Case Study Bridge proposed for further VoI analysis

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Quantifying the Value of Structural Health Monitoring
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Introduction

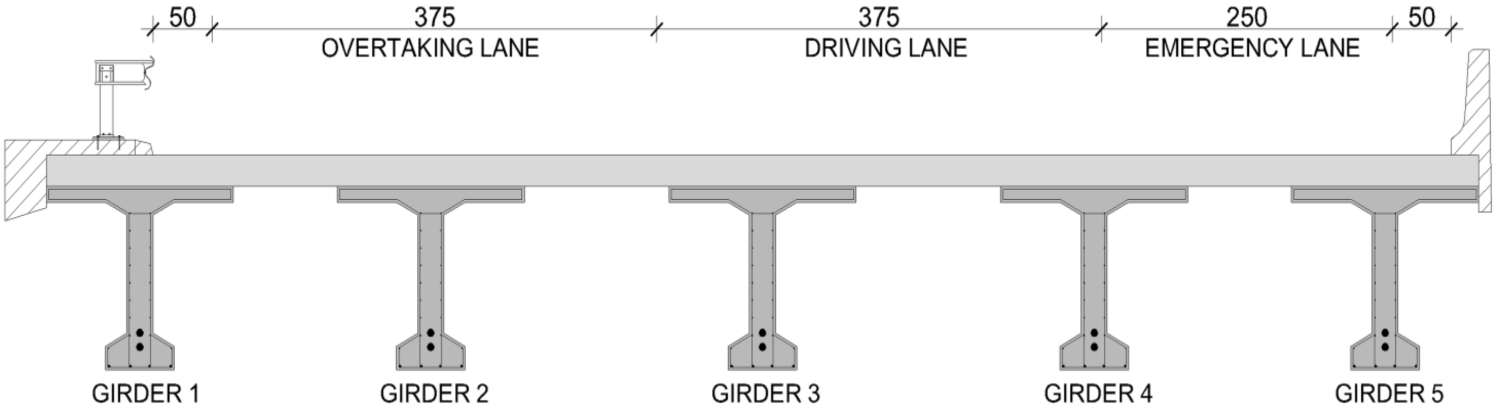
- **Main purpose** – prove that initial investment in SHM will result in:
  - Extended bridge service life
  - Overall more sustainable bridge management

- **Monitoring data**:
  - Obtained with **Bridge Weigh-in-motion** measurements (**B-WIM**):
  - Traffic information:
    - Volume, weight, speed etc.
  - Bridge structural data:
    - Realistic influence lines
    - Girder distribution factor
    - Dynamic amplification factor

- **Post processing of monitoring data**:
  - Site-specific traffic load model
  - Improved bridge numerical model

Introduction

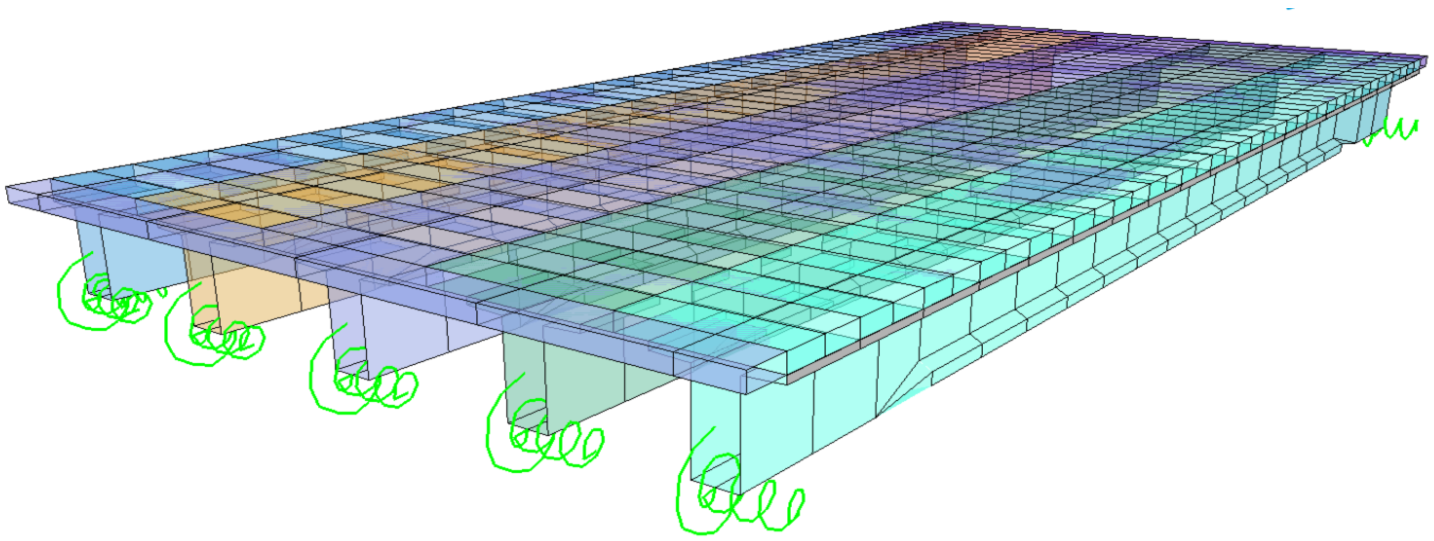
- **Bridge description**:
  - Simply supported highway bridge
  - Single span of 24,8 meters
  - Superstructure – 5 prestressed I-type girders and monolithic deck
  - Original designs and reinforcement drawings available from the archives



