INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

COST ACTION TU1406

Funded by the Horizon 2020 Framework Programme of the European Union

22nd November 2018
Bergisch Gladbach, Germany

Contents

COST Action TU 1406
Owners Meeting at
Federal Highway Research Institute

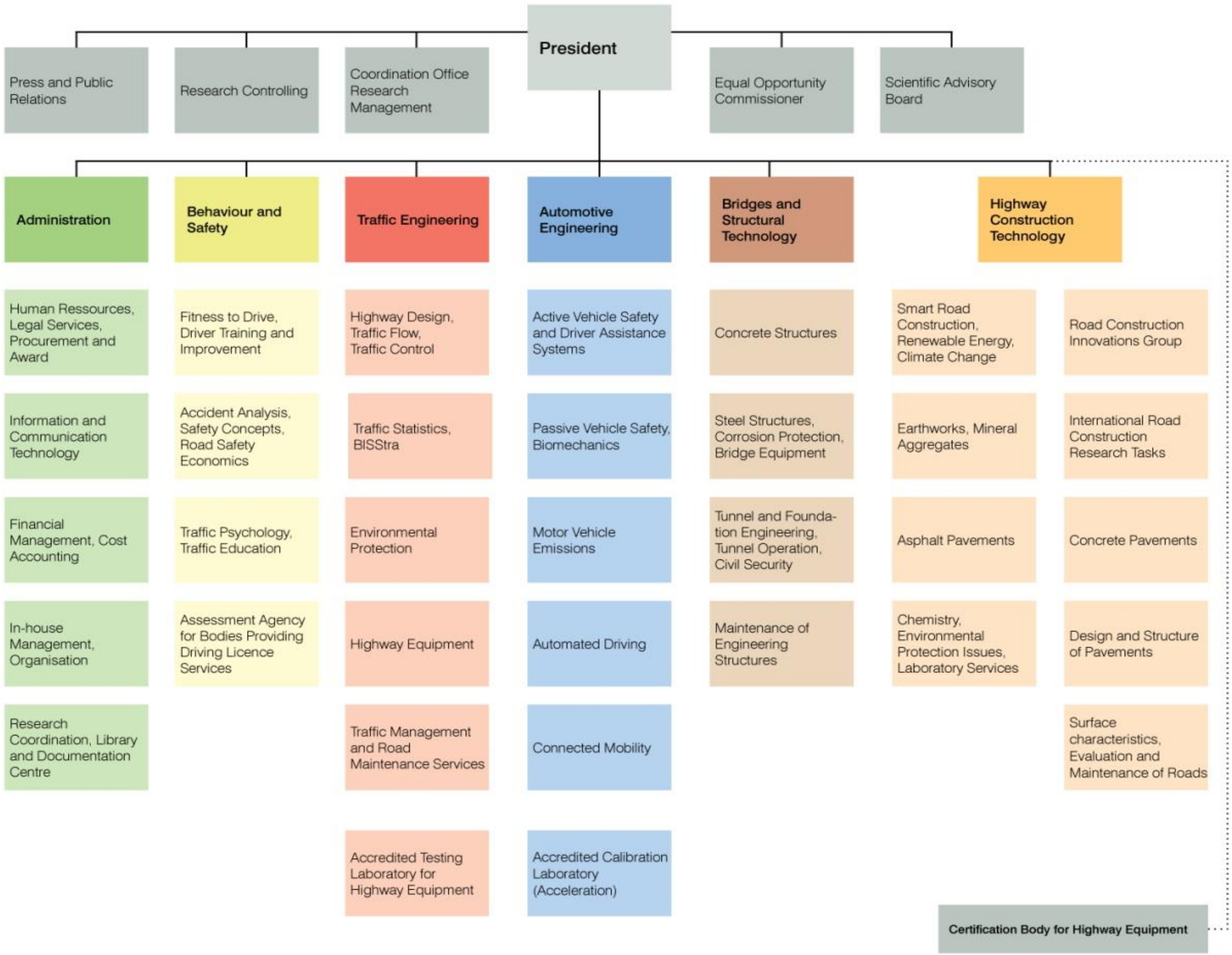
Greetings

Dr. Peter Haardt

Deputy Head of Division Bridges and Structural Technologies

Federal Highway Research Institute (BASt)

- Technical and Scientific Research Institute
- Subordinate to the Federal Ministry of Transport
- Approximately 400 Employees
- Founded in 1951, since 1983
  in Bergisch Gladbach



President
Press and Public Relations
Research Controlling
Coordination Office Research Management
Equal Opportunity Commissioner
Scientific Advisory Board
Administration
Behaviour and Safety
Traffic Engineering
Automotive Engineering
Bridges and Structural Technology
Highway Construction Technology
Human Ressources, Legal Services, Procurement and Award
Information and Communication Technology
Financial Management, Cost Accounting
In-house Management, Organisation
Research Coordination, Library and Documentation Centre
Fitness to Drive, Driver Training and Improvement
Accident Analysis, Safety Concepts, Road Safety Economics
Traffic Psychology, Traffic Education
Assessment Agency for Bodies Providing Driving Licence Services
Highway Design, Traffic Flow, Traffic Control
Traffic Statistics, BISStra
Environmental Protection
Highway Equipment
Traffic Management and Road Maintenance Services
Accredited Testing Laboratory for Highway Equipment
Active Vehicle Safety and Driver Assistance Systems
Passive Vehicle Safety, Biomechanics
Motor Vehicle Emissions
Automated Driving
Connected Mobility
Accredited Calibration Laboratory (Acceleration)
Concrete Structures
Steel Structures, Corrosion Protection, Bridge Equipment
Tunnel and Foundation Engineering, Tunnel Operation, Civil Security
Maintenance of Engineering Structures
Smart Road Construction, Renewable Energy, Climate Change
Earthworks, Mineral Aggregates
Asphalt Pavements
Chemistry, Environmental Protection Issues, Laboratory Services
Road Construction Innovations Group
International Road Construction Research Tasks
Concrete Pavements
Design and Structure of Pavements
Surface characteristics, Evaluation and Maintenance of Roads
Certification Body for Highway Equipment

Responsibilities and Tasks

- Scientifically sound decision support for the ministry
- Regulations and standards at national and european level
- Testing and certification body (road equipment)
- Driving licence procedure assessment centre
- Research

Research Aims

- Improving and increasing efficiency of construction and maintenance and improving reliability of road infrastructure
- Improving efficiency of the road transport system
- Improving road safety
- Improving environmental sustainability of road construction and road transport
- Strengthening resilience of the road transport system
- Strengthening technological progress

Results

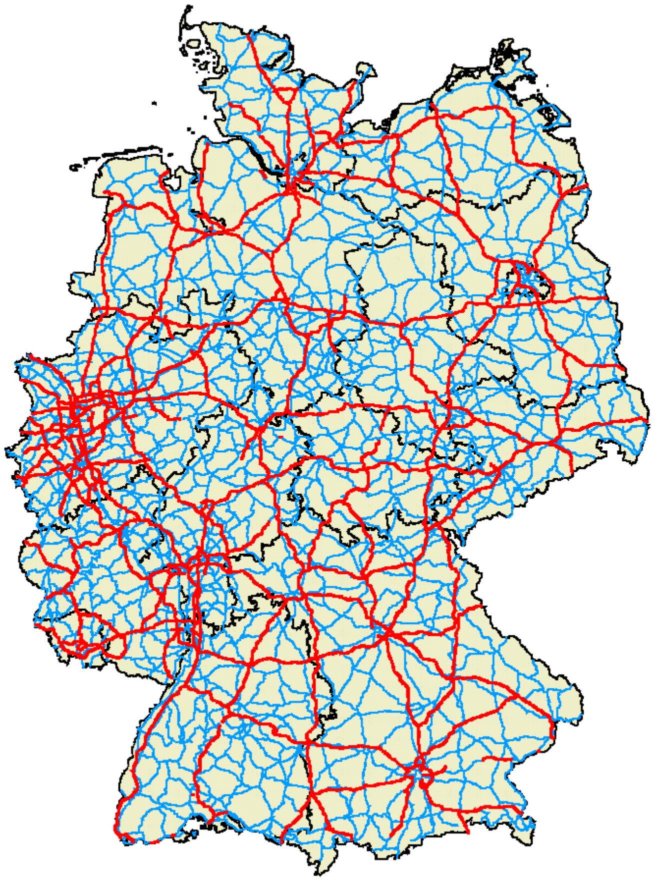
- More than 300 internal research projects per year
- About 500 external research projects
- Monitoring of national, European and international legislative and harmonisation procedures in more than 750 national and international committees

BASt Financial Resources

• Annual Budget of BASt	46,7 Million Euro
• Resources from the Research Budget of the Federal Ministry of Transport	10,0 Million Euro
Total	**56,7 Million Euro**

