount and effect of repair and maintenance work, among others.

Deterministic analysis counteracts ignorance by two means. On one hand, there is perpetual incentive to quantify and formalize all assessments, eliminating “guesswork”. On the other, qualitative expert judgments and opinions contain all the admittedly vague wisdom accumulated over the professional experience. Since determinism is inevitable, so is the formalized treatment of its vagueness. Thus, randomness entails ignorance, which implies vagueness.

2.3 Vagueness

By definition, vagueness defies definition. Bertrand Russell stated that “everything in this world is vague to a degree we don't realise until we try to make it precise”. The most commonly used qualitative assessments are particularly susceptible. They include condition ratings, load ratings, remaining useful life, redundancy, safety, reliability, vulnerability, potential hazards, socio - economic constraints. Vaguely defined bridge and element conditions have been modelled by fuzzy sets, genetic algorithms and neural networks, producing ranges of possibilities with perceived likelihood.

McNeill and Freiberger [2] list various combinations of vagueness with other uncertainties resulting in fuzziness, including the following:

Nonspecificity: Ambiguity or lack of informativeness. A one-to-many relation between statement and possible meaning. Can be addressed by crisp set theory. This definition appears similar to ignorance.

Dissonance: Pure conflict. Treated as Bayesian probability of one statement being correct as opposed to another.

Confusion: Pure and potential conflict. There is conflict and the meaning of the data is unclear. Treated by 'possibility' theory.

Fuzziness: Vagueness, e.g. to what degree does a term apply. Treated by fuzzy set theory, which considers Bayesian probability (e.g. randomness) as a subset.

For the purposes of Bayesian probability, Thoft-Christensen and Baker [3] distinguish physical, statistical and model uncertainties. Melchers [4], recognizing that predecessor, organizes uncertainties into phenomenological, decision, modelling, prediction, physical, statistical and human (error and intervention). Any one of the latter seven groups can contain the former three in numerous combinations of somewhat fuzzy distinction.

Ang and De Leon [5] identify the following two types of uncertainty, which seem related to randomness and ignorance, respectively:

Aleatory: a non-deterministic property of natural randomness, modelled by random variables.

Epistemic: an inability to correctly represent a possibly deterministic reality, particularly significant in risk-informed decisions.

Photo 1-BY. Brooklyn and Manhattan Bridges across East River

3 UNCERTAINTIES IN BRIDGE MANAGEMENT

The engineering practice encounters all of the uncertainties described so far in combinations which do not lend themselves to easy separation. Thus it is critically important to model uncertainties according to their source and to recognize the limitations of the adopted methods. Several examples from the field of bridge management illustrate this point.

3.1 Present worth (PW) and life-cycle cost analysis (LCA)

The mathematically formalized modelling of uncertainty has been fundamental to economics at least since the publication of [1], as it has been to gambling since Pascal. Recent upheavals in the global financial markets have demonstrated that purely "ferquentist" models are unsuitable for discontinuities, instabilities, the ignorance associated with the phenomena, and the vagueness typical of human behaviour. In contrast, the highly uncertain discounting of future costs and benefits to an estimated present worth is modelled by the purely deterministic present worth analysis (PWA). Contrary to inflation rates, discount rates " i " are subjective and apply to specific investments, rather than to the overall economy. Hudson et al. [6] wrote:

"The discount rate selected by most agencies is a policy decision, but usually it is the difference between the interest rate for borrowing money and the inflation rate."

Hawk [7] defined three components of discount rates as follows:

$$i = (1 + cc) (1 + fr) (1 + pi) - 1 \quad (1)$$

where:

cc = "real" opportunity-cost of capital

fr = required premium for financial risk associated with the considered investments

pi = anticipated rate of price inflation

Neglecting the higher order terms is justified by the relatively small values involved and reduces Eq. (1) to the following:

$$i = cc + fr + pi \quad (2)$$

The present worth of an amount " a " occurring " N " years into the future is reduced by the factor $1/(1+i)^N$. If amounts " a " occur annually, their cumulative present worth over $N-1$ years from the present is obtained by Eq. (3).

