TRUSS ITN

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TRUSS
Training in Reducing Uncertainty in Structural Safety

Structural health monitoring of bridges: a Bayesian network approach

Matteo Vagnoli, Rasa Remenyte-Prescott, John Andrews

The University of Nottingham

UNITED KINGDOM · CHINA · MALAYSIA

Outline

- Where we are today
- Bridge condition monitoring and damage detection using Bayesian Belief Network
- A case study

Bridge failures

1 year old!!!

17 February 2016,
Gudbrandsdalslågen (Norway)

Bridge failures

2 August 2016,
Leicestershire (UK)

Bridge failures

19 August 2016,
Pitrufquén (Chile)

Bridge failures

7 September 2016,
Dimbokro (Ivory Coast)

Bridge failures

28 October 2016, Milan (Italy)

9 March 2017, Ancona (Italy)

18 April 2017, Fossano, Cuneo (Italy)

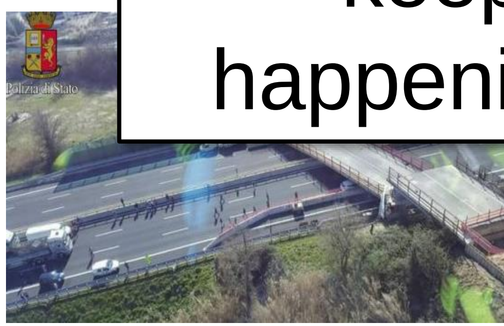
Bridge failures

6 February 2018, Brasilia (Brazil)

Bridge failures

14 August 2018, Genoa (Italy)

Why does this keep happening?



Bridge condition monitoring today

Bridge condition assessment and damage detection strategies are usually carried out by subjective visual inspection, at intervals of one to six years.

More than 35% of the over 1 million bridges across Europe are over 100 years old.

European Commission, EU transport in figures, statistical pocketbook, 2012.

Deterioration processes may lead to a lower safety level and, potentially, to catastrophic events.

How can we change the way we approach this problem?

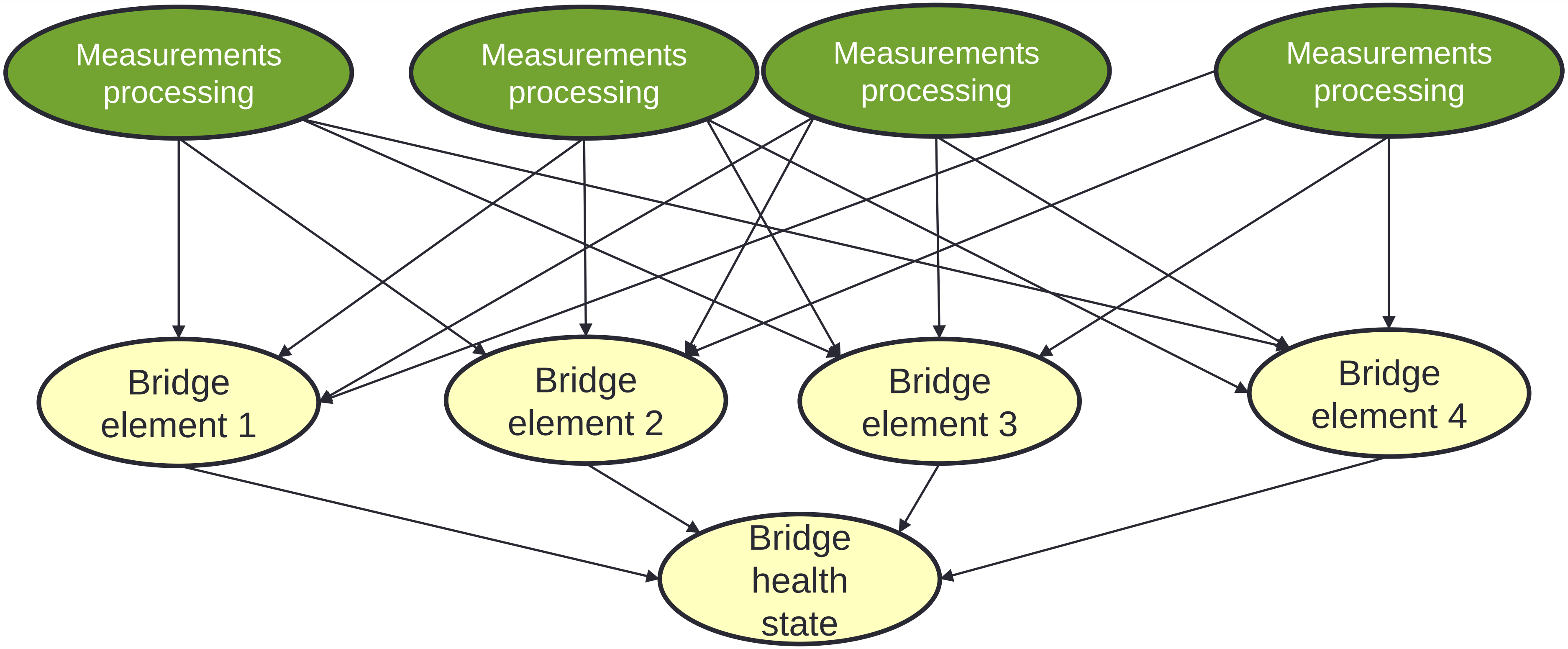
Bridge condition monitoring tomorrow

Real-time measurement system

- ✓ Remote structural health monitoring and damage detection
- ✓ Overcoming of the visual inspection limitations
- ✓ Assessment of the health state of the whole bridge by analysing the bridge behaviour
- ✓ Maintenance can be scheduled based on the real health state of the bridge