As per: 2017

Challenges

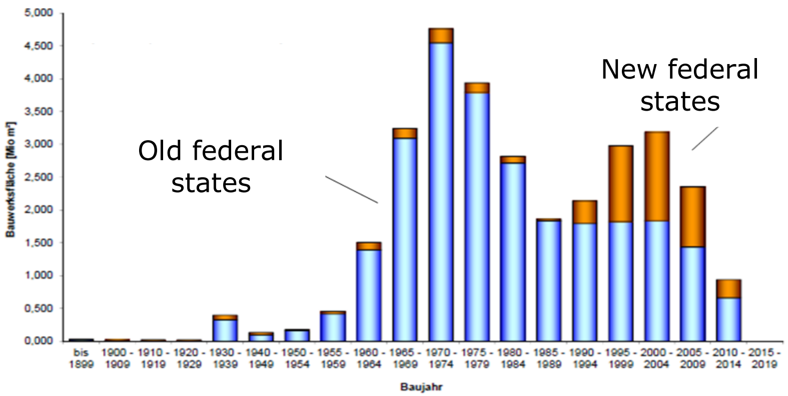


Overall road network: ca.687.000 km
Federal Highways: 12.987 km
Federal Trunk Roads: 38.068 km

Federal Roads: 39.535 bridges
Highways: 17.729 bridges
Trunk Roads: 21.806 bridges
Fixed assets: ~60 Bio €

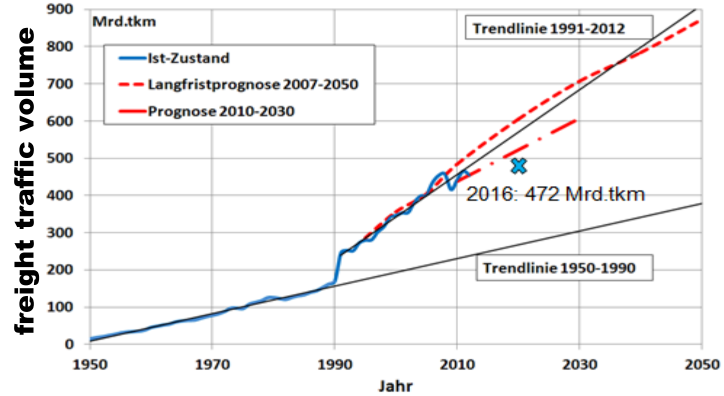
Challenges

(BASt)



age structure bridges on BAB

(BASt)



road freight transport on BAB

- Traditional design, construction and maintenance processes dominate
- Older bridges are not “fit for future”
- Mobility requirements conflict with actual availability of bridges

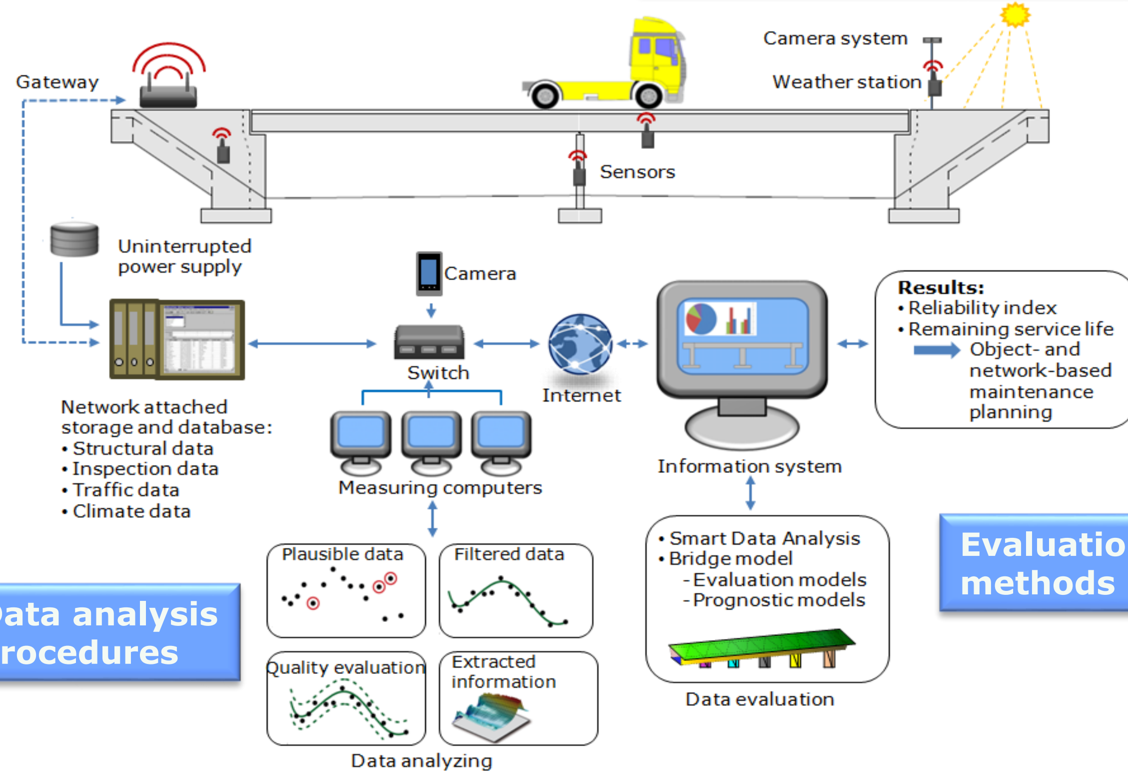
digital transformation, lifecycle-oriented solutions, advances in construction technology

Intelligente Brücke

Smart Bridge - Conception and integration

Innovative sensors and measurement systems

- Adaptive system for continuous provision of relevant information on the condition, loadbearing capacity, reliability and remaining service life of a bridge and its components
- holistic solutions, lifecycle oriented



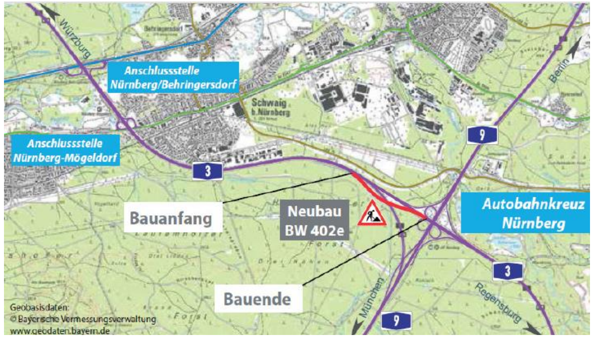
Data analysis procedures

Evaluation methods

Intelligente Brücke

Smart Bridge in the Digital Test Area Autobahn (Pilot study)

- New bridge structure equipped with sensors in the highway interchange A3/A9
  - 4-span prestressed concrete box girder bridge
  - Length: 156 m, 2 lanes



- Determination of actions and reactions using measurement and evaluation technology to assess the condition, reliability and remaining service life
- Information system „Structural Condition", wireless sensor network, instrumented bearings, instrumented expansion joint

Instrumented expansion joint

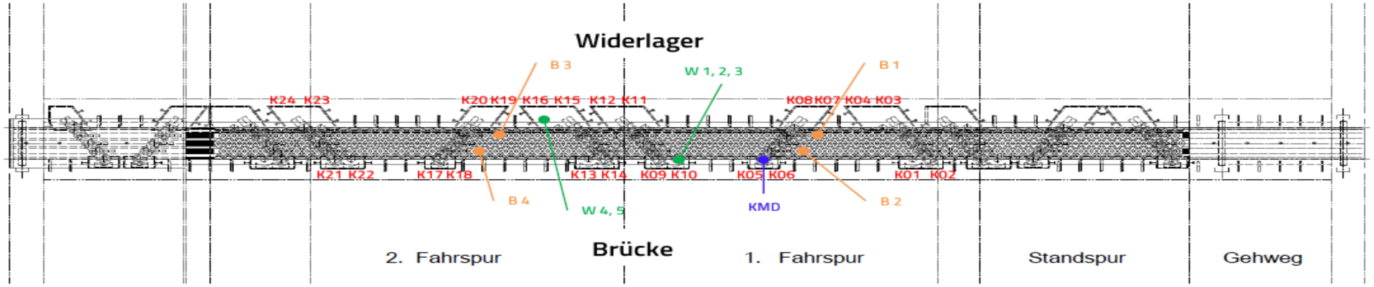
- Swivel joists expansion joint
- Recording of traffic data
  - Number of vehicles, vehicle speed
  - Number of axles, axle distances, axle loads
- Self-monitoring
  - Gap width, lamella spacing
  - Lamella eigenfrequencies

Bundesministerium für Verkehr und digitale Infrastruktur

MAURER

Abkürzungen: B = Beschleunigungssensoren, W = Seilzugsensoren, K01-K24 = Kraftsensoren, KMD = Kraftmessdose

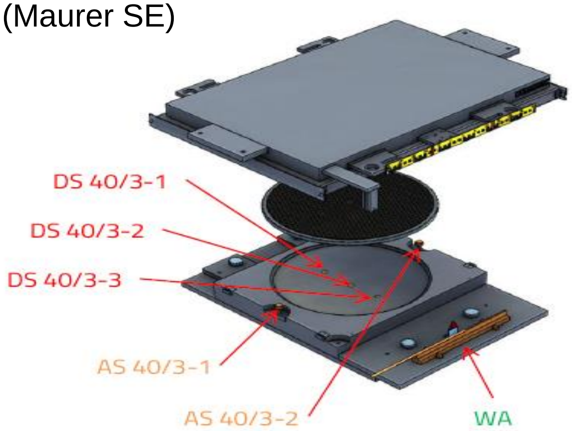
Accelerometers, wire-rope sensors, load cells, pressure sensors



Instrumented bearing

- Spherical bearing
- Actions and reactions relevant to the structure
  - Determination of loads using pressure sensors
  - Determination of glide paths, deformations and rotations
  - Derivation of structural eigenfrequencies
- Self-monitoring
  - Bearing rotation around the bridge axis
  - Accumulated glide path

(Maurer SE)



Pressure sensors
Distance sensors
Displacement transducers

Thank you for your Attention!