$$a \sum_{n=0}^{N-1} 1/(1+i)^n = a (1+i) [1 - 1/(1+i)^N] \quad (3)$$

$$\lim_{N \rightarrow \infty} a \sum_{n=0}^{N-1} 1/(1+i)^n = a (1+i) \quad (4)$$

If " N " tends to infinity, the non-convergent infinite series ($a, a, a, a, \dots$) converges to a finite sum determined by " i ", as in Eq. (4). Fig. 1 [8] shows the curves defined by Eq. (4) within the realistic range of values of " i ". Their purpose is to illustrate the limited attention span of PWA. That span is quantified by the ratio of the finite and the infinite sums obtained in Eqs. (3) and (4), as shown in Eq. (5).

$$a (1+i) [1 - 1/(1+i)^N] / a (1+i) = [1 - 1/(1+i)^N] \quad (5)$$

For a given discount rate " i ", the period " N " can be selected such that the error " ϵ " due to ignoring the present worth of increments " a " beyond " N " becomes negligible, as shown in Eq. (6):

$$N = -\ln \epsilon / \ln (1+i) \quad (6)$$

Eq. (6) implies that, for a given ϵ , the relationship between N and the cumulative present worth is linear. Higher values of " i " correspond to a shorter financial "attention span". At $i = 3\%$, that span declines fast after 70 years and all but vanishes after 100. The American Association of State Highway and Transportation Officials (AASHTO) recommends a 75-year useful life for new bridges, however 40 years is not uncommon. Leeming [9] observed that "any costs beyond 30 or 40 years have a negligible influence on the outcome". He concluded:

"If maintenance of our bridge stock is to remain a fixed percentage of the total governmental expenditure on construction, then there is an argument for a zero discount rate in calculating the net present value of maintenance."

Figure 1. Cumulative present worth of infinite uniform series at different discount rates

In order to minimize the effect of discounting without completely eliminating it from life-cycle cost analysis, a low discount rate $i = 2\%$ is typically assumed. For infrastructure facilities requiring periodic maintenance and replacements (Ph. 2), De Gramo et al. [10] recommend "perpetuity", e.g. a uniform series of indefinitely running payments. In order to provide for annualized payments X , a principal P must be set aside at annual interest in % ($in \neq i$), such that $P in = X$. If the payments are not annual but arise at k periods, the relationship becomes:

$$X = P [(1 + in)^k - 1] \quad (7)$$

Where: P is the capitalized value of X .

On the feasibility of capitalized annual maintenance expenditures, Leeming [9] commented:

"Governments do not usually put aside sums of money for future expenditure, but maintain out of income from the taxes we pay... It would be necessary to invest at 8% compound [interest] in order to keep pace with the increase in the road construction price index [UK]."

Photo 2-BY. The Queensboro Bridge

3.2 Bridge design

The design of vehicular bridges in the United States has been regulated by AASHTO (originally AASHO) since 1928. In 1998 AASHTO superseded the earlier codes with the Load Resistance and Factor Design (LRFD) specifications [11]. The reasoning behind this innovation is clearly detailed in [3] and [12]. Traditional design, based on the deterministic allowable stress and ultimate strength methods, requires the supply of structural resistance " R " to exceed the demand of all loads " Q " by a "safety" factor or by an array of "load" factors. The central innovation of LRFD is to treat Q and R as normally distributed statistically independent random variables. The margin of safety is represented by the limit state function defined as $g(R, Q) = R - Q$. Failure occurs when $g(R, Q) < 0$. The overlap between the two distributions shown in Fig. 2 is the "reliability boundary".

In this notation, the probability p_f of failure can be expressed as follows:

$$p_f = 1 - F_u(\beta) \quad (8)$$

F_u is the standard normal cumulative distribution function and β is the reliability index defined as:

$$\beta = (\bar{R} - \bar{Q}) / (\sigma_R^2 + \sigma_Q^2)^{1/2} \quad (9)$$

R and Q are mean values, σ_R and σ_Q are standard deviations.

AASHTO LRFD (1998) was calibrated to a target reliability index $\beta = 3.5$, implying a probability of failure of 0.0233% for new structures. For older structures β is estimated closer to 2.5, corresponding to a failure probability of 0.621%. Both values are based on assumptions about the probability of failure of individual structural components in non-redundant systems. The reliability index β has been calibrated for existing satisfactory design loads. The result is a recommendation for strength and load factors. Attempts are made to optimize

Figure 2. Normally distributed supply of structural resistance R and demand of loads Q

β with respect to cost, however life-cycle cost estimates are highly speculative. A number of NCHRP publications report on the calibration of β for structural redundancy and extreme events.