Case Study Bridge

- **Bridge selection**:
  - Subject of COST TU1402 supported STSM at ZAG, Slovenia:
    - Visual inspection report
    - Long term monitoring data
    - Detailed numerical model calibrated with monitoring data
    - Traffic load model for different time periods
    - Detailed assessment results

STSM report



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Case Study Bridge

- **Load carrying capacity assessment** :
  - Bending and shear resistance – based on built in reinforcement
  - Deterministic approach – M_{Rd}/M_{Ed} and V_{Rd}/V_{Ed} ratio
  - Probabilistic approach – resulting reliability index β for bending and shear

- **Limit State Function:**

$$Z = \theta_R \cdot M_{Rd} - \theta_E \cdot M_{Ed}$$

  - Critical failure mode – bending in the middle of the span
  - M_{Rd} - girder cross section resistance to bending M_{Ed} and V_{Rd}/V_{Ed} ratio
  - M_{Ed} - bending moment in the middle of the span
  - θ_R - model uncertainty for resistance
  - θ_E - model uncertainty for loading

Case Study Bridge

- **Variables of Limit State Function**

RESISTANCE

Variable	Units	Distribution
Girder height	h [m]	Deterministic
Concrete cover	c [m]	Normal
Number of bars / girder	n_{b}	Deterministic
Number of tendons / girder	n_{g}	Deterministic
Diameter of bar	Φ_b [m]	Deterministic
Yield strength of reinforc. steel	f_{y} [kN/cm^2]	Normal
Area of rebar	A_{s} [cm^2]	Normal
Diameter of tendon	Φ_t [m]	Deterministic
Effective depth of tendons	d [m]	Normal
Tensile strength of prestress. steel	f_{ypk} [kN/cm^2]	Normal
Area of tendon	A_{p} [cm^2]	Normal
Resistance uncertainty	θ_R	Lognormal