Federal Highway Research Institute
Brüderstraße 53
51427 Bergisch Gladbach – Bensberg / Germany
Fon +49 (0) 2204 43-0
info@bast.de
www.bast.de

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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

Organizational Points

Ralph Holst – Federal Highway Research Institute (BASt)

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22nd November 2018
Bergisch Gladbach, Germany

22 NOVEMBER 2018 in BERGISCH GLADBACH near COLOGNE in GERMANY

10:00-10:30	Registration
	1st Session: Chair Poul Linneberg, Co-Chair Arjen van Maaren
10:30-13:00	• Greetings from **Dr. Jürgen Krieger** (Head of Department, Bridges and Structural Technology, BASt, DE) • Organizational Points **Ralph Holst**, BASt, DE • Introduction of COST action TU1406 **José Matos**, UMinho, PT • Relevance for bridge owners **Nicolas Bardou**, VINCI Autoroutes, FR and **João Amado**, Infraestruturas de Portugal, PT • Performance indicators and performance goals – evaluation and recommendations **Alfred Strauss,** BOKU, AT • Quality Control Framework **Rade Hajdin**, Uni. Belgrade, RS • Case-study **Amir Kedar**, Kedmor Engineers, IL
13:00-14:00	Lunch and networking
	2nd Session: Chair: Niels Peter Høj, Co-chair Ralph Holst
14:00-16:00	• Case-study **Amir Kedar**, Kedmor Engineers, IL • Guidelines and recommendations **Helmut Wenzel**, Vienna Consulting Engineers ZT GmbH, AT • Panel discussion with **active participation from the audience**, moderated by Niels Peter Høj (HOJ Consulting GmbH, CH) Panel consist of – Alfred Strauss (BOKU, AT), – Amir Kedar (Kedmor engineers, IL), – João Amado (Infraestruturas de Portugal, PT), – José Matos (UMinho, PT), – Nicolas Bardou (VINCI Autoroutes, FR), – Poul Linneberg (COWI A/S, DK), – Rade Hajdin (Uni. Serbia, RS), – Ralph Holst (BASt, DE) and – Helmut Wenzel (Vienna Consulting Engineers ZT GmbH, AT) • Closing **Joan Casas**, UPC, ES
16:00-16:30	Coffee and networking
16:30-	Tour in Cologne followed by networking dinner

bast

SP 6	Montag 19.11.18		Dienstag 20.11.18		Mittwoch 21.11.18		Donnerstag 22.11.18		Freitag 23.11.18	
MENÜ 1					…ter Erbseneintopf mit …		Kartoffelgratin mit Broccoli , Blumenkohl und Käse überbacken		Blumenkohl-Käsemedallion mit Kräuterdip und Petersilienkartoffeln	
Allergene	A;D;E;F;G;	3,50 €	A;B;C;D;E;F;;	3,50 €	A;B;D;E;F;	3,50 €	A;B;C;D;E;	3,50 €	A;B;D;E;	3,50 €
MENÜ 2	Spießbraten mit Zwiebelsauce, Butterspätzle und einem Beilagensalat		Thüringer Rostbratwurst mit Currysauce, Pommes frites, dazu ein Beilagensalat		Paniertes Schweinerückenschnitzel mit Zigeunersauce und Pommes frites		Szegedinger Gulasch mit Sauerkraut und Kartoffeln		Grünkohl mit Kartoffeln und Mettwurst,Senf	
Allergene	A;B;D;E;F;	5,00 €	A;C;D;E;	5,00 €	A;B;C;D;E;	5,00 €	A;B;D;E;	5,00 €	A;B;D;E;F	5,00 €
Frisch vom Feld	Gartengemüse	1,50 €	Rahmerbsen	1,50 €	Vichykarotten	1,50 €	Broccoli	1,50 €	Tagesgemüse	1,50 €
Special im Snackwerk	Gemüsepizza A;B;C;D;E;	3,00						0 €	Bratwurstschnecke mit Brötchen A;C;E;F;3;4;	2,80 €
Dessert / 1,20 €	Tiramisucreme								Dessert Variation	

1. Cassler with pointed cabbage and mashed potatoes

2. Szegedinger goulash with sauerkraut and potatoes

Zusatzstoffe

1.Farbstoff
2. Konservierungsstoffen
3. Antioxidationsmittel
4.Geschmacksverstärker
5.geschwefelt
6.geschwärzt
7.gewachst
8.mit Süßungsmittel
9. gentechnisch veränderten Organismen
10. Phosphat
11.Coffein
12.Chinin,Chininsalze
13.Taurin

Allergene

A) Soja und Erzeugnisse
B) Milch und Erzeugnisse einschließlich laktose
C) Eier und Erzeugnisse
D) Glutenhaltiges Getreide und Erzeugnisse
E) Sellerie und Erzeugnisse
F) Senf und Erzeugnisse
G)Sesam und Erzeugnisse
H) Schalenfrüchte und Erzeu…
I) Krebstiere und Erzeugniss…

3. Cassler with pointed cabbage and mashed potatoes

Guten Appetit wünscht Ihnen Ihr Team von BCC!

Betriebsgastro Concept Catering

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WC
Garderobe

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HAUPTBAHNHOF
HÖHENHA
HOLWEIDE
DELLBRUCK
Wald
BENSBERG
REFRATH
NIPPES
RIEHL
MÜLHEIM
Rhein
506
8
3
4
55a
Rheinpark
BUCHFORST
MERHEIM
ELD
9
ALTSTADT-NORD
HÖHENBERG
55
Köln
KALK
VINGST
NEUBRÜCK
HUMBOLDT
- GREMBERG
ALTSTADT-SÜD
51
559
orst
Uwe Kriescher

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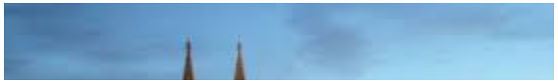
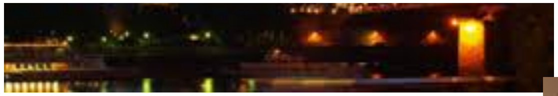
Bus leaves BASt: 5 PM,

Tour in Old Town: 5:30 – 6:30 PM

Dinner in Brewery: 6:45 PM 10 PM



I wish you a fruitful Owners Meeting and a good time in Cologne



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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

COST ACTION TU1406

José C. Matos
TU1406 Chairman
University of Minho, Guimarães, Portugal

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Federal Highway Research Institute

22nd November 2018
Bergisch Gladbach, Germany

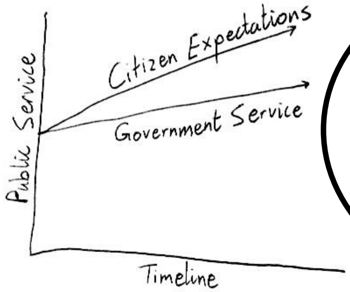
Background

Decay Process

Public Demands

Efficient Management

Limited Resources

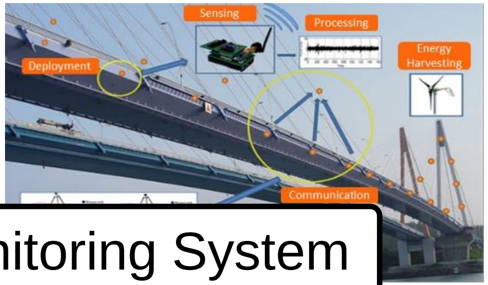


Public Expectations

Background

Visual Inspection

NDT Testing



Monitoring System

Performance Indicator

Performance Goal

Quality Control Plan

Reasons for the Action

There is a **REAL NEED** to standardize the quality assessment of roadway bridges at an European Level

CSO Approval	Start of the Action	End of the Action
13/11/2014	16/04/2015	15/04/2019

Objectives

Develop a guideline for the establishment of Quality Control (QC) plans in roadway bridges

reachable by pursuing the following 5 objectives:

(i) **Systematize knowledge on QC plans for bridges**;