3.3 Bridge condition

Bridge condition is subjected to all the uncertainties identified in Section 2. Since the collapse of the Silver Bridge over the Ohio River at Point Pleasant in 1967, a federal law mandates the biennial inspections of all vehicular bridges in the United States. The National Bridge Inventory (NBI) contains and annually updates condition evaluations of roughly 630,000 bridges. Rather than seek the perfect model of these evaluations and then attempt to gather the data needed for their reliable determination, bridge managers rely on a variety of more or less independent assessments. The set shown in Fig. 3 supports bridge management decisions at New York State Department of Transportation (NYS DOT) and is similar to those employed by other bridge owners and FHWA. A brief description of each follows.

Figure 3. Various concurrent systems of bridge condition assessment

3.3.1 Structural condition rating

Structural condition is subject to randomness and causality. Condition ratings are vague. They can be descriptive or prescriptive. The policy adopted by the Federal Highway Administration (FHWA) is to compare inspection findings to the presumed “as built” condition. Hence a descriptive condition rating says more about the state of maintenance than about the load carrying capacity. NYS DOT rates the condition of bridges and their elements on a scale of 7 (new) to 1 (failed). Inspections are visual.

The NYS database is component- and span-specific. A weighted average formula combines the worst ratings of 13 key structural components throughout a bridge to obtain an overall condition rating as shown in Eq. (10). Included are primary member, secondary member, deck, piers, seats, bearings, backwalls, wingwalls, abutments, curbs, wearing surface, sidewalks, joints. Yanev [8] recommended the inclusion of paint for steel structures.

$$R = \sum_{i=1}^{13} W_i R_i / \sum_{i=1}^{13} W_i \quad (10)$$

R is the overall bridge condition rating; R_i is the minimum condition rating of element “ i ” observed on the bridge during the inspection (not necessarily in the same span), W_i are the element weights of the NYS DOT bridge condition formula, ranging from 10 for primary member to 1 for curb.

The alternative is the prescriptive approach, favored for example by the American Railroad Engineering and Maintenance Association (AREMA). Conditions are described by the amount and urgency of the remedial work, recommended by the inspecting engineer (Ph. 3). It is assumed that all recommended actions will be executed, hence the method is suited for a network in superior condition. The rating-descriptive method must be supplemented by a prescriptive evaluation, such as “potential hazards” for prompt corrective actions.

A 4- and 5- level rating system for commonly recognized (CoRe) structural elements was developed for the use of the FHWA Bridge Management System (BMS) PONTIS. In 2014 AASHTO proposed and FHWA introduced the Bridge Element rating protocol. Elements are quantified in 4 “condition states”. The vagueness of

Photo 3-BY. Suspenders in Manhattan Bridge

the original 10-level qualitative NBI ratings may be reduced, however the quantities rated in the 4 “condition states” are susceptible to randomness and ignorance. The number of bridges with comparable quantities would increase, requiring more detailed evaluations in order to prioritize their needs qualitatively.

3.3.2 Load rating

Load rating is obtained through calculations based on the design of the structure described in Section 3.2. Significant departures from the as-built condition require new ratings. NBI recognizes inventory and operating ratings, the former reflecting the regularly presumed structural capacity, the latter – its extreme capacity. In a well-functioning system, the qualitative condition ratings should inform about visible deterioration before the quantitative load ratings determine that the structure is functionally deficient.

3.3.3 Potential hazards

NYS DOT designates conditions perceived as potential hazards as “flags”. Flags can be structural or safety (where the former always implies the latter, but not vice versa). Their urgency can vary from requiring prompt interim action (PIA) within 24 hours to low priority (allowing for monitoring until the next regular inspection). Yanev [8] reported a correlation between flag incidence and condition ratings of the most frequently flagged bridge elements, such as decks, primary members, railings, expansion joints and so on. Hazards related to traffic accidents and climatic changes occur at a relatively steady rate, whereas those caused by structural conditions increase predictably with deterioration.

3.3.4 Vulnerability (NYS DOT)

This rating anticipates hazards, rather than react to them. NYS DOT has developed procedures for addressing vulnerabilities related to the following causes:

hydraulic, seismic, collision, overload, steel details, concrete details, sabotage.