Case Study Bridge

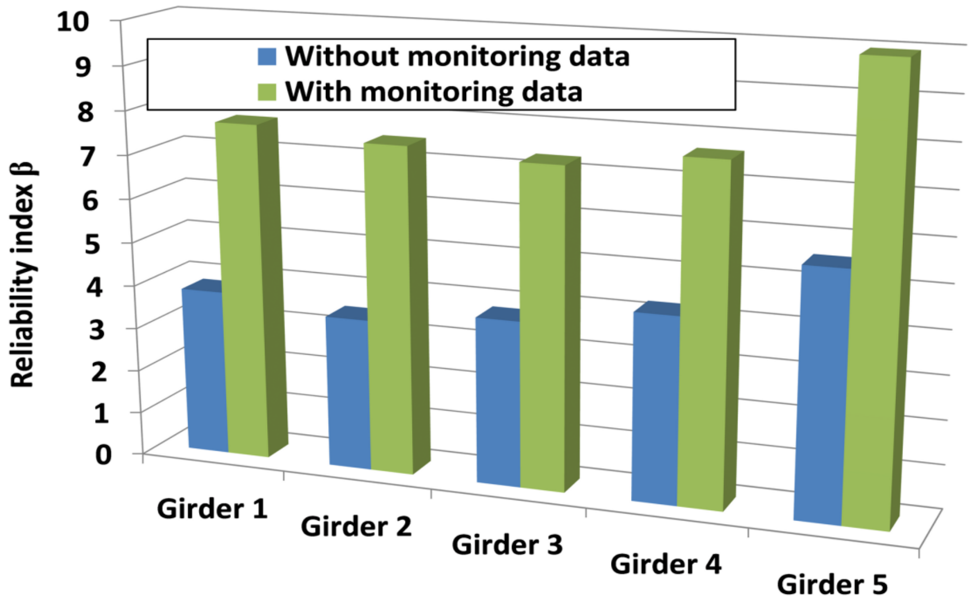
- **Variables of Limit State Function**

LOADING

Variable	Units	Distribution
Concrete density	γ_C [kN/m^3]	Lognormal
Bridge span	L [m]	Deterministic
Girder cross section area	A [cm^2]	Normal
Deck height	h_d [m]	Deterministic
Deck width	b_d [m]	Deterministic
Additional permanent load	ΔM_g [kNm]	Normal
Traffic load – EN 1991-2	$M_{T,1}$ [kNm]	Gumbel
Traffic load – B-WIM	$M_{T,2}$ [kNm]	Gumbel
Dynamic amplification factor	DAF	Gumbel
Permanent load uncertainty	$\theta_{E,G}$	Lognormal
Traffic load uncertainty	$\theta_{E,Q}$	Lognormal

Case Study Bridge

- **Assessment results**:
  - Reliability index for bending (obtained with FORM analyis)



- **Results analysis:**
  - Clear quantification of B-WIM measurements as a part of SHM
  - Foundation for further analysis of Case Study Bridge trough VoI analysis

Implementation of VoI analysis

a) Decision maker

- Bridge owner – national Road Directorate – no additional stakeholders
- Main objectives (owner's perspective):
  - Optimization of bridge management system
  - Priority ranking of bridge maintenance
- Objectives are achieved trough:
  - Normal and steady traffic flow
  - Extended bridge service life
- Conclusion:
  - Additional investments in SHM tools and advanced calculation procedures can be justified by fulfilling these objectives, and by that, minimizing the cost of bridge management.

Implementation of VoI analysis

b) Regulative constraints

- Investment cost:
  - Increase in initial investment
  - Minimizing overall cost of bridge management trough time
- Closing bridge for traffic – owner’s income and reputation loss:
  - B-WIM - minimum interference with traffic flow
  - Visual inspection during calibration
  - Bridge re-opened in few hours

c) System and spatial boundaries

- Bridge selection:
  - B-WIM system can be used on variety of bridges
  - Not limited by the dimensions and bridge types
- Requirements:
  - Qualified personnel for installation and data post-processing
  - Additional knowledge for advanced calculation methods

Implementation of VoI analysis

d) Events of interest

- Assessment according to valid codes – simple calculation
- Assessment according to short – term B-WIM measurements
- Assessment according to long – term B-WIM measurements

e) Consequences

- Based on whether B-WIM data is used or not:
  - Unnecessary vs. necessary bridge strengthening
  - Appropriate vs. unsuitable bridge strengthening
  - Unnecessary vs. necessary traffic restriction
  - Minor or no action vs. medium or major measures on bridge before next assessment (e.g. in 5 years)
  - Money loss vs. money saving

Implementation of VoI analysis

f) Indicators to observe

- Structural response:
  - Realistic influence lines
  - Girder distribution factors
  - Dynamic amplification factors – DAFs
- Traffic data:
  - Development of site-specific traffic load model
- Resulting indicator:
  - Reliability index – basis for the further decisions regarding the bridge