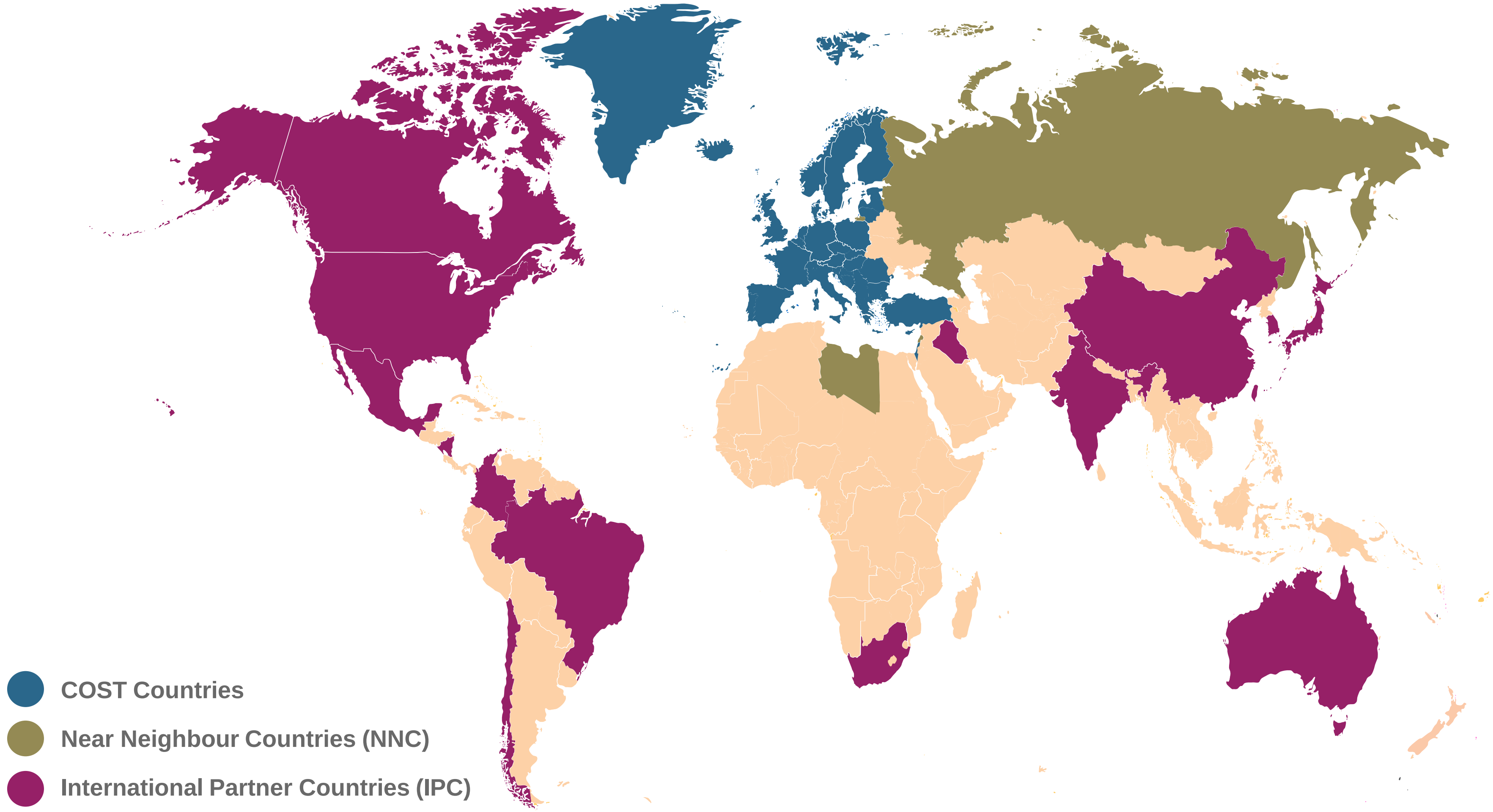
(ii) **Collect** and contribute to **up-to-date knowledge on performance indicators**

(iii) **Establish a wide set of performance goals**;

(iv) **Develop detailed examples for practicing engineers**;

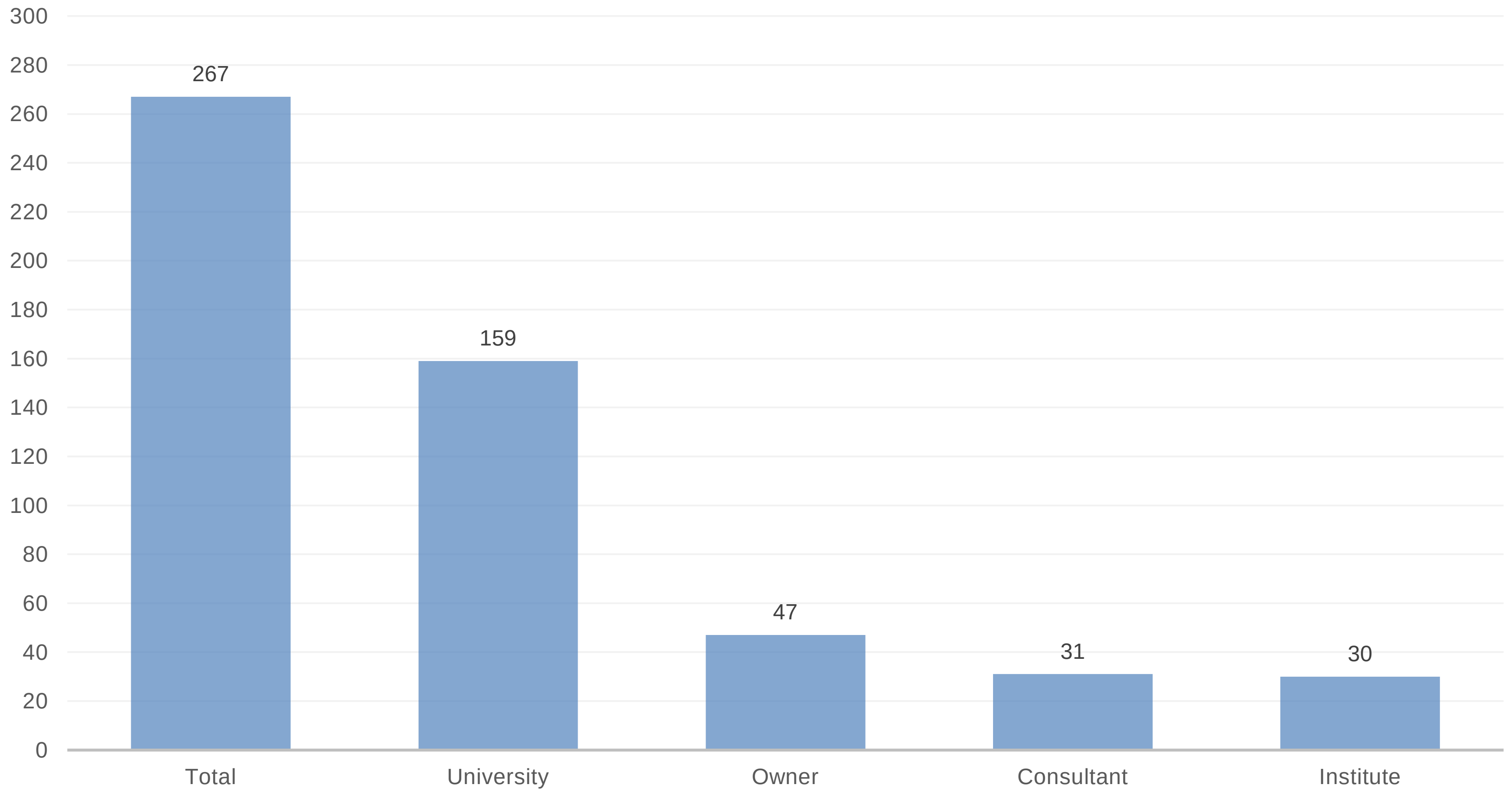
(v) **Create a glossary and a database from COST countries** with performance indicator values and respective goals.

Participants



38 COST Countries + 3 COST NNC + 15 IPC = 56 Participating Countries

Participants



Scientific Programme

- WG1 – Performance Indicators for Roadway Bridges
- WG2 – Performance Goals for Roadway Bridges
- WG3 – Establishment of a Quality Control plan
- WG4 – Implementation in case studies
- WG5 – Guidelines/Recommendations – Final Report

Final TU1406 Conference

Joint Event
COST Action TU1406
EuroStruct

25-26 March 2019
Guimarães, Portugal

Universidade do Minho
Escola de Engenharia

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Sustainable Bridge Management

RELEVANCE FOR BRIDGE OWNERS

João Amado - Infraestruturas de Portugal, Portugal
Nicolas Bardou – Vinci Autoroutes, France

Infraestruturas de Portugal

VINCI AUTOROUTES

22nd November 2018
Bergisch Gladbach, Germany

AGENDA

- Are we facing the same Problems?
- Bridging the GAP
- Common Challenges
- The Future
- A Final Word

ARE WE FACING THE SAME PROBLEMS?

- Decreasing budgets
- Aging infrastructure
- Extraordinary events and increased costs
- Fewer staff
- Pressure to ensure the availability
- Increase of the traffic loading
- Pressure to increase safety

Bridging the GAP

Challenge 1

- How to translate bridge performance?