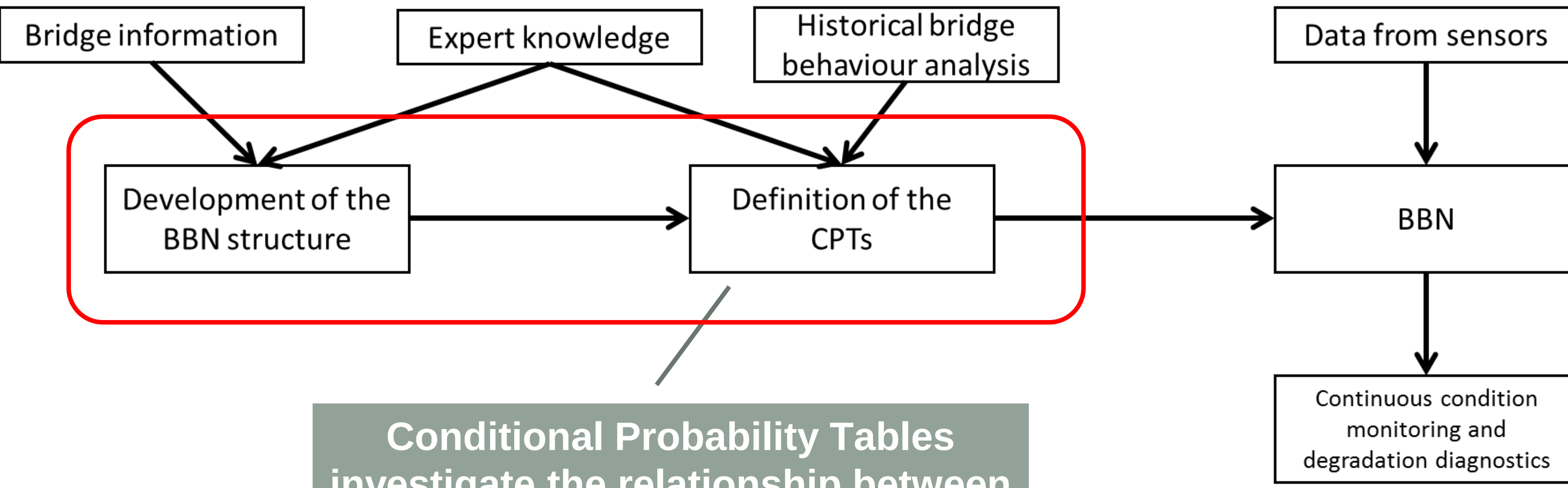
Bayesian Belief Network approach

To continuously monitor and the condition of the bridge and diagnose its unexpected behaviour by assessing the health state of each bridge element and the whole bridge simultaneously, without requiring complex and time-consuming process of analysis.



Bayesian Belief Network definition and use

BBN allows to merge expert knowledge of the engineers, with the analysis of the measurement of the bridge behaviour



Conditional Probability Tables investigate the relationship between different bridge elements

A new method for defining Conditional Probability Tables (CPTs)

The CPTs of the BBN are defined by merging the expert knowledge with the analysis of the bridge behaviour during different health states of the bridge

$$P(A) = \alpha P(A_{bridge}) + (1-\alpha) P(A_{exp})$$

Probability of a that a bridge element is degraded

Probability assessed by analyzing a database of bridge behavior

Probability assessed by interviewing bridge experts using what-if scenarios

A new method for defining Conditional Probability Tables (CPTs)

Alpha is a weighting factor defined through a sensitivity analysis

$$P(A) = \alpha P(A_{bridge}) + (1-\alpha) P(A_{exp})$$

Probability of a that a bridge element is degraded

Probability assessed by analyzing a database of bridge behavior

Probability assessed by interviewing bridge experts using what-if scenarios

The Conditional Probability Tables (CPTs)

Expert knowledge elicitation process

Bridge engineers and professors of structural engineering are interviewed by the means of a online surveys, in order to assess the influence of a bridge element on the health state of the other bridge elements.

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Linguistic probability scale	Description
Very Unlikely (VU)	It is highly unlikely that influences occur
Unlikely (U)	It is unlikely but possible that influences occur
Even Chance (EC)	The occurrence likelihood of possible influences is even chance
Likely (L)	It is likely that influences occur
Very Likely (VL)	It is highly likely that influences occur

Fuzzy Analytic Hierarchy process

CPTs value

Expert judgments

The Conditional Probability Tables (CPTs)

Historical bridge behaviour analysis

The influences between different elements of the bridge are assessed by reconstructing the probability density function of a Damage Index (DI), that assesses the health state of the bridge elements when the degraded element of the bridge is known.