Vulnerability is determined first through a review of the inventory, then confirmed by field inspections. The rating prioritizes the pre- and post event needs of the potentially vulnerable structures. Procedures for mitigating the conditions (for example by capital rehabilitation) and for responding to them in emergency mode are established.

3.3.5 Serviceability (NBI)

Serviceability is said to be appraised, rather than evaluated, however the federal rating is once again from 9 to 0. The quality of service is influenced by structural conditions, but depends also on factors, such as importance, obsolescence, and poor geometric alignment.

3.3.6 Sufficiency (NBI)

Sufficiency is an overall rating combining structural (55%) and serviceability (30%) factors, weighted by importance (15%). Albeit vague, this rating helpfully illustrated the state of the national vehicular bridge network. The 4 Element Level “condition states” cannot generate it and bridge managers are hard-pressed to find a substitute.

3.3.7 Diagnostics

Diagnostics is a rapidly developing field of condition assessment. It utilizes the non-destructive testing (NDT) and evaluation (NDE) techniques which are becoming commercially available for the first time. The developments follow three partly independent paths. Scientific research focuses on measurable events, commercial production develops marketable technologies, bridge owners must manage the life-cycle of their assets optimally. The resulting 3-dimensional space shown in Fig. 4 [8] defines the domain of structural health monitoring.

Figure 4. Bridge health monitoring by NDT and NDE

4 DETERMINISM AND PROBABILITY OF THE CONDITION ASSESSMENTS

The described assessments are grouped in Tab. 1 according to their contribution to decision support on the project and network levels in the short and long term. Rigorous overall optimization is not possible, however deterministic and probabilistic methods are combined towards an actionable outcome, either by limited optimization, vaguely or deterministically.

According to Tab. 1, short term and project level decisions are usually based on deterministic assessments, whereas long term and network level ones tend to employ probabilistic techniques. The relationship between deterministic and probabilistic methods in the most important assessments is briefly reviewed.

4.1 Bridge condition (rating) deterioration

The condition ratings described in the preceding Section should enable the modeling of bridge condition deterioration, and hence, provide estimates of infrastructure life-cycle needs. While the needs must address actual conditions however, the estimates are often based on condition ratings.

Condition models are phenomenological. They take into account material properties, design, construction and maintenance practices, service demands, climate, and so on. Consequently, they may vary from one project to another. If a reliable phenomenological model of condition deterioration existed, condition ratings would

not be needed every two years for all bridges. A current proposal to relax the mandate for biennial inspections makes that argument, however the primary motive is economy.

Condition rating models are indispensable on the network level. The abundant data lends itself to stochastic methods of evaluation. The FHWA bridge management program PONTIS relied on the Markov chain model, but is replacing it with a Weibull distribution one, in part because of the former inability to model past history. Accumulation of new data may contribute to the decision.

There has been considerable debate whether the likeliest deterioration path is convex, concave or "S"-shaped (and if so, type Fig. 5-a or -b). Yanev [8] recommended a distinction between the project and network levels, as well as between the phenomenological models of condition and the stochastic models of condition rating. For condition ratings on a network level, the shape of the curve depends on the distribution of the data points along the two axes, as Fig. 5 demonstrates. For a large bridge network, a near-normal distribution is likely along both axes (X, representing time and Y, representing condition rating). Hence, the straight line of Fig. 5-c may be sufficiently accurate given other uncertainties.

For a reality check, the New York City bridge condition and sufficiency ratings for a typical year are plotted with respect to the structural age in Fig. 6-a and -b. The Bridge Element "condition states" cannot generate a bridge sufficiency rating. The need for it becomes immediately obvious. A stochastic model of the general

Table 1. Deterministic and probabilistic assessments on the project and network levels

