Expert judgment in life-cycle degradation and maintenance modelling for steel bridges

A. Kosgodagan, O. Morales-Napoles, J. Maljaars, W. Courage

Phd Student

TNO - École des Mines de Nantes

Outline

- Introduction
- Modelling degradation for a network of steel bridges
- Elicitation
- Results and analysis
- Conclusion & future work

- Introduction
- Modelling degradation for a network of steel bridges
- Elicitation
- Results and analysis
- Conclusion & future work

Whom is this presentation for ?

- Structured expert judgment practitioners
  Application of Cooke's classical method

- Civil engineers
  How a large-scale network of deteriorating assets can be modelled

Objectives and problem statement

- Represent a network of motorway steel bridges subject to fatigue deterioration
- Use and propagate information when available
- Make use of scarce data to quantify the model

- Introduction
- Modelling degradation for a network of steel bridges
- Elicitation
- Results and analysis
- Conclusion & future work

Deterioration model

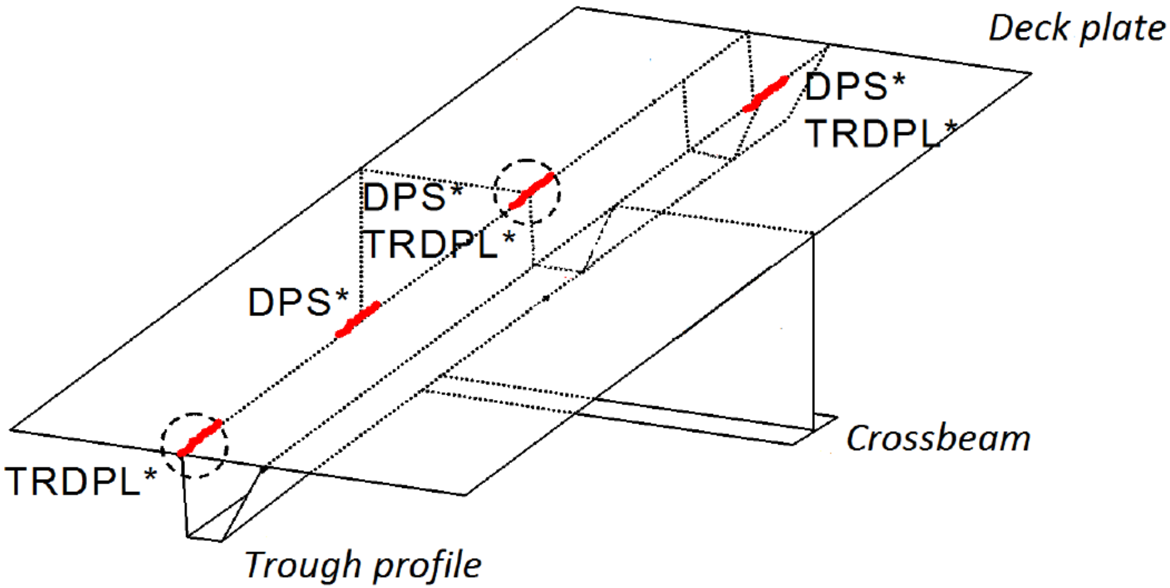
- Markov process to model deterioration of a single bridge
  - Stochastic process-based approach
  - Widely used as a suitable process for civil engineering infrastructures (Mirzaei *et al.* 2014)

Bayesian network

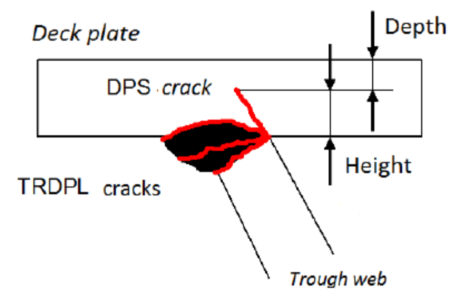
- Use a dynamic Bayesian network to build up the network
  - Handle randomness → physical quantities impacting degradation can behave randomly
  - Handle probabilistic dependencies → account for dependencies/correlations between these quantities
  - Ability to represent high-dimensional probabilistic modelling
  - Dynamically propagate evidence → update forecasts locally and globally

Bridge cracking

Consider cracks **only in the deck plate** (referred to as *DPS* in Figure below*)*



* Cross-section trough/deck plate
TRDPL = Trough to deck plate
DPS = Deck plate



Bridge classes

- Two classes of orthotropic steel bridges are considered
  - Moveable
  - Fixed

→ Reduces the network quantification complexity
→ Build a network composed of the above two classes

Degradation state space Ω

State	Description
1	Almost no damage/cracks are present. A new bridge is assumed to start from this state.
2	At least one crack in the deck plate that can be detected ultrasonically [30mm, 100mm]
3	Multiple cracks are present [30mm, 500mm]; at least one crack requires repair
4	Multiple significant fatigue cracks with at least one >500mm in the deck plate that needs urgent repair; this condition does not mean a collapse but a threat to safety and/or functionality.