The Conditional Probability Tables (CPTs)

Historical bridge behaviour analysis

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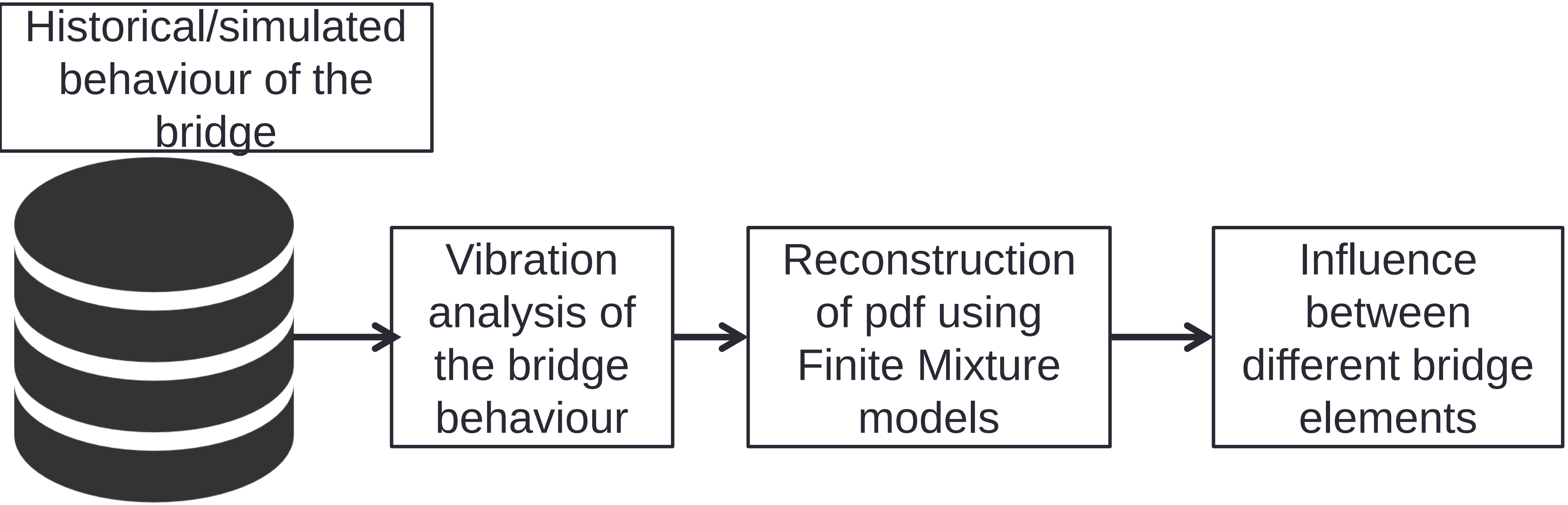
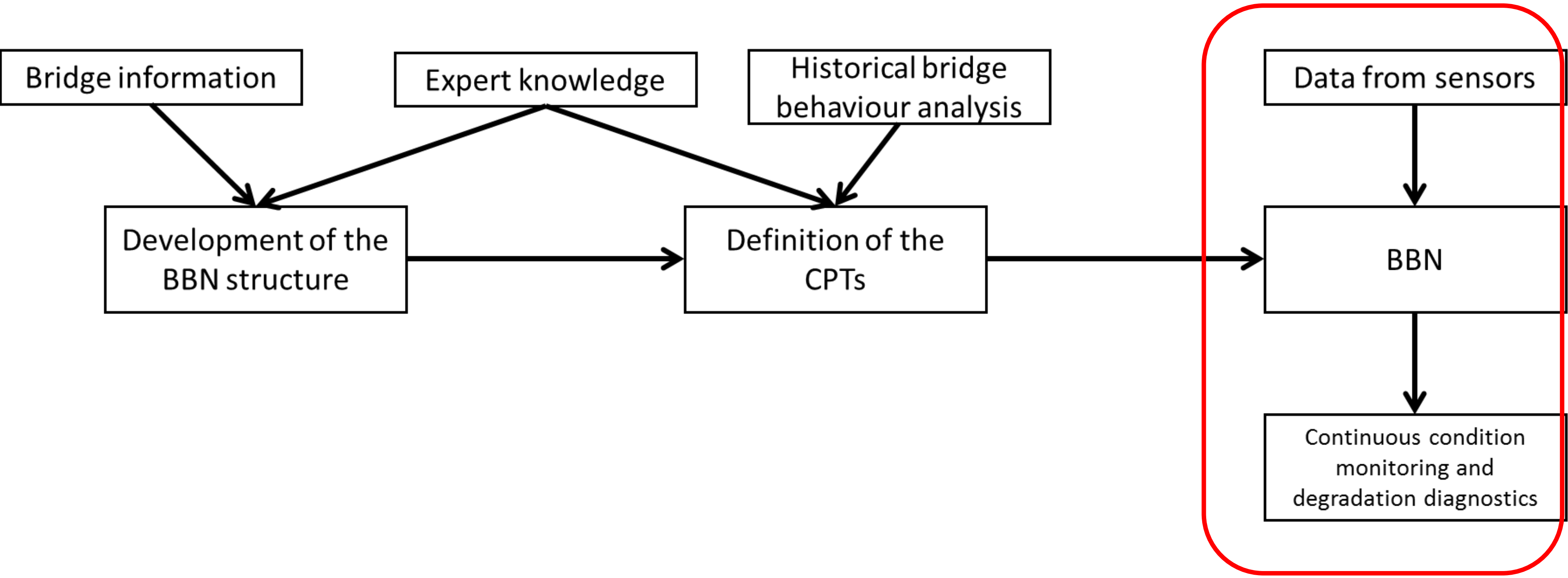