g) Decision alternatives – monitoring and/or inspection

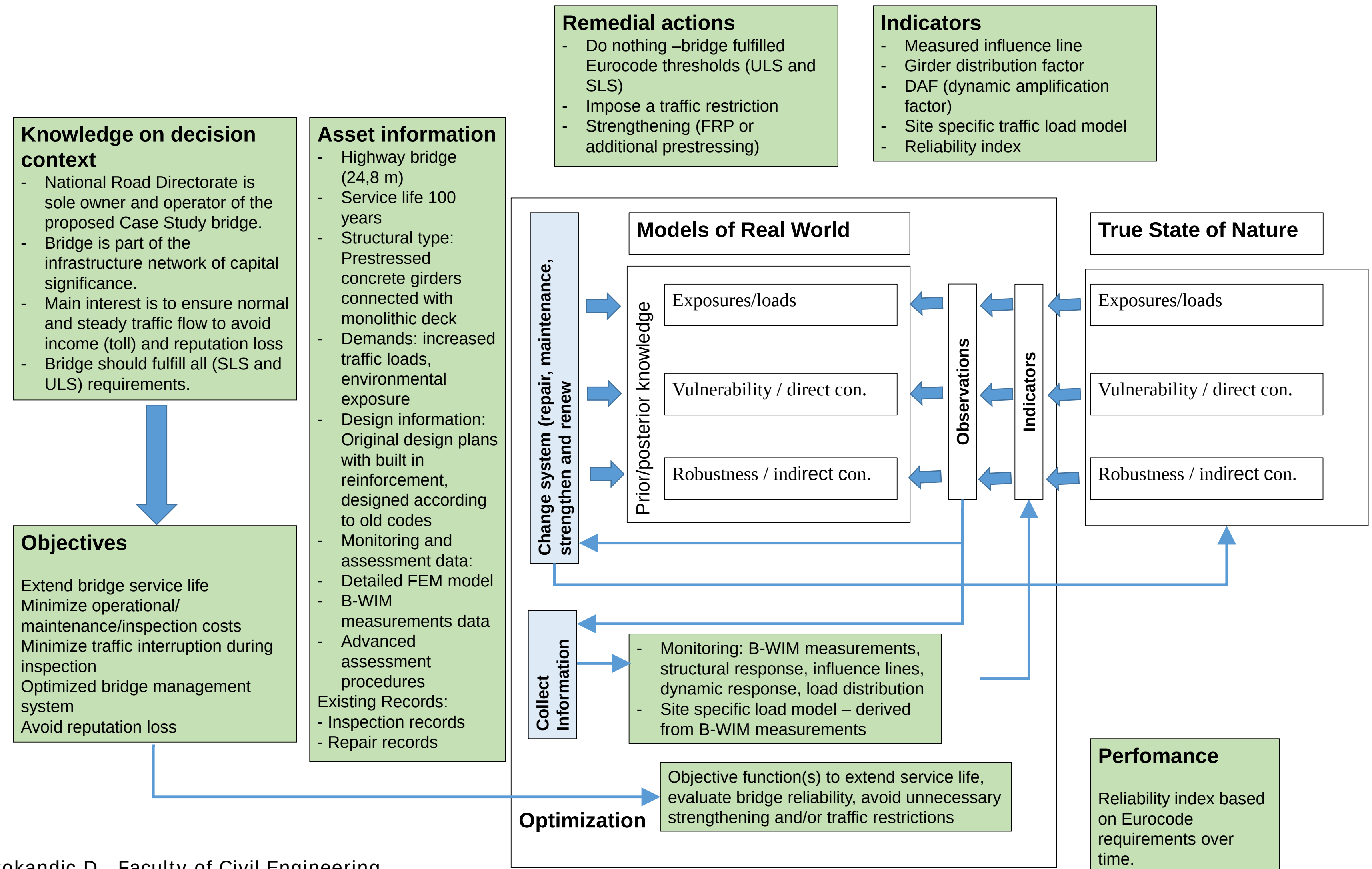
- Bridge requirements:
  - Based on visual inspection and preliminary assessment
  - B-WIM measurements – different time – periods
  - Threshold values for indicators