Markov chain

- Discrete distributions and domains Ω → Each bridge transit between various discrete conditions
- Each bridge condition modelled by a time-homogeneous Markov chain;$(X_t^m)_{\substack{t\geq 0\\ m\geq 0}}: p_{ij} =$
  $P(X_t = j \mid X_{t-1} = i, X_{t-2} = i_{n-2}, \dots, X_0 = i_0) = P(X_t = j | X_{t-1} = i)$
- Pure degradation → either remain in the same state or move to the next worse state but cannot move backwards to better states

$$\boldsymbol{P} = \begin{pmatrix} 1-p_{12} & p_{12} & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & 0 & 1-p_{n-1n} & p_{n-1n} \\ 0 & \cdots & \cdots & 0 & 1 \end{pmatrix}$$

- 1 time step = 1 year; $t_s - t_{s-1}$ = 1 year $(t_1, \dots, t_{s-1}, t_s, \dots \in \mathbb{N})$
- Discrete process γ_t for the global health of the system

Markov chains

Assume endogenous stochastic processes impacting degradation

- Traffic density (T_t) with 3 states (High, Medium, Low)
- Loading (L_t) with 3 states (Heavy, Normal, Light)

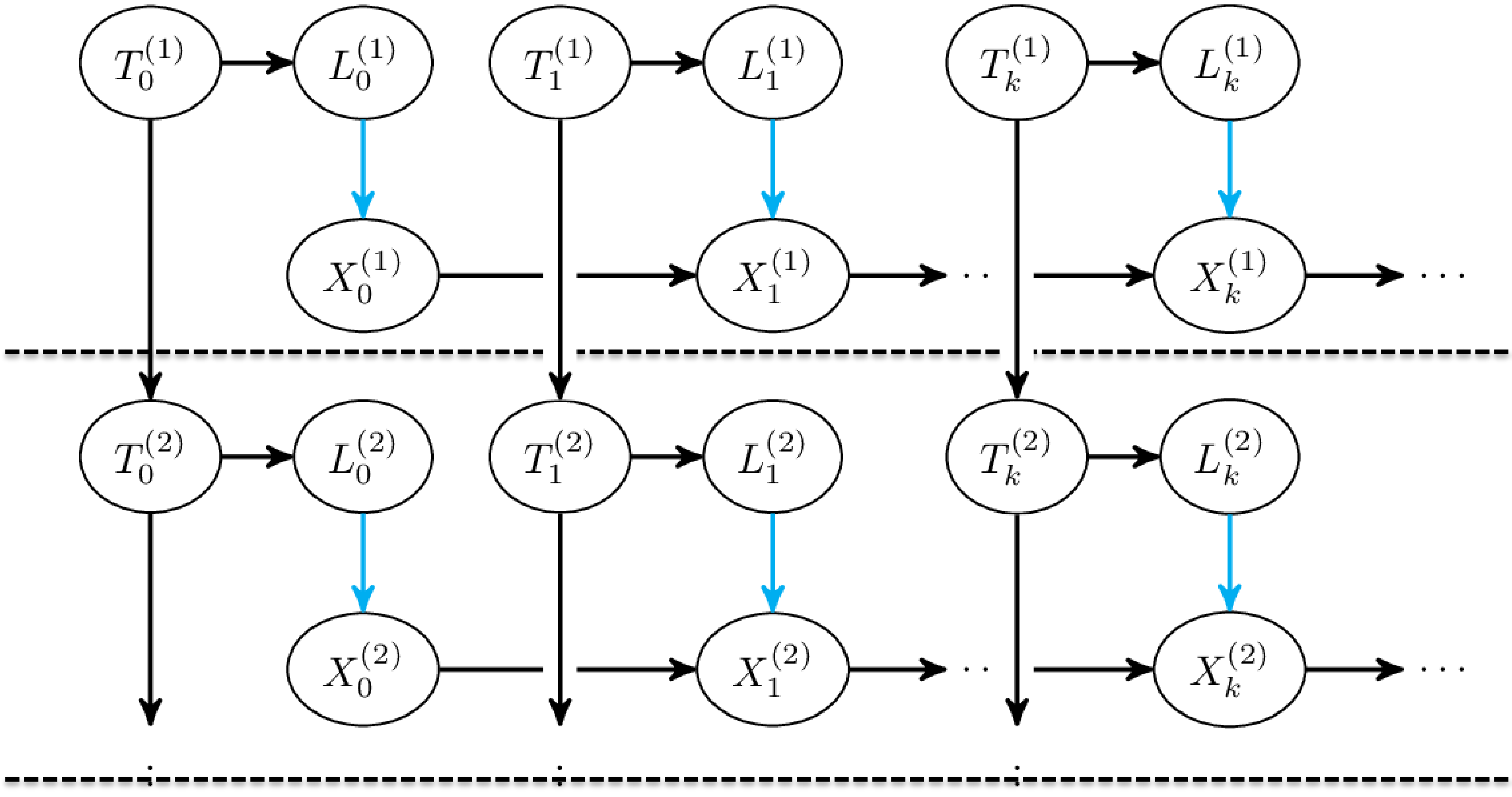
→ Markov transition also depend on these covariates