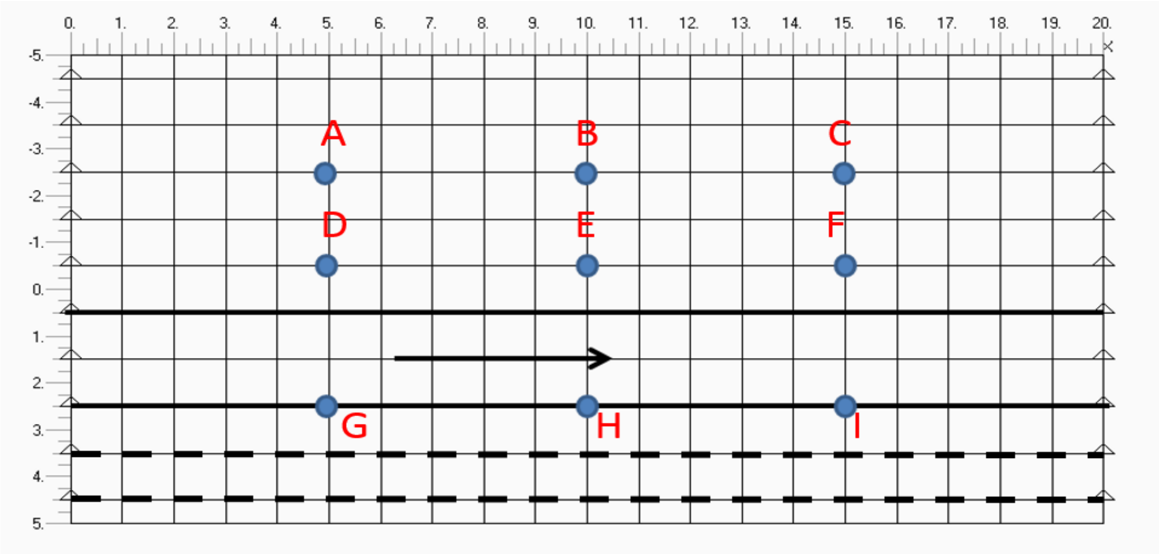
Bayesian Belief Network approach

When the BBN structure is developed and the CPTs are defined, the BBN is used to monitor in real time the bridge health state