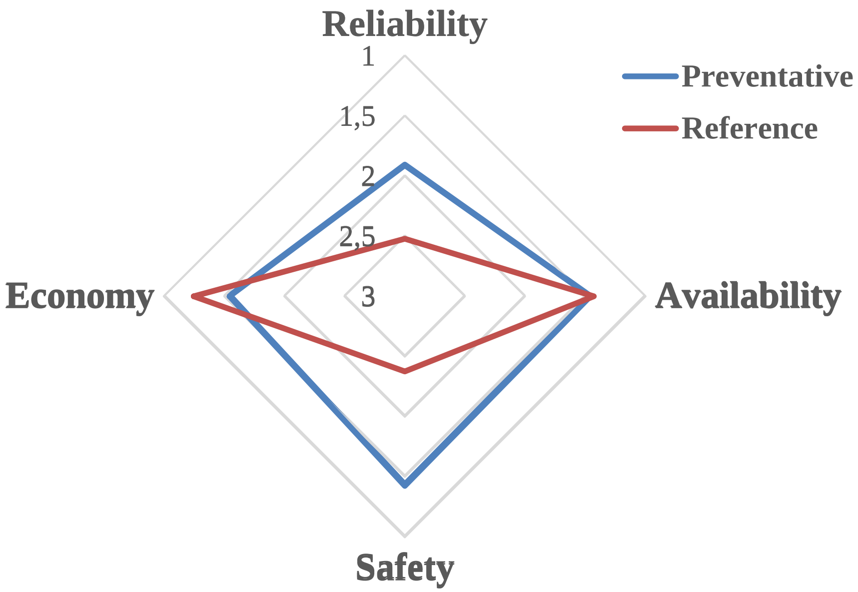
PI

- Defects
- Related to loads
- Related to cost & Importance
- Related to rating
- Related to material properties
- Environmental based
- Related to equipment & protection
- Related to dynamic behaviour
- Related to geometry changes
- Related to bearing capacity, structural integrity & Joints
- Related to Original construction & design

➢ Survey of indicators used throughout Europe
➢ Database with +750 terms
➢ 300 terms after homogenization and clustering

Challenge 2

- How to increasing transparency?

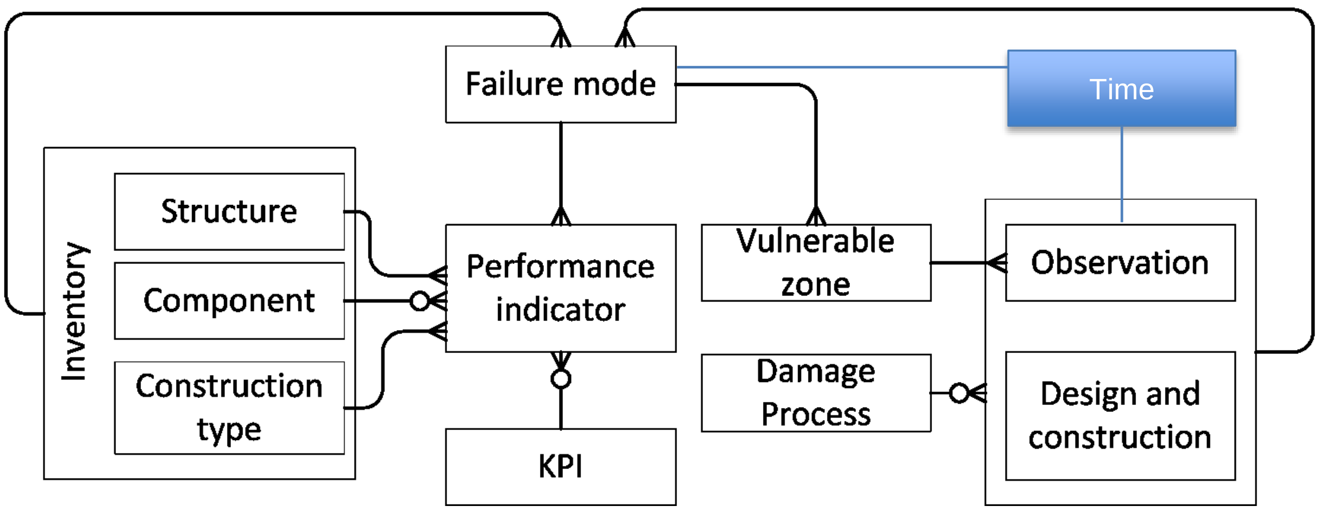


➢ Key Performance Indicators

➢ Comparative scenario

Challenge 3

- How to increase **accuracy of our assessments?**



- ➢ Framework that clearly mirrors inspector's reasoning
- ➢ Able to support a life cycle assessment

IN A NUTSHELL…

- ⇧ **Compliance** with best practices, harmonization
- ⇧ **Transparency** allowed by new indicators to better translate needs
- ⇧ **Accuracy** of the assessments with new tools, new frameworks
- ⇔ Keep control of the outcome
- ⇔ Reasonable costs

FUT
URE

A FINAL WORD

Reliable, safer and cost-effective structures are the common quest of bridge Owners.

More cooperation, reliable data and harmonization are the keys for these goals.

We expect that **COST TU1406** is the beginning of a **long-term path!**

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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

PERFORMANCE INDICATORS & PERFORMANCE GOALS

Alfred Strauss
University of Natural Resources and Life Sciences, Vienna, Austria
Irina Stipanovic
University of Twente, Enschede, Netherlands

BOKU

22nd November 2018
Bergisch Gladbach, Germany

Objectives
explore for bridge structures

Performance Indicators, PIs

- mechanical,
- technical,
- environmental

performance and degradation processes.

- complexity in time not covered in norm specifications
- not homogenized between the European countries

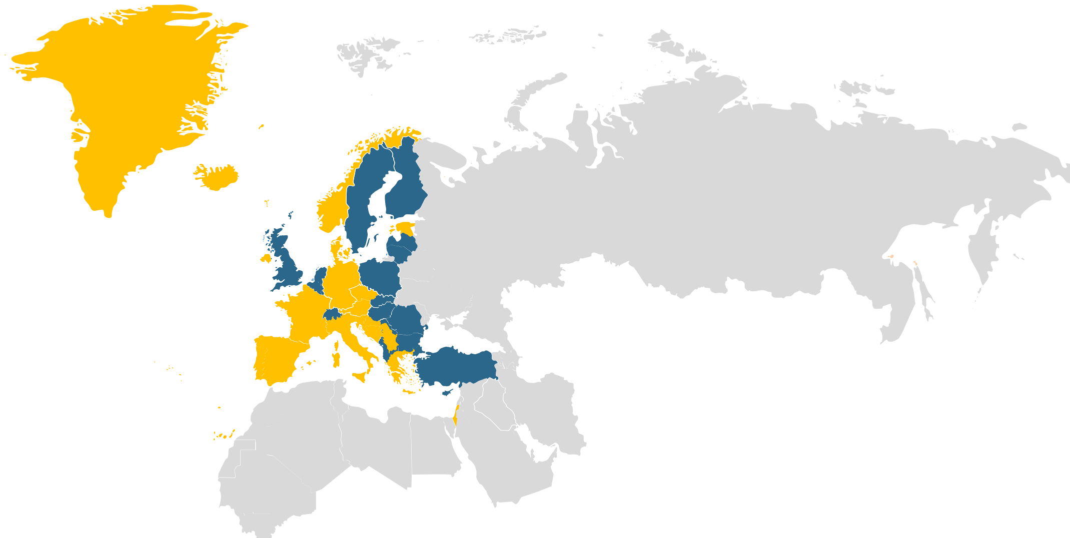
provide an overview

Performance Goals, PGs

linked to identified Key Performance Indicators.

- technical,
- environmental,
- economic, and
- social factors.

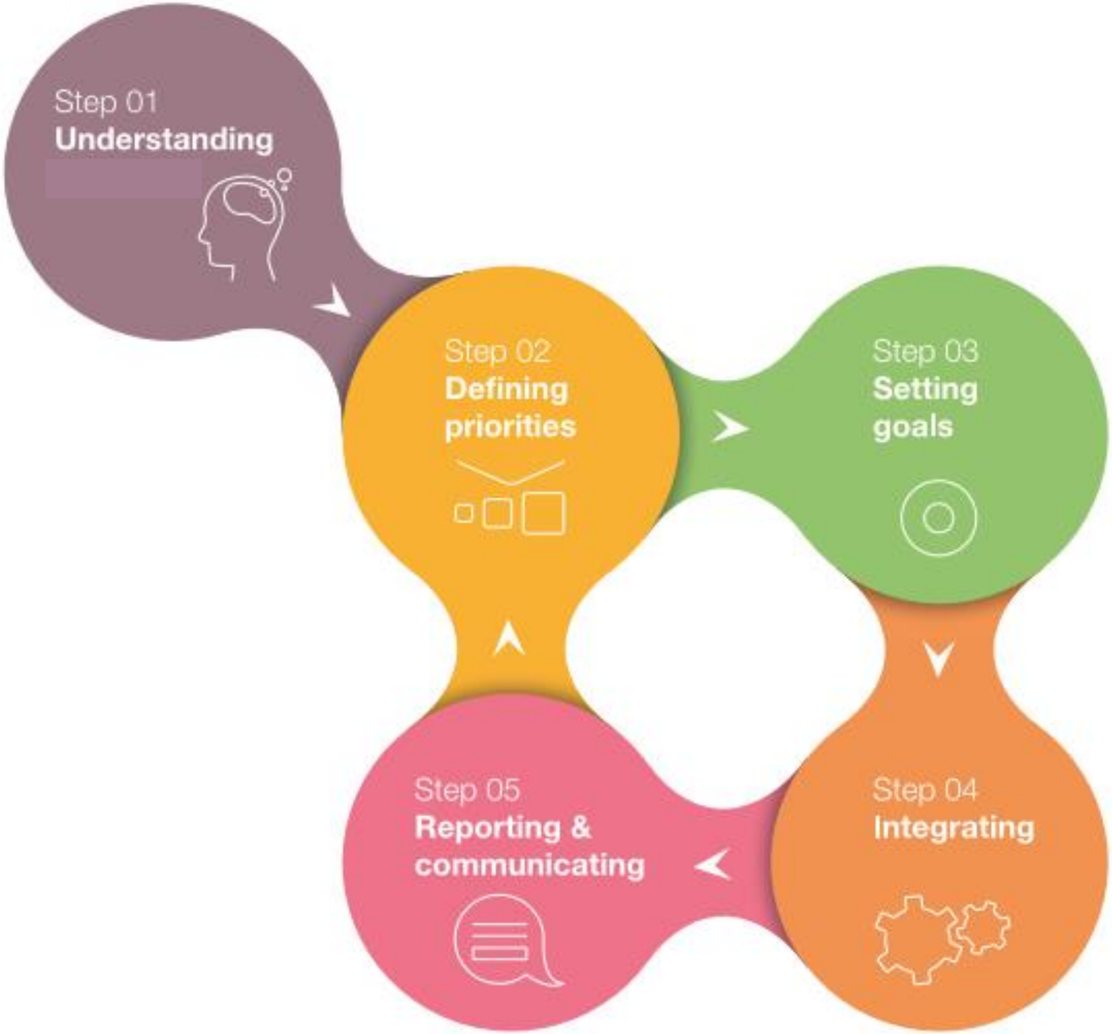
Screening of inspection, evaluation, assessment documents from the participating countries