Level	Deterministic by expert opinion	Probabilistic by various methods
Project	Condition rating	Condition (phenomenological)
	Load rating for AASHTO design loads	Load rating using probabilistically calibrated factors
	Potential hazards prioritized by urgency	
	Vulnerability prioritized by deterministic decision tree	
	Diagnostics: field measurement	
	Serviceability	
	Sufficiency	
	Needs: short term	
Network	Condition rating Worst case, Linear regression Other	Condition rating deterioration Markov chains, Normal, Weibull distribution, Monte Carlo simulation, Other
	Load rating based on the worst condition on a traffic corridor	Load rating based on design criteria
	Potential hazards Correlation with condition rating	Potential hazards Risk = likelihood x penalty
	Vulnerability	Vulnerability using probabilistic forecasts of extreme events
		Diagnostics: stochastic analysis
	Serviceability	Serviceability using economic and deterioration forecasts
		Sufficiency using economic and deterioration forecasts
	Needs: short term, emergency, Present worth	Needs: life-cycle structural conditions

deterioration pattern would reduce the data scatter of Fig. 6 to a near - straight line, as in Fig. 5-c, obtaining a useful life of approximately 85 years. That would correspond to roughly US \$300 million in annual rehabilitation expenditures. The worst conditions in both graphs however, jointly indicate a useful life of 30 years. During the last two decades annual expenditures have exceeded US \$500 million, corroborating that result. Many factors contribute to the data scatter. Rehabilitations are

not always reflected in the database by changing the age of the bridge. Hundred-year old bridges can be rated as new after a billion-dollar rehabilitation (Ph. 4). Bridges in average condition receive numerous undocumented repairs. Thus, stochastically obtained forecasts invariably underestimate the needs. The worst ratings are both least compromised statistically and most urgent deterministically.

Figure 5. Cumulative distribution curves corresponding to normal distribution along one or both axes

Figure 6. Condition (a) and sufficiency (b) ratings for New York City bridges over time

Photo 4-BY. Old and new suspenders

4.2 Load rating

The LRFD specifications assume a normal or log-normal probability function resulting in a linear failure function. When the failure function is not linear, the reliability index β can be estimated by Monte-Carlo Simulation (MCS) or by the iterative linearization procedures known as FORM (First Order Reliability Method) or SORM (Second Order Reliability Method), described by Ang and Tang [13]. The LRFD load rating model is appropriately conservative, but not always realistic. AASHTO recognized this and has recently approved load testing as an additional method of establishing the capacity and integrity of vehicular bridges. On railroad bridges, where loads are more predictable, visual assessments and load ratings can be more conclusive.

4.3 Potential hazards

Since network level need estimates are based on condition ratings, rather than on conditions, the costs of emergencies and hazard mitigation are not directly included. Hazard is associated with risk, which is defined as the product of likelihood of occurrence and the penalty. Some sources multiply by an additional factor for the likelihood of timely discovery. Since the penalty is a perception, it is assigned deterministically. The likelihood of occurrence is treated as a random variable, but it too can be assigned deterministically, pending the accrual of sufficient data.

Although potential hazards are phenomenologically correlated with conditions, the correlation with condition ratings, reported in [8] is not the same. Dominant is the correlation with actual events. After a fatal bridge-related accident in New York City in 1989, reports of potential hazards escalated from 800 to 2,000 / year.

4.4 Diagnostics

The 3-dimensional space of Fig. 4 might be interpreted as an indication that academic research, commercial production and bridge ownership have divergent objectives. More constructive would be the Cartesian view that they operate under a different balance between determinism and uncertainty. Bridge owners operate in a deterministic domain where actions must be taken and implemented, available monies must be committed and accounted for and, ultimately, safe traffic must be maximized. Their ideal bridge that does not need diagnostics at all. Their preferred methods are deterministic. Manufacturers are supplying a product and depend on the demand. In their view every bridge should be instrumented. They are governed by economic forecasts. Depending on their subject, researchers develop phenomenological or random models.

4.5 Serviceability

This is ultimately, a deterministic rating, based on qualitative assessments. In a safe system, the network level assessments must be the more conservative ones. In general, and in New York City, bridge life-cycles are governed by serviceability deficiencies, rather than by structural failures, as Fig. 6 shows. Although safe service is a rigid constraint, its maintenance cannot be rigorously optimized because the priorities and their quantification are heterogeneous, as illustrated in Fig. 7. User costs due to traffic closures are a product of time delays, average time cost and number of users. The losses due to accidents are subjective. Life-cycle maintenance costs and benefits are not directly quantifiable. In contrast, the clarity of the process and the deliverable product of construction make it the preferred option for bridge improvement in the short term. FHWA has advanced the alternative of "Bridge Preservation" on grounds of serviceability and life-cycle benefits.