- **Quantify Markov transition probabilities for each (class of) bridge through structured expert judgment →** p_{ij}

TNO innovation for life

MINES Nantes

Bayesian network



- Introduction
- Modelling degradation for a network of steel bridges
- Elicitation
- Results and analysis
- Conclusion & future work

Elicitation

- 3 experts

- 24 variables of interest

  3 transitions x 2 loading states x 2 classes of bridges
  +
  3 conditional probabilities x 2 loading states x 2 classes of bridges

- 12 seed (or calibration) variables
  - refer to crack condition data on a steel bridge located in the Netherlands

Variable of interest (example)

“ We are looking at the motorway steel bridges at the time of their construction. Could you provide with the 5th, 50th and 95th quantiles of your uncertainty distribution about the expected years that it takes for the bridge considered to transit between state 1 and state 2? ”

5th :___________ 50th :___________ 95th :___________

Variables of interest

1. Elicit the uncertainty distribution over the expected duration for each class of bridge
2. Assess lacking conditional probabilities in the BN (with respect to loading)

Variable	Description	Variable	Description
Q1	Expected duration (in years) to transition between the following condition states	Q2	Probability that bridges transitioning to their next worse state conditional on a given load and state at previous time step
V1	1 → 2	V13	$P(X_t = 2 \mid X_{t-1} = 1, L_t = \text{Normal})$
V2	2 → 3	V14	$P(X_t = 3 \mid X_{t-1} = 2, L_t = \text{Normal})$
V3	3 → 4	V15	$P(X_t = 4 \mid X_{t-1} = 3, L_t = \text{Normal})$
…		…	

A total of **24** variables to elicit

Seed variable (example)

“ A crack was detected by the **Crack-PEC** technique to be a certain length **32 years** after construction**,** what would be its **length (in mm) the following year** using the same measurement technique**?**
”