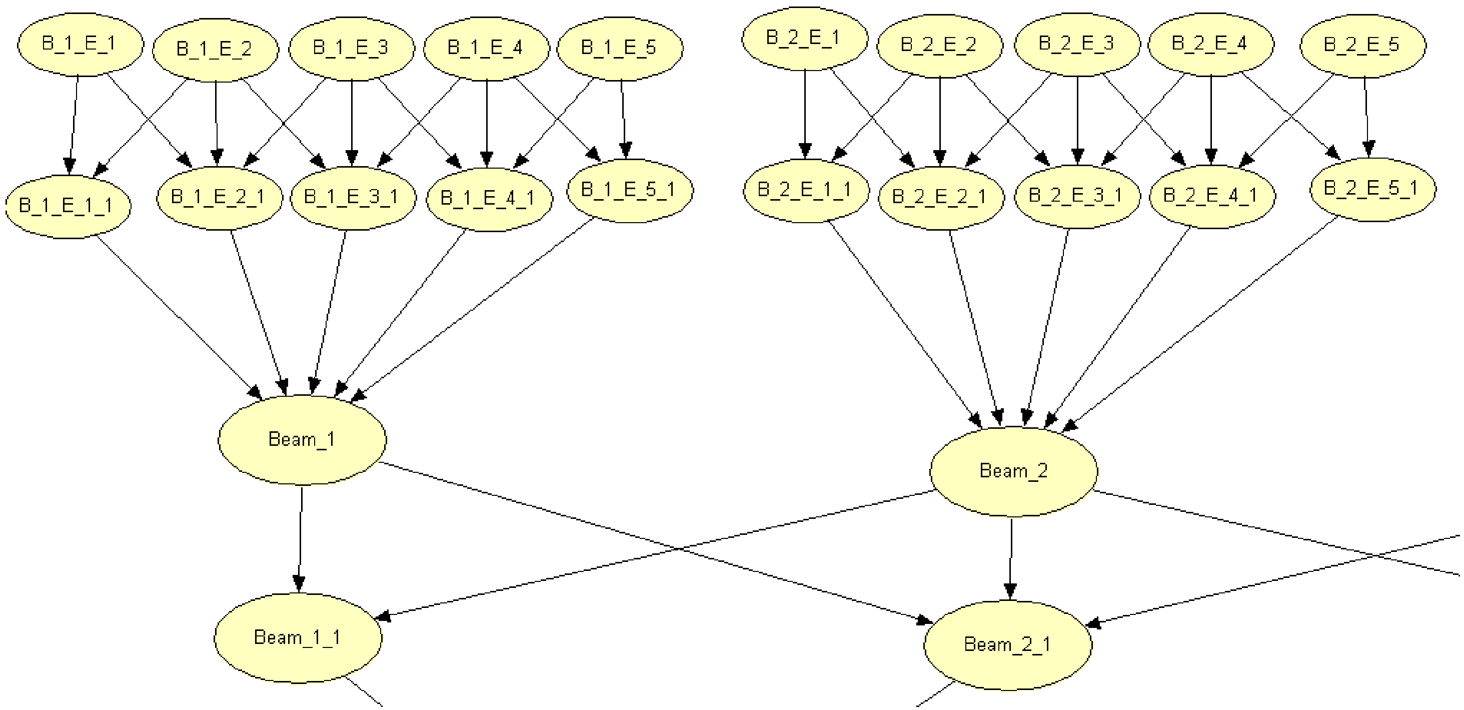
A case study

- A FEM of a simply supported beam-and-slab bridge is considered. The bridge is 20 m long and 10 m wide structure
- The passage of a truck over the bridge at constant speed is considered
- The speed of the truck is unknown
- 9 accelerometers are used to monitor the bridge behaviour
- 16 unknown damage scenarios of the bridge are evaluated



BBN model

Each beam of the bridge (10 longitudinal beams) is considered as major element (20 m long). Each longitudinal beam is divided into 5 smaller elements 4 m long (e.g. beam 1 and 2, and their smaller elements). The BBN allows to assess interdependencies between different elements. The health state of the whole bridge is assessed by taking account of the health state of each bridge element



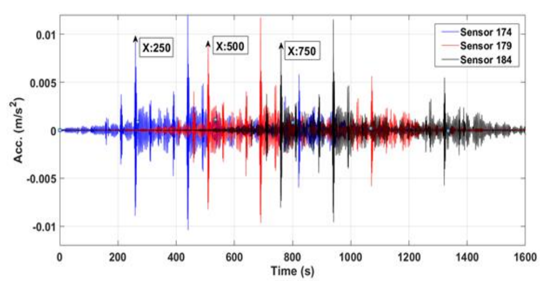
CPT definition - Historical bridge behaviour analysis

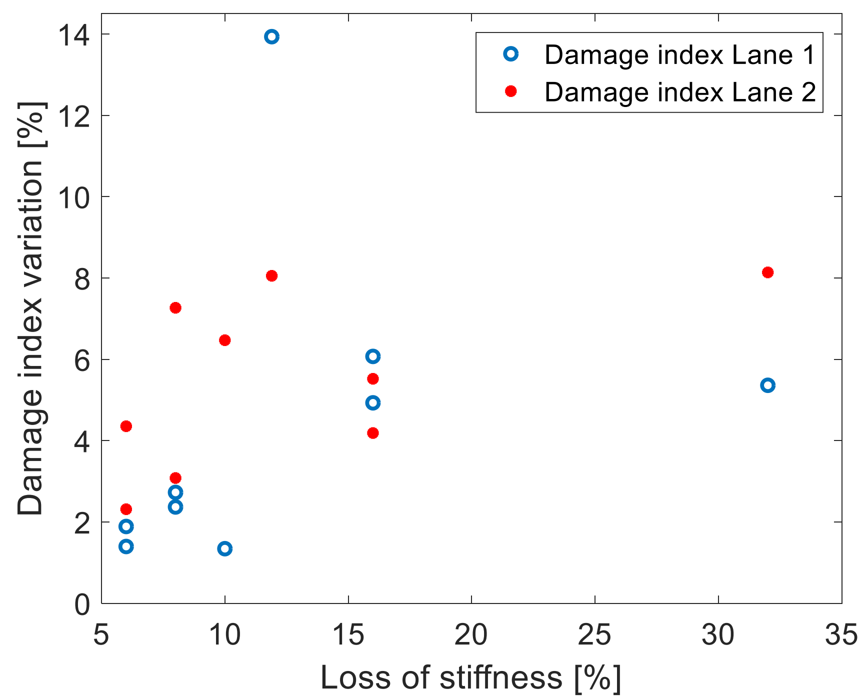
A Damage Index (DI) is introduced to evaluate the bridge acceleration