Implementation of VoI analysis

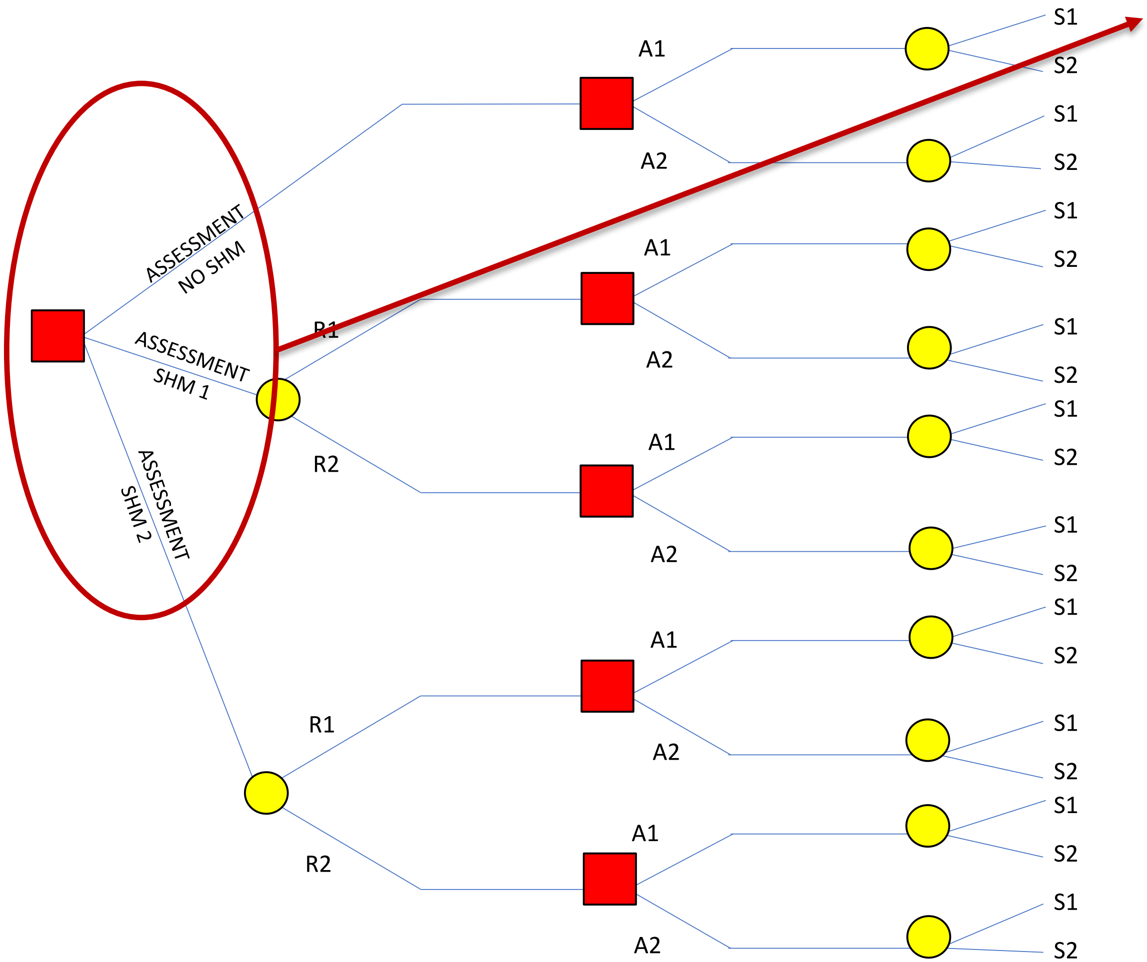
h) Decision alternatives – other measures, repair, replacement, etc.

- Multi – level assessment method based on B-WIM:
  - Monitoring data requirements
  - Advanced calculation methods
  - Increased bridge reliability
- Bridge do not meet minimum requirements:
  - Redefine the use of the bridge
  - Impose a traffic weight restriction
  - Bridge strengthening
  - Demolition and total replacement of the bridge