Austria
Belgium
Bosnia and Herzegovina
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Israel
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Montenegro
Netherlands
Norway
Poland
Portugal
Romania
Serbia
Slovakia
Slovenia
Spain
Sweden
Switzerland
Turkey
United Kingdom

Screening of inspection, evaluation, assessment documents from the participating countries

Nature of existing processes
Performance indicators, PIs
Key Performance indicators, KPIs
Definitions
Inspection to management



Understanding Definitions, PI's and KPI's

Observation

It is **a datum** (i.e. piece of information) …, which may **be acquired by human senses** or by **measuring/recording** of some properties via adequate instruments. Observations can be qualitative i.e. only the absence or presence of a property is noted, or ... The observation is a perception of human senses or data measured by instrument that is regarded as relevant within the context of the inquiry.

Indicator

It is something that **shows** what **a situation is like**. The "situation" depends on the context of an inquiry. The indicator can be **qualitative** (e.g. bad, good, etc.) or **quantitative** and is based on analysis of one or several observations.

Understanding Definitions, PI's and KPI's

Performance Indicators, PI's

Performance indicator **measures fitness** for purpose of a physical object such as bridge or its element. Since the fitness for purpose (i.e. quality) can change over time, so does the value of a performance indicator. Maintenance interventions can also change the value of performance indicator and therefore the performance indicators of physical objects also mirror the performance of agency responsible for their maintenance. It is obvious that **bridge performance relates** to **safety** and **serviceability**, but other performance criteria can be useful as well.

Understanding Definitions, PI's and KPI's

Key Performance Indicators, KPI's

KPIs relate to a whole bridge and are as follows:

- **Reliability** is the probability of structural failure (safety), operational failure (serviceability) or any other failure mode occurring during the service life of the bridge.
- **Availability** is the proportion of time a bridge is open for service. It does not include failure-related service outages but the ones due to planned maintenance interventions. Alternatively, the Availability can be measured as additional travel time due to an imposed traffic regime on bridge.
- **Safety** is the situation of life and limb being protected from harm during the service life of a bridge. Loss of life and limb due to structural failure is not included by this definition (since it would overlap with the Reliability).
- **Economy** is related to minimizing the long-term cost of maintenance activities over the service life of a bridge.
- **Environment** is related to minimizing the harm to environment during the service life of a bridge.

Screening of inspection, evaluation, assessment documents from the participating countries → 375 Terms

Performance Indicators, PIs	Performance Indicators 2nd Order	Observations
absence/missing	special inspection requisite	blistering
contamination	step in transition slab	bulging
cracking	resistance	cavitation
damage	system functionality	clogged
…	…	…
displacement	robustness	inadequate clearance
movements	safety index	traffic restrictions
execution defects	vulnerability	traffic volume
vibrations/oscillations	element functionality level	traffic loading

- ✓ Material
- ✓ Component
- ✓ System

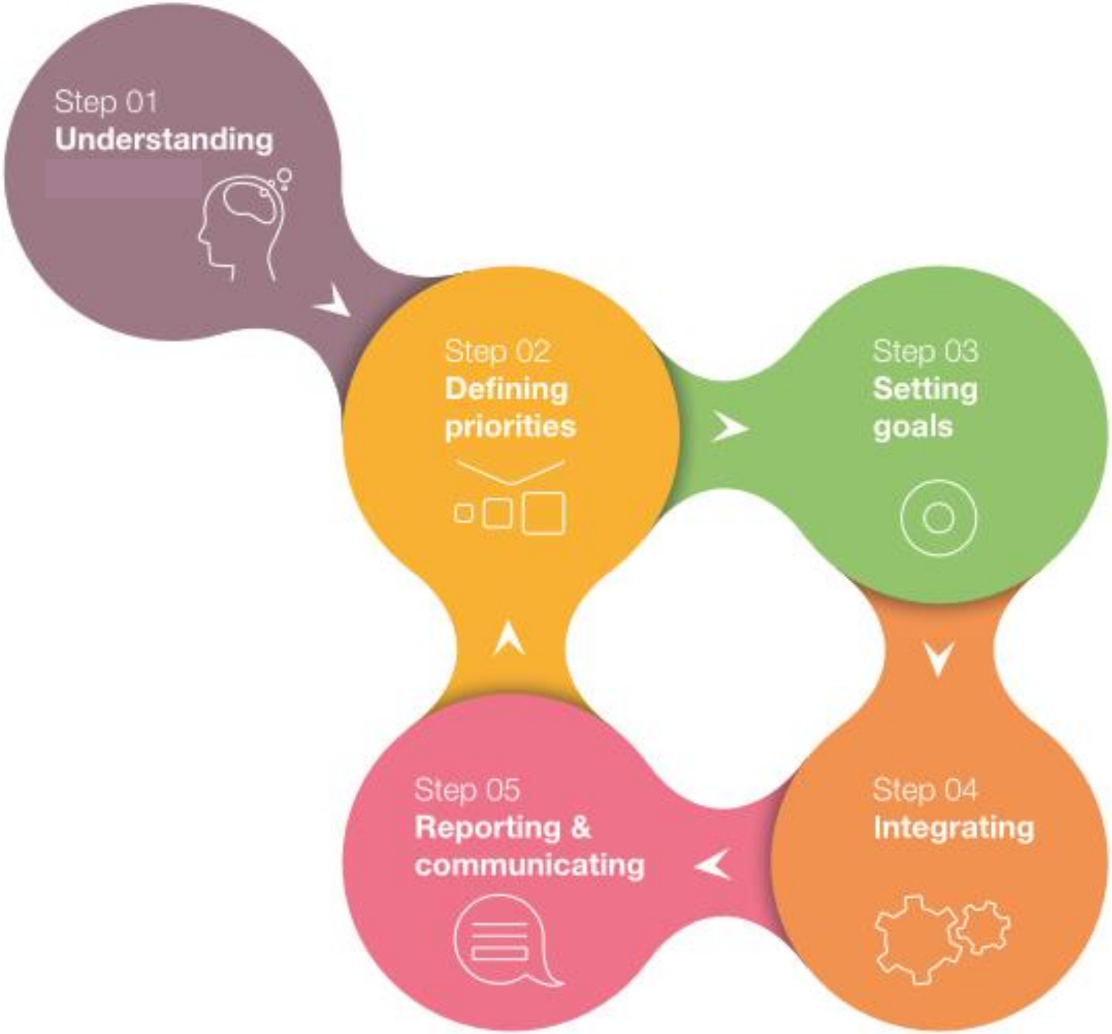
TU1406 database comparison of terms between countries

Damage Processes	Other Data
abrasion	accessibility to damage
aggradation (alluviation)	carrying capacity factor
…	…
biological growth	gross weight of a vehicle
freeze-thaw	permanent loading

Screening of inspection, evaluation, assessment documents from the participating countries

Nature of existing processes
Key Performance indicators, KPIs

KPI	**Management**
PI_i	Inspection
Component, *k*; System	



From Performance indicators (PIs) to Key Performance indicators (KPIs)

KPI	Management
PI_i	Inspection
Component, *k*; System	

PIs	Performance Indicators
1	absence/missing
2	contamination
3	cracking
4	damage
5	…
6	displacement
7	movements
	…
20	Vibrations/oscillations

KPI_r	Reliability $r = 3$		
PI_6	displacement	weights	2
PI_3	cracking		3
	…		
PI_{13}	…		3
Component, *k*; System		α_{ik}	r_i