Figure 7. Bilateral and multi-layered models of infrastructure management

5 CONCLUSION

As all of society, engineering, and management in particular increasingly modify deterministic methods by allowing for uncertainty. Throughout most of history, the infrastructure was governed by supply and managed deterministically, as in the bilateral model of Fig. 7 – a. In contrast, democracies are governed by demand in a multi-layered interaction of leadership, management and the electorate, as in Fig. 7 – b. The major interested groups operate under diverse priorities.

The different explicit or implicit models borrow selectively from the method of Descartes and the view of Pascal. Users seek to maximize traffic while minimizing the taxation for its maintenance. The private sector is constrained by supply / demand and maximizes short-term return on investments. The political community is constrained by 4-year election terms. Bridge managers (tolled facilities excepted) rely on public funds which fall short of the estimated needs for maintaining the assets in their highest “ratings” or best “condition states”. As the probabilistic treatments of uncertainty gain wider application, it is increasingly necessary to clarify the range of their validity in these heterogeneous overlapping domains. The following observations emerge:

- Modelling random processes by normal and Weibull distributions is deterministic in its own way. Not all of the variables are independent, as their models imply. For example, bridge conditions, condition ratings and potential hazards are vaguely, but not randomly correlated.

- Future costs / benefits are discounted deterministically, imposing a limited “attention span” on life-cycle planning. In the meanwhile, the uncertainty of the market is taken as proof that the physical infrastructure cannot be managed deterministically. The “reverse” influence of the infrastructure in the market is taken into account deterministically, only when its condition approaches failure. In 2019 AASHTO has rated the overall condition of the United State infrastructure as D+ (from A to D). This purely deterministic qualitative assessment has become a main argument in a Congress debate on funding allocation.

- Quantitative statistical methods are better suited for modelling future expectations and strategic guidelines, than for supporting immediate and tactical decisions. Poor reasoning cannot be replaced by a mathematical model but by correct reasoning.

- Determinism and uncertainty are not mutually exclusive alternatives, but complementary at every step of engineering in general, and the bridge management process in particular. Appropriately, the “reliability based” AASHTO LRFD bridge design specifications ultimately make deterministic choices. The transition of NBI from

10-level qualitative ratings to 4-level “condition states” illustrates the same point. The always inevitable uncertainty, consisting of randomness, ignorance, and vagueness must be treated with a well-balanced mix of probability and determinism.

6 LITERATURE

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ABSTRACT

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Probabilistic models and methods are replacing deterministic ones in many areas of theoretical and applied sciences. To keep up with this development, the engineering profession is revising design specifications and updating forecasting techniques, whereas economics is adopting increasingly complex statistical models. At the intersection between the two fields, the management of the infrastructure must use effectively all new tools without abandoning established and reliable existing practices. The gathering and evaluation of meaningful data are critical to decisions with profound consequences in terms of monetary cost and quality of life. The article presents the author's observations drawn from his bridge management experience in New York City over 30 years.

Keywords: bridge, deterioration, determinism, management, probability, uncertainty

Research area: infrastructure management

APSTRAKT

VEROVATNOĆA I DETERMINIZAM U UPRAVLJANJU MOSTOVIMA

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U brojnim oblastima teorije i primenjene nauke, probablistički modeli i metode predstavljaju zamenu za determinističke. Da bi održala korak sa tom činjenicom, inženjerska struka trenutno revidira projektantske uslove/specifikacije i ažurira tehnike predviđanja, dok ekonomska struka istovremeno usvaja sve složenije statističke modele. Između ove dve sučeljene oblasti, od menadžmenta (upravljača) infrastrukture se očekuje da efikasno primenjuje sve novije alate, a da se istovremeno ne odrekne uhodanih i pouzdanih metoda koje danas postoje. Prikupljanje i procenjivanje najvažnijih podataka predstavlja ključni faktor u odlučivanju, sa dalekosežnim posledicama u smislu novčanih troškova i kvaliteta života. U ovom radu predstavljeni su autorovi zaključci do kojih je došao na osnovu iskustava u oblasti upravljanja mostovima u gradu Njujorku.

Ključne reči: upravljanje infrastrukturom, most, određivanje dotrajalosti, menadžment, verovatnoća, neizvesnost