Flow chart for VoI analysis



Decision Tree for VoI analysis



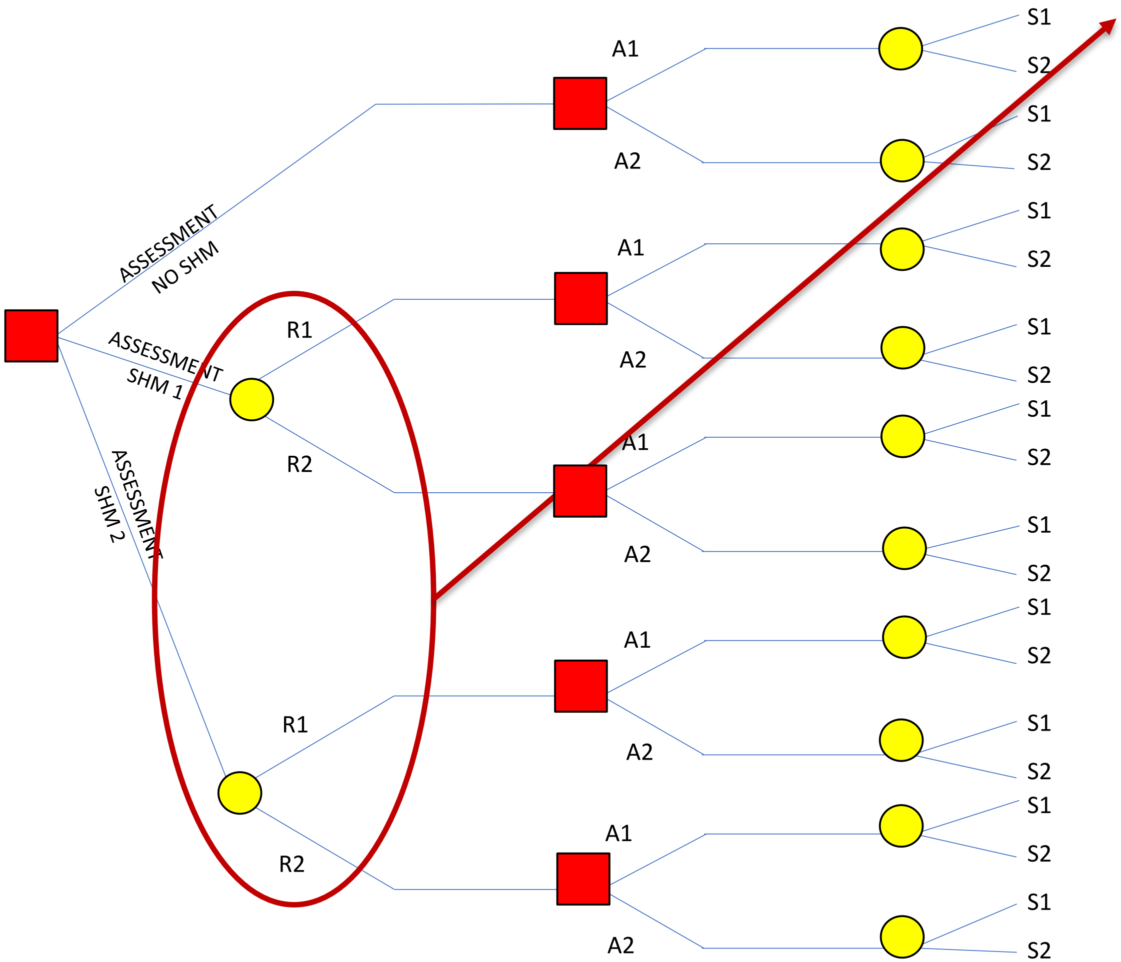
STRATEGIES

- Assessment without SHM
- Assessment with SHM – level 1
- Assessment with SHM – level 2

SHM types

- SHM level 1
  - Short time B-WIM
  - Structural data
- SHM level 2
  - Long time B-WIM
  - Structural dana
  - Dynamic characteristic
  - Traffic model