$$DI = \frac{\frac{\pi}{2g}\int_0^{\infty} \ddot{x}(t)^2\,dt}{v_o^2}$$

Bridge vibration energy

Number of acceleration crossings per unit time

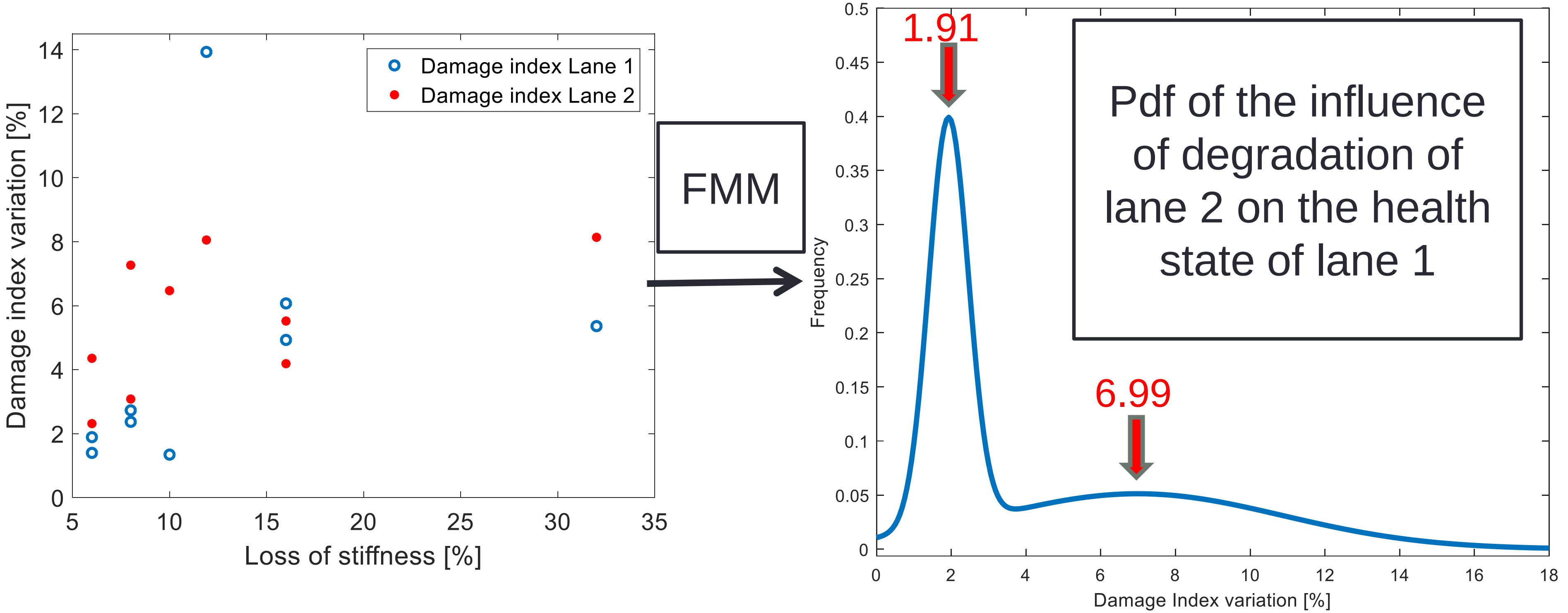




The larger the loss of stiffness of the bridge, the higher the value of the damage index