KPI_a	Availability $a = 3$		
PI_{15}	deflection	weights	3
PI_2	…		3
	…		
$PI_{..}$	…		3
System		α_i	a_i

KPI_s	Safety $s = 3$		
PI_1	absence/missi	weights	3
PI_4	…		3
	…		
$PI_{...}$	…		3
Component, *k*; System		α_{ik}	s_i

KPI_E	Economy $e = 3$		
PI_{18}	maintenance	weights	3
PI_{15}			3
	…		
$PI_{...}$	…		3
System		α_i	e_i

KPI_U	Environment $u = 3$		
PI_{23}	CO_2 footprint	weights	1
PI_{24}	…		3
	…		
$PI_{...}$	…		3
System		α_i	u_i

R. Hajdin, M. Kušar, S. Mašović, P. Linneberg, J. Amado and N. Tanasić 2018. WG3 Technical Report Establishment of a Quality Control Plan. COST TU 1406 Quality Specification for European Roadways

Status

WG1

Technical Report

Performance Indicators for Roadway Bridges of Cost Action TU 1406

General

Performance Indicators terms after surveying

Operators

Operators list of documents and database per country

Research

Research list of documents and database per country

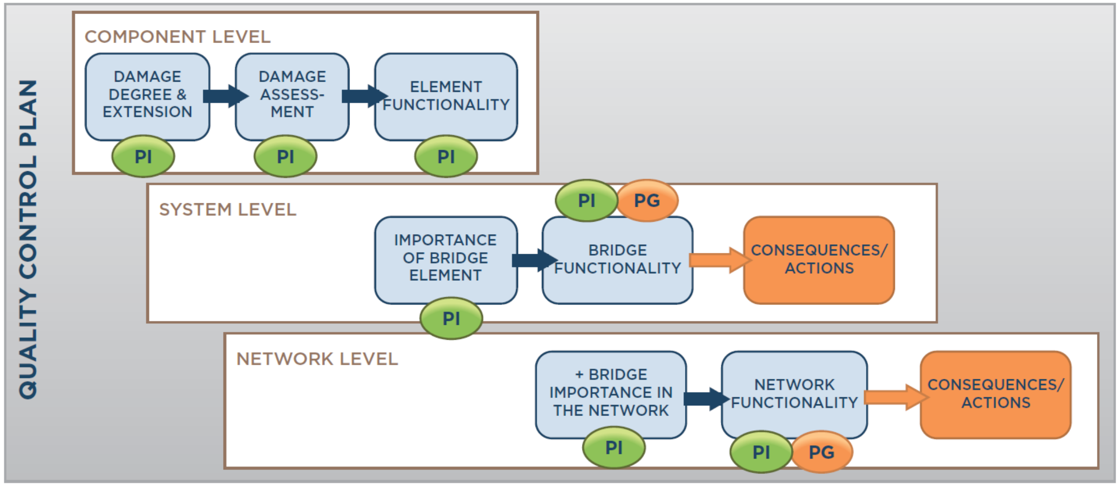
Glossary

Glossary and specific term sheet per country

available on website: www.tu1406.eu

Status

WG2
Technical Report
Performance Goals for Roadway Bridges
OF COST ACTION TU 1406



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COST ACTION

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COST ACTION

INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

QUALITY CONTROL FRAMEWORK

Prof. Dr. Rade Hajdin - University of Belgrade, Serbia

Грађевински факултет Универзитет у Београду

ESF provides the COST Office through a European Commission contract

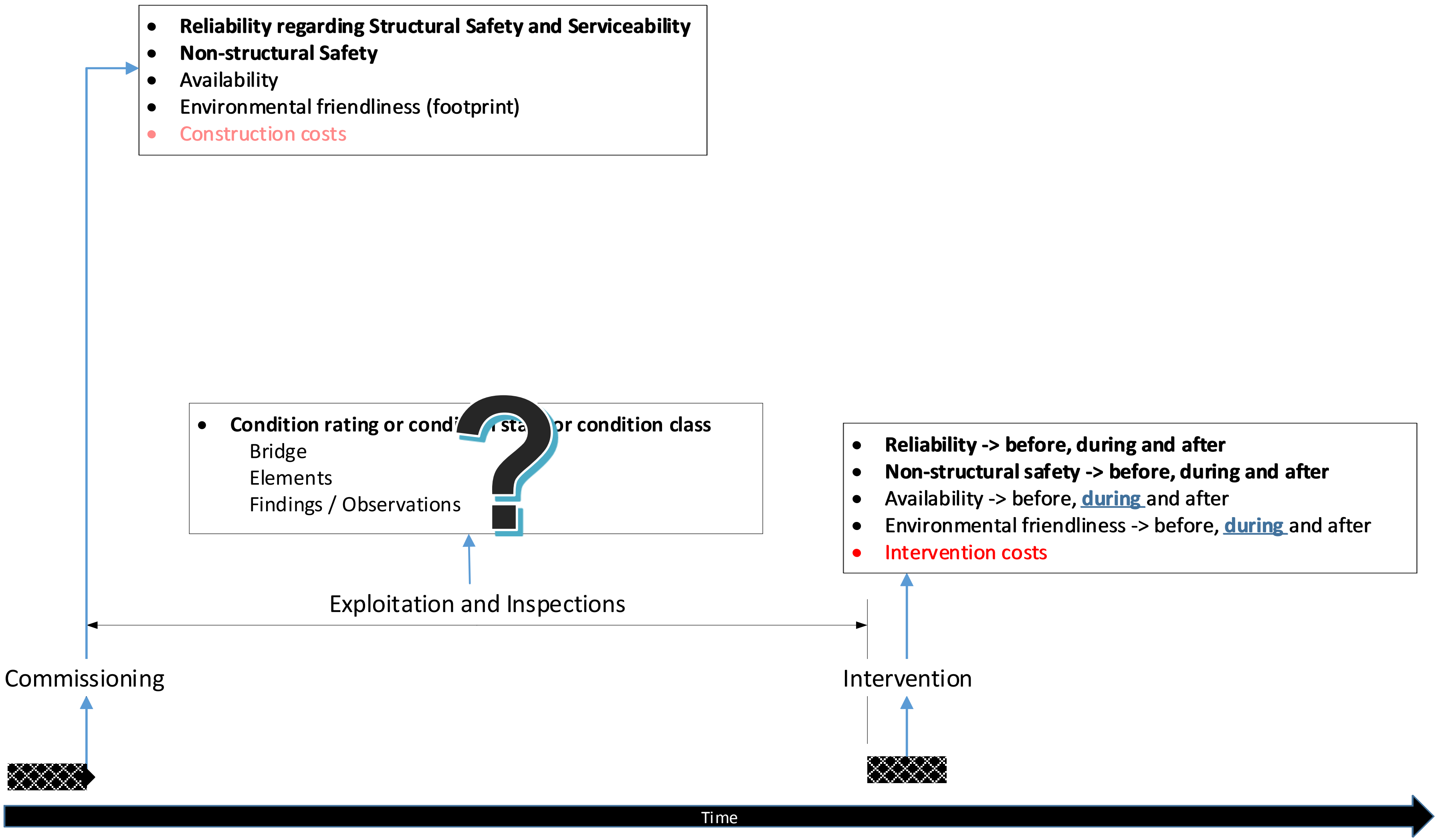
COST is supported by the EU Framework Programme

COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

22nd November 2018
Bergisch Gladbach, Germany

Design

- Actions that are relevant for the design:
  - Dead load
  - Live load (purpose of the bridge)
  - Environmental loads
- Combination of these actions pose a threat for the safety and serviceability of structures.
- The structural analysis and checks are performed so that this threats doesn’t induce a failure of a bridge
- Different combination of action trigger different failure modes.
- This is not limited to overall collapse.
- The failure modes or prevention of these is a basis for design.
- It should be a basis for diagnosing existing structures.



- Reliability regarding Structural Safety and Serviceability
- Non-structural Safety
- Availability
- Environmental friendliness (footprint)
- Construction costs

- Condition rating or condi … sta … or condition class
Bridge
Elements
Findings / Observations

- Reliability -> before, during and after
- Non-structural safety -> before, during and after
- Availability -> before, during and after
- Environmental friendliness -> before, during and after
- Intervention costs

Exploitation and Inspections
Commissioning
Intervention
Time

Constraints to QC Framework

- **Current inspection practice should not significantly change!**
  - Acceptance and costs
- Collect findings visually or with simple tools
- “Onion” model:
  - Level of Accuracy can be increased by sophisticated techniques if they provided the information that justify their costs.
- Challenging task!