Decision Tree for VoI analysis



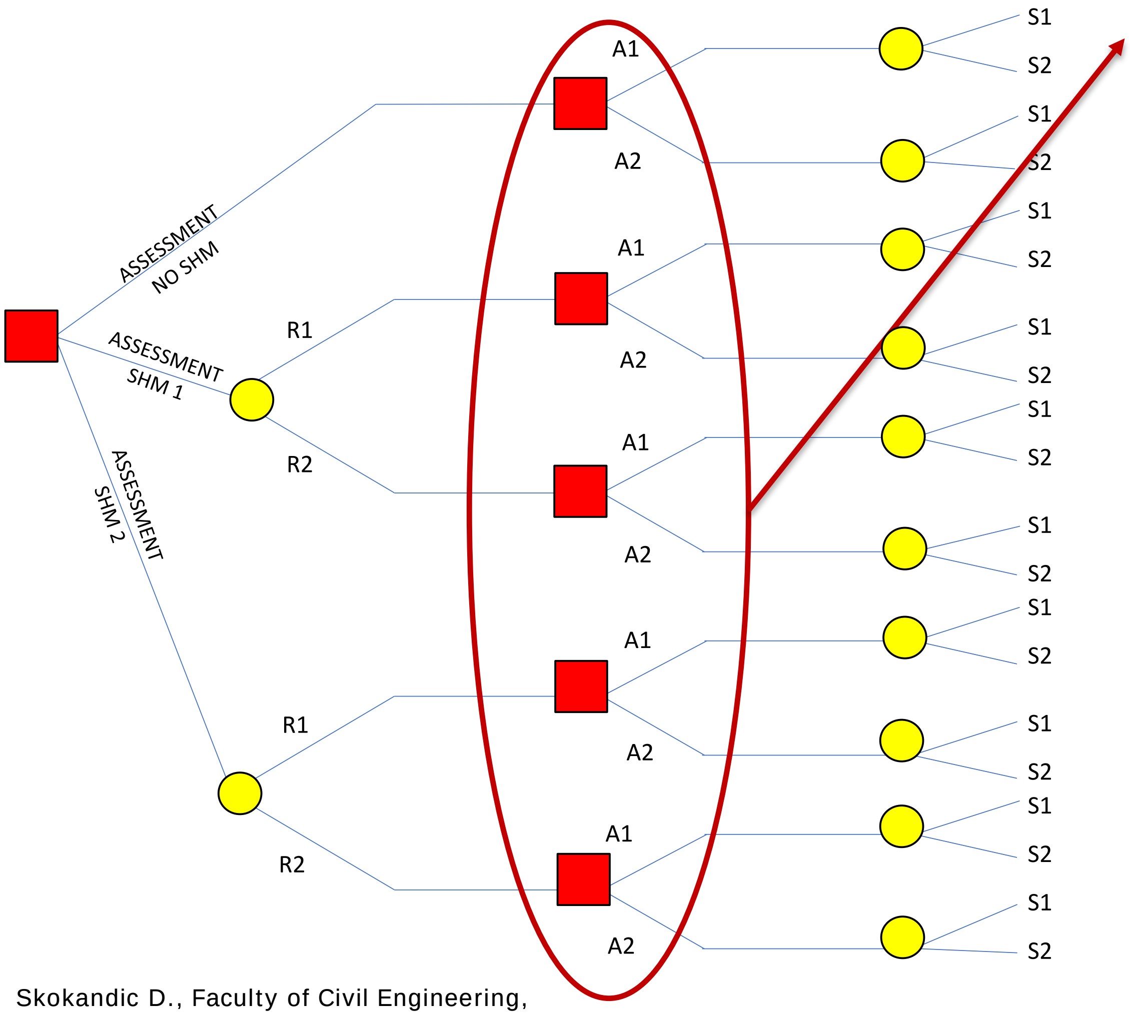
SHM OUTCOMES

- R1 – improvement in reliability
- R2 – no improvement in reliability

IMPORTANT

- SHM uncertanties
- SHM costs
- SHM time and type tresholds

Decision Tree for VoI analysis



ACTIONS
- A1 – no repair
- A2 – repair

A2 - REPAIR TYPES
- Bridge strengthening
- Weight restriction
- Bridge replacement

A2 - CONSEQUENCES
- Road closing
- Traffic jams
- Loss of money
- Loss of reputation