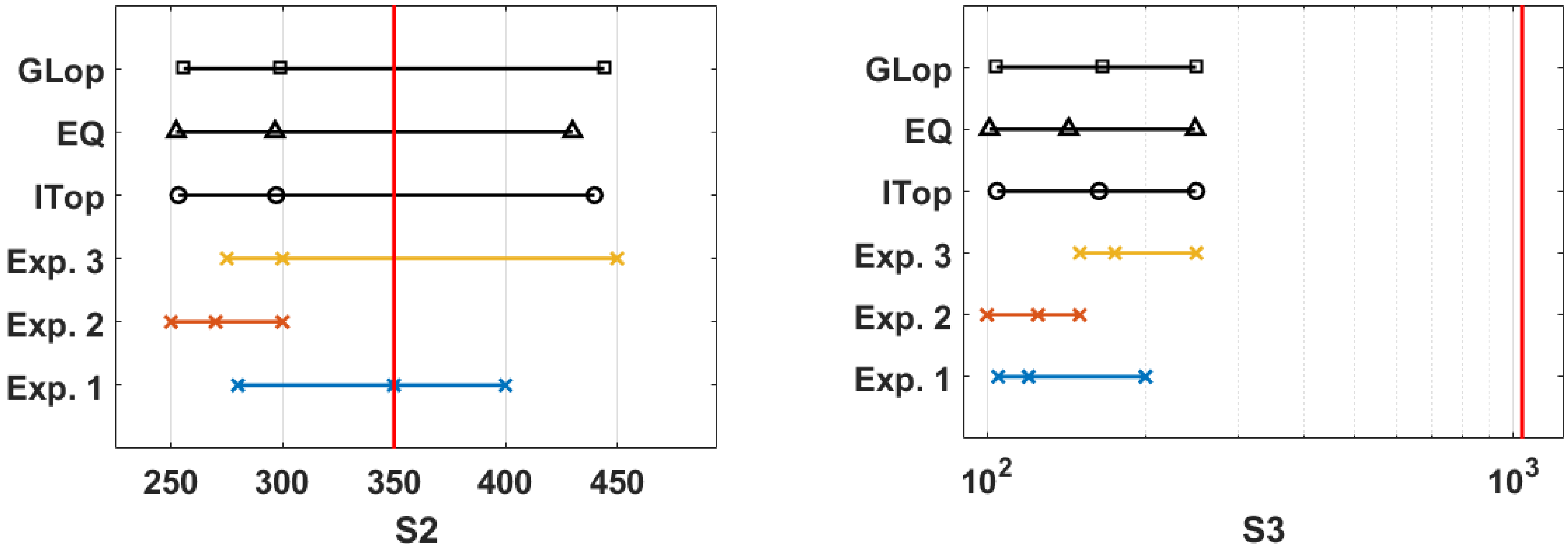
5th :___________ 50th :___________ 95th :___________

Seed variables

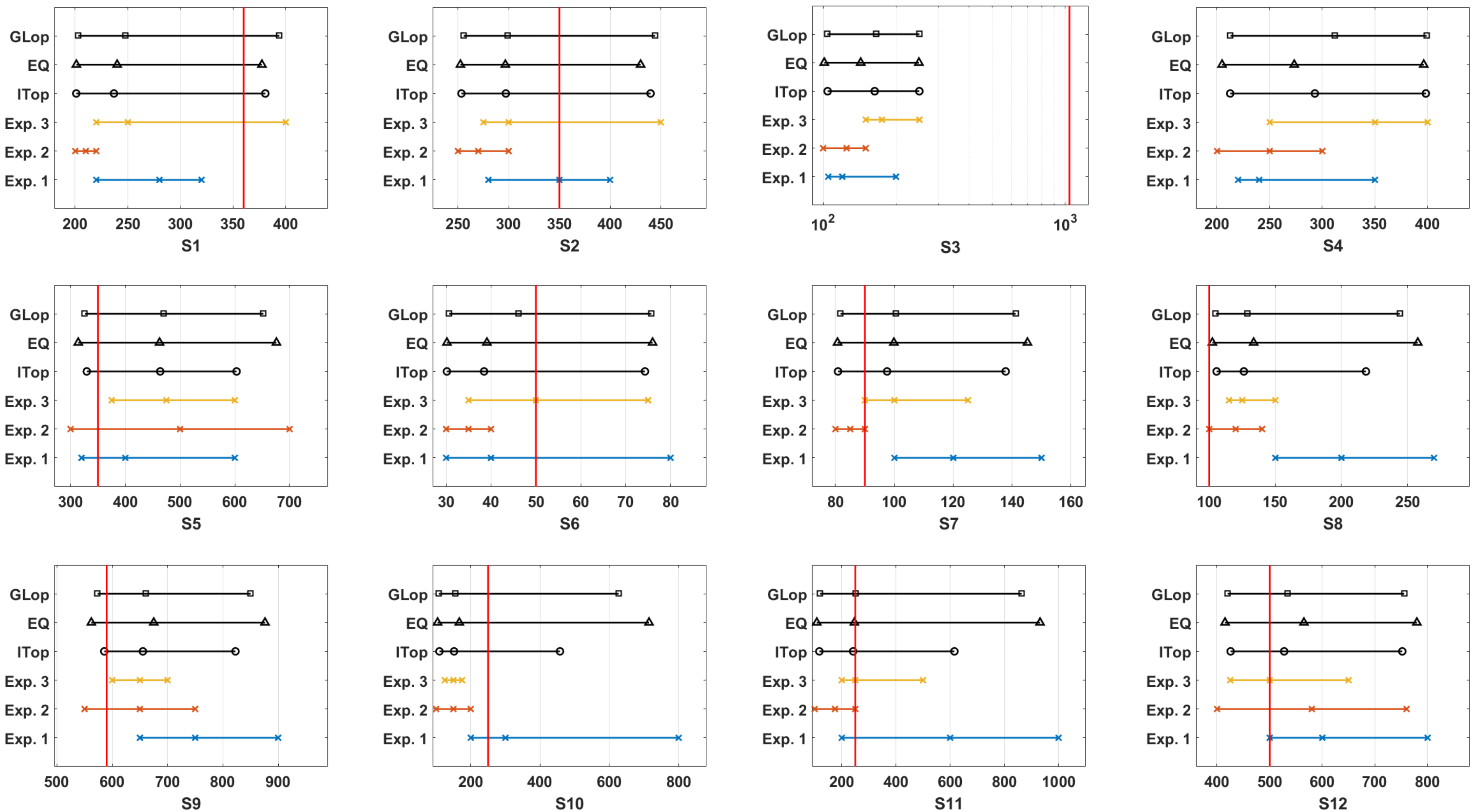
Item ID	Measurement technique	Location of crack	Year 1st measurement	Crack Length (mm)	Year 2nd measurement	Crack Length (mm)
S1	Crack-PEC	DPS	2008	200	2009	**360**
S2	Crack-PEC	DPS	2008	250	2009	**350**
S3	Crack-PEC	DPS	2006	100	2009	**1040**
S4	Crack-PEC	DPS	2006	200	2009	**500**
S5	Crack-PEC	DPS	2006	300	2009	**350**
S6	UT	DPS	2009	30	2010	**50**
S7	UT	DPS	2009	80	2010	**90**
S8	UT	DPS	2009	100	2010	**100**
S9	UT	DPS	2009	550	2010	**590**
S10	VO	TRDPL	2008	100	2009	**250**
S11	VO	TRDPL	2008	100	2010	**250**
S12	Crack-PEC	DPS	2010	400	2011	**500**