Approach I

Work packages

1. Preparatory work (commissioning or after changes in actions)
   - Define the vulnerable zones
   - Evaluation reliability of undamaged structure = “virgin” reliability for current loading
   - The background data need to be readily accessible in a database
2. Inspections incl. in-depth investigation if needed (regular intervals)
   - Identify damages
   - Identify symptoms
   - Test material properties
   - Lab test
   - Assessment of reliability and non-structural safety

Approach II

Work packages

3. Planning (generally after every intervention)
   - Identify active damage processes
   - Damage forecast
   - Development of reliability and non-structural safety over time
   - Define the reference scenario (e.g. intervention at the end of service life)
   - Define further scenarios inkl. cash-flow, availability, reliability, non-structural safety and environmental impact
   - Decision making i.e. triggering of interventions
4. Collecting intervention data

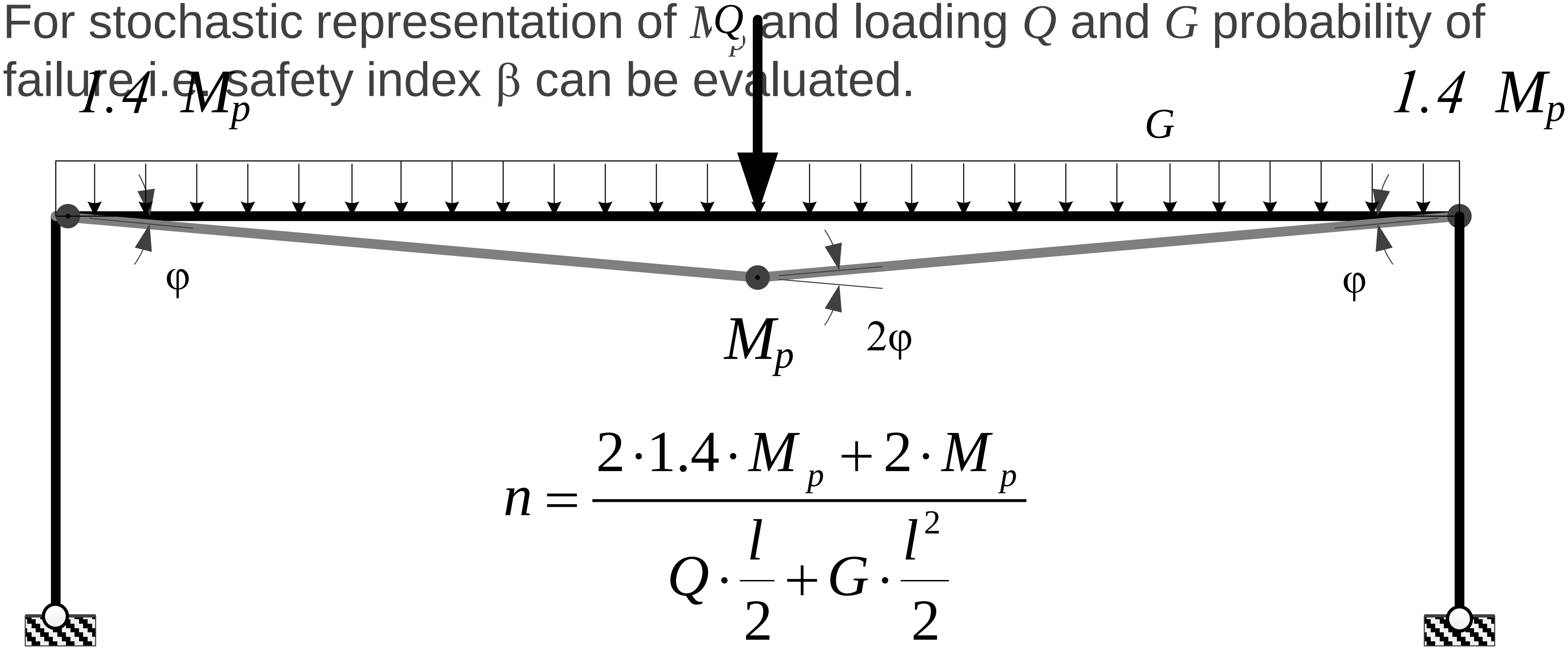
"Virgin" reliability

- **"Exact" evaluation by structural analysis for current loading**
  - **1D (frame), 2D (plates and shells) or 3D (solids) structural analysis**
  - **Limit states theorems**
- **Simplified evaluation:**
  - Non-landmark bridges, simplified structural systems
  - Undamaged bridge, resistance based on a design code
    - Dead load
    - Live load

    } **Characteristic values & quantile assumptions**
  - Relevant sample of bridges of same type
    - Errors in bygone codes, conceptual weaknesses/detailing issues to be duly considered

Application of limit states theorem

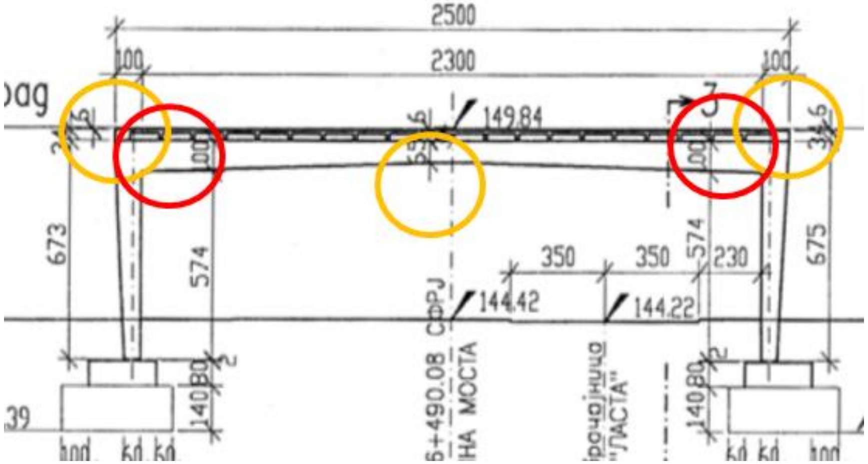
For stochastic representation of M_p, and loading Q and G probability of failure i.e. safety index β can be evaluated.



$$n = \frac{2 \cdot 1.4 \cdot M_p + 2 \cdot M_p}{Q \cdot \frac{l}{2} + G \cdot \frac{l^2}{2}}$$

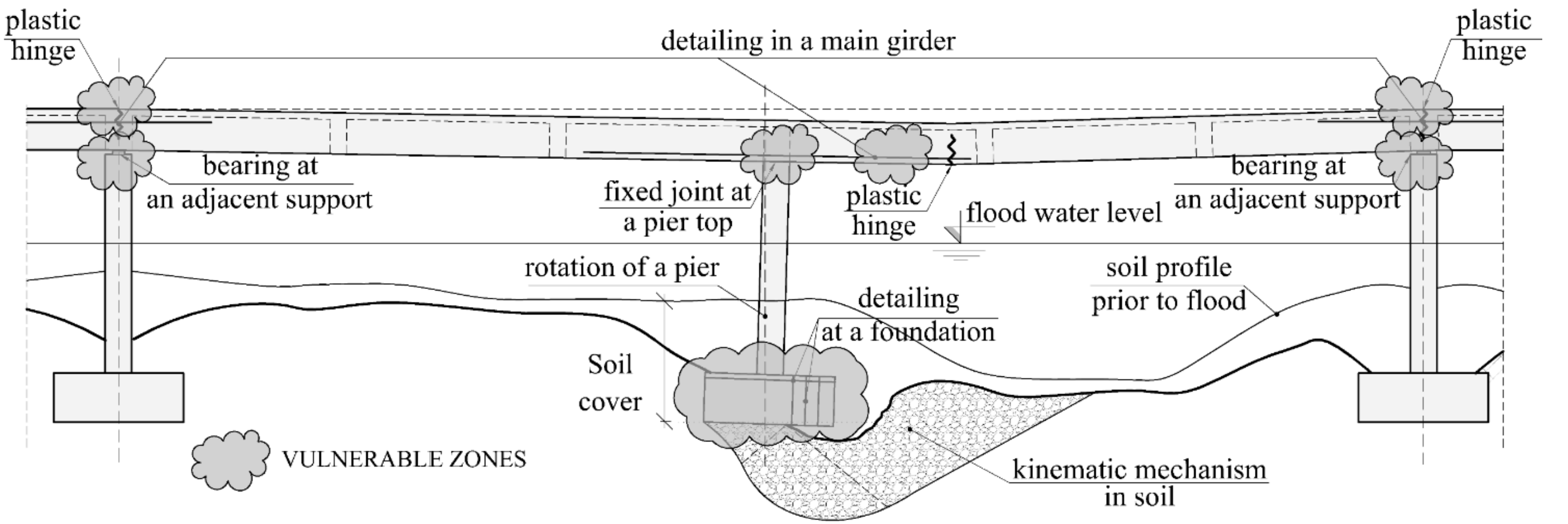
Vulnerable zones – live load

- Ductile vulnerable zone contribute to the same failure mode
- modes on their own.

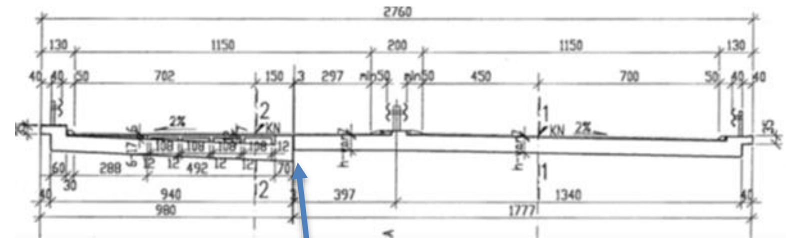