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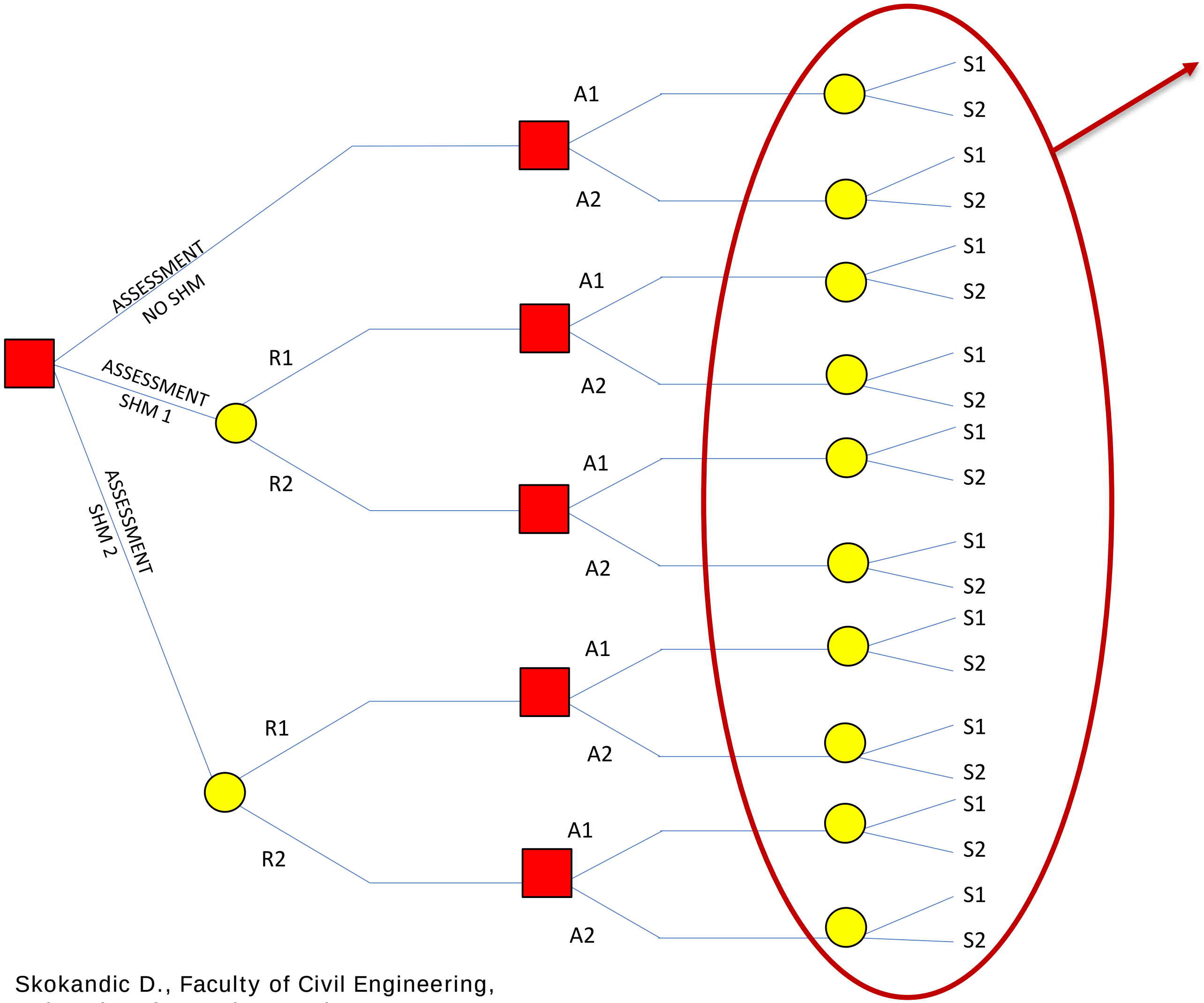
Decision Tree for VoI analysis



SYSTEM STATES

- S1 – bridge safe
- S2 – bridge not safe

S2 – DIRECT CONSEQUENCES

- Road closing
- Bridge collapse
- Human casualties
- Loss of money
- etc.

S2 – INDIRECT CONSEQUENCES

- Traffic jams on alternate routes
- Loss of reputation
- etc.

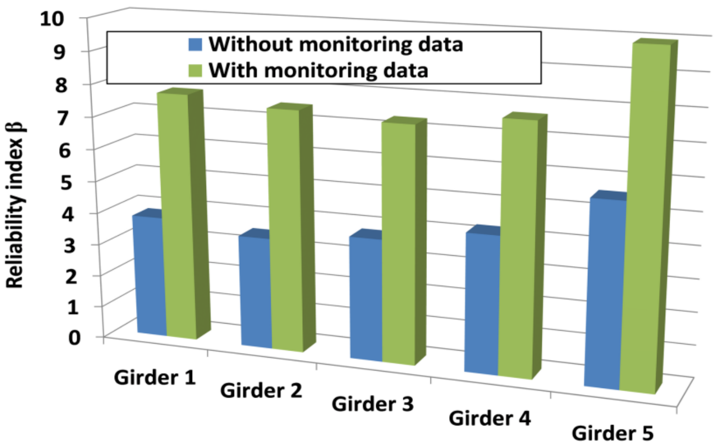
Critical appraisal, simplifications

- **VoI analysis requirements:**
  - Complete assessment on each level
  - Results and substantial costs included
  - Evaluation of bridge importance on the network level
  - Consequences of eventual bridge closing
  - Alternate traffic routes

- **Simplifications:**
  - 3D bridge numerical model → 2D girder numerical model
  - Assumptions of bridge importance – based on similar bridges data

Conclusions and further steps

- **General conclusion** – contribution of B-WIM measurements as a part of SHM in bridge management is proven.



- **Advantages of proposed Case Study Bridge:**
  - Case Study Bridge evaluated during the STSM
  - Complete multi level assessment results available
  - 3D numerical model available

- **Further steps and requirements:**
  - Detailed cost and feasibility analysis of all parameters
  - Setting up VoI analysis – additional knowledge?

Thank you for your attention!

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