CPT definition - Historical bridge behaviour analysis

Finite Mixture Models (FMM) are used to reconstruct the pdf of the DI

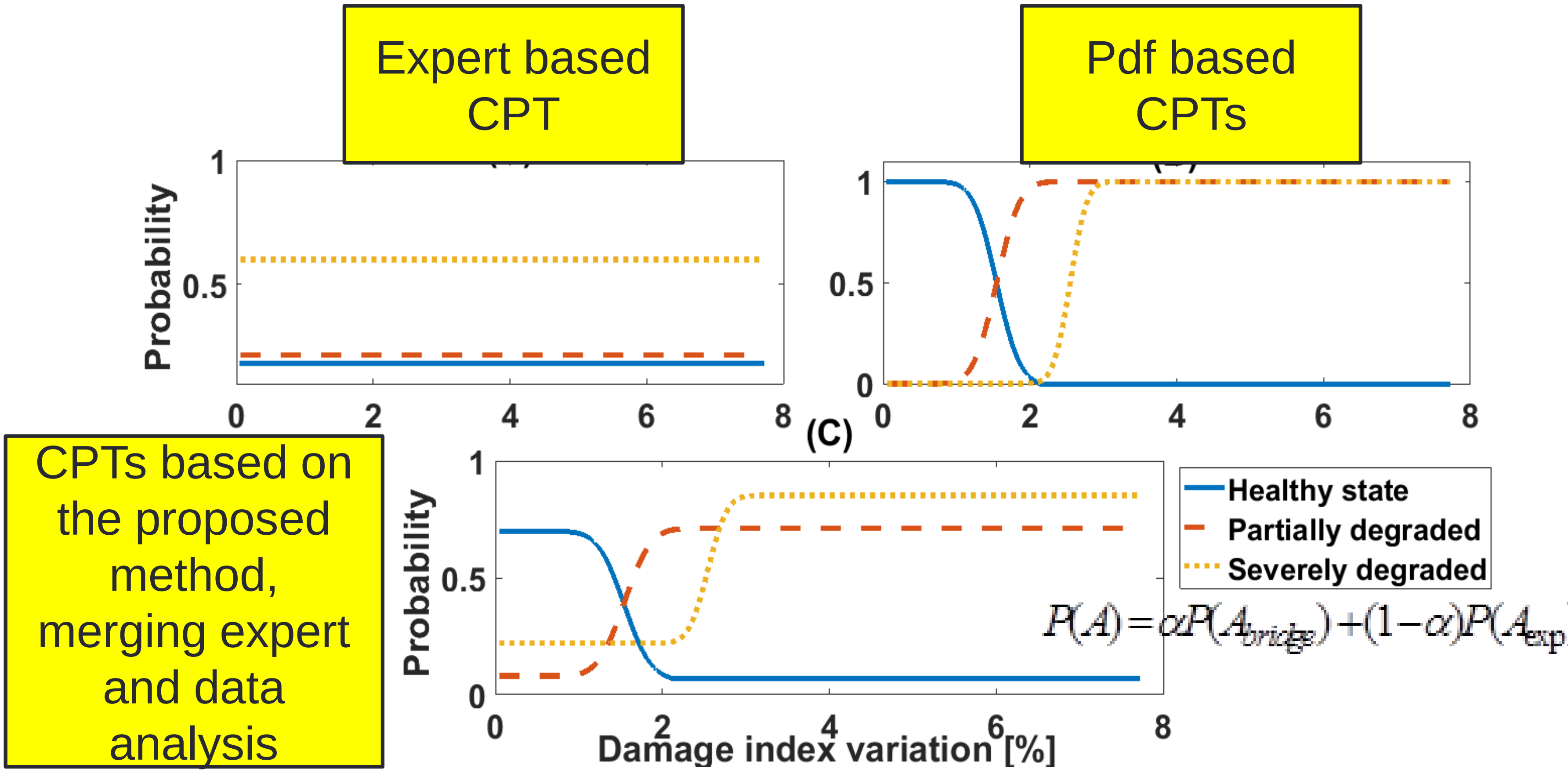


The reconstructed pdf is made of two Gaussian distributions:

- one with mean 1.91 (**partial degradation** of lane1)
- another with mean 6.99 (**severe degradation** of lane 1)

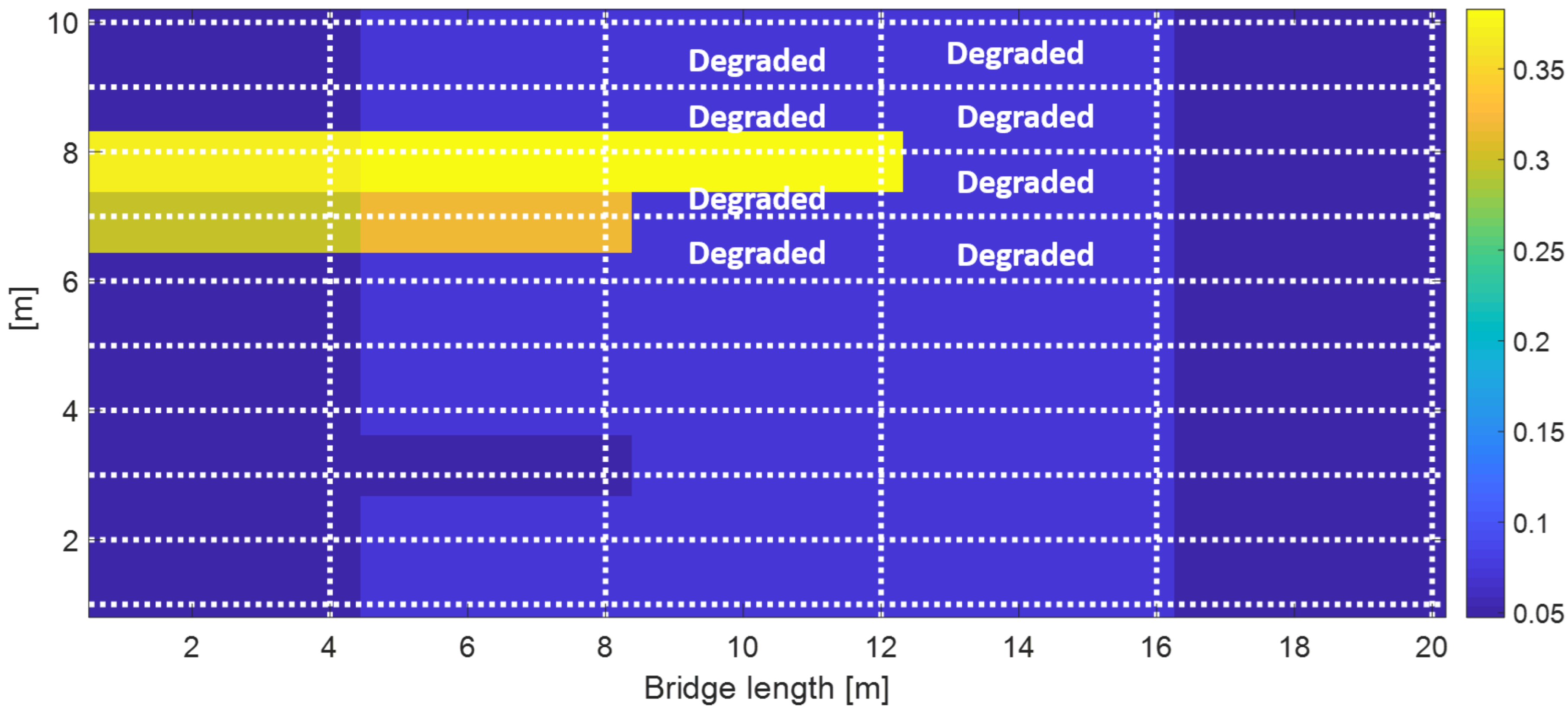
CPT definition – Merging expert and data analysis

The proposed method allows to update the CPTs based on the actual health state of the bridge elements

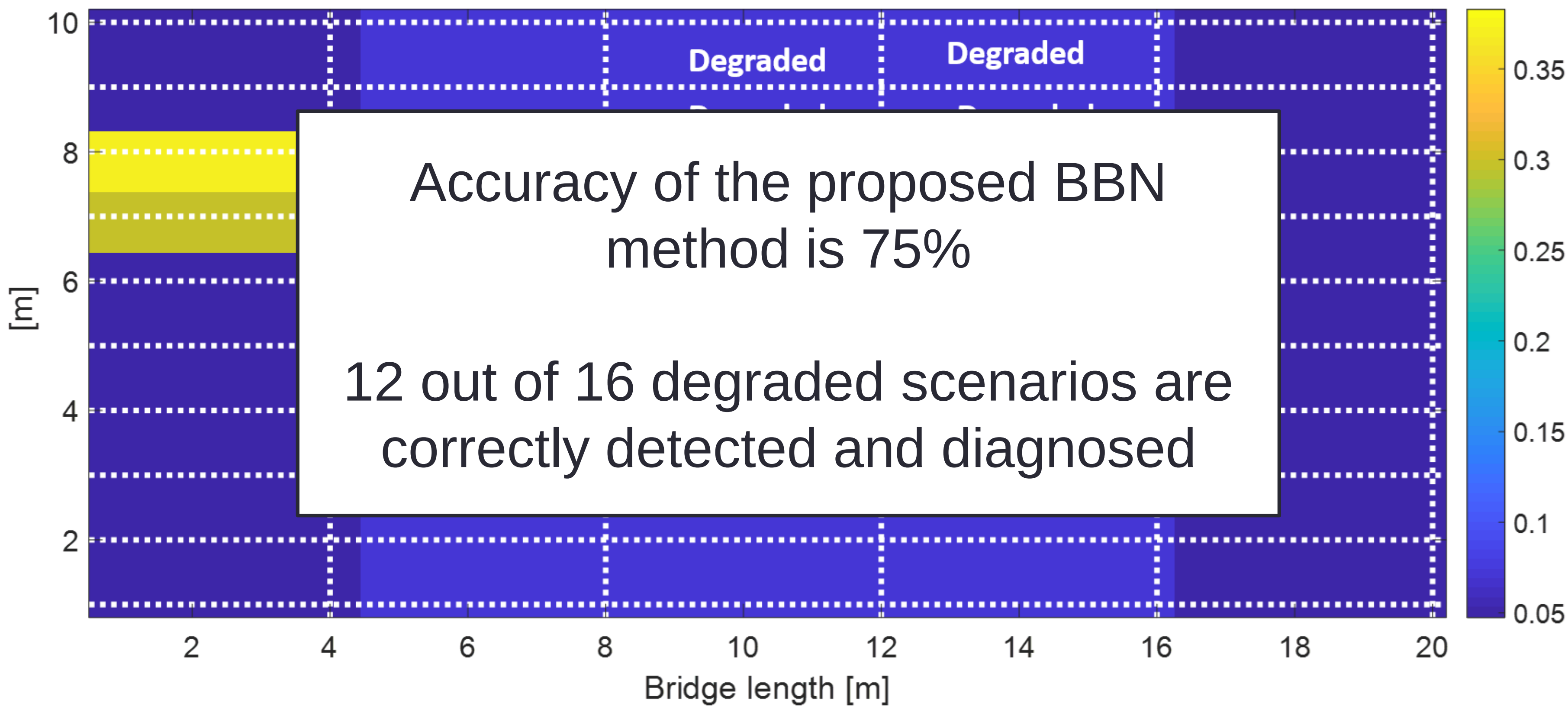


$$P(A) = \alpha P(A_{bridge}) + (1-\alpha) P(A_{exp})$$

Damage detection and diagnostic



Damage detection and diagnostic



Accuracy of the proposed BBN method is 75%

12 out of 16 degraded scenarios are correctly detected and diagnosed

- There is a need for real-time remote structural health monitoring and fault detection by overcoming the limitations of traditional manual bridge SHM.
- The influence of each single bridge element should be considered on the assessment of the bridge health state.

We propose a BBN-based SHM method to monitor the evolution of a bridge health state

Pros:

- Each bridge element influences the health state of the whole bridge.
- The health state of the bridge and its elements is updated each time when new evidence of the bridge behaviour is available
- The expert knowledge is merged with the analysis of the bridge behavior.

Cons:

- The definition of the CPTs can be time-consuming, by requiring data or interviews.
- The accuracy of the BBN in diagnosing unexpected behaviour can depend on the number of nodes of the BBN.
- The measurement of the bridge behaviour needs to be pre-processed when an in-field bridge is analysed.

Thanks for your attention

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