- Introduction
- Modelling degradation for a network of steel bridges
- Elicitation
- **Results and analysis**
- Conclusion & future work

Seed Variables



Seed Variables



SEJ output

Expert ID	Calibration	Relative Information		Normalized weight without DM		Normalized weight with DM		
		Total	Realization	Global	Equal	Global	Equal	Item
1	8.3E-4	1.77	1.09	0.28	1/3	3.6E-3	4.3E-3	2.4E-3
2	1.0E-3	2.42	0.35	0.12	1/3	1.4E-3	1.8E-3	1.0E-3
3	2.4E-3	0.80	0.80	0.60	1/3	7.5E-3	9.0E-2	5.2E-3
Equal	0.85	0.41	0.24				0.98	
Global	0.85	0.19	0.30			0.99		
Item	0.85	1.02	0.43					0.99

TNO innovation for life

MINES Nantes

Main observations

- None of them exceeds the calibration cut-off level (0.05)

- All DMs have the same calibration score (0.85)

→ Significantly larger than individual calibrations

- Expert 3 gets the biggest weight (0.6) for the GL DM while expert 1 (0.28) and 2 (0.12) contributions are low

- When accounting for the DM, for all three schemes the DM gets almost the whole weight (0.99)

Conclusion and future work

- Applicable to different assets
- In scarce-data scenario on inspections, Cooke's method appears attractive
- Allow for maintenance with Markov transition matrix having no zeros on upper and lower triangular part

References

Cooke (1991). Experts in uncertainty*, Oxford University Press*.

FHWA. (1995). Recording and coding guide for the structure inventory and appraisal of the nation's bridges. *Report No. FHWA-PD-96-001*. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C..

Kallen (2007). Markov Processes For Maintenance Optimization for Civil Infrastructure In The Netherlands, *PhD Thesis.*

Madanat, Mishalani, Hashim, Ibrahim (1995). Estimation of Infrastructure transition probabilities from condition rating data, *Journal of Infrastructure Systems.*

Morcous (2006). Performance prediction of bridge deck systems using Markov chains*, Journal of Performance of Constructed Facilities.*

A. Kosgodagan, O. Morales-Napoles, J. Maljaars, W. Courage (2016). **Expert judgment in life-cycle degradation and maintenance modelling for steel bridges**, *Proceedings of The Fifth International Symposium on Life -Cycle Civil Engineering, IALCCE2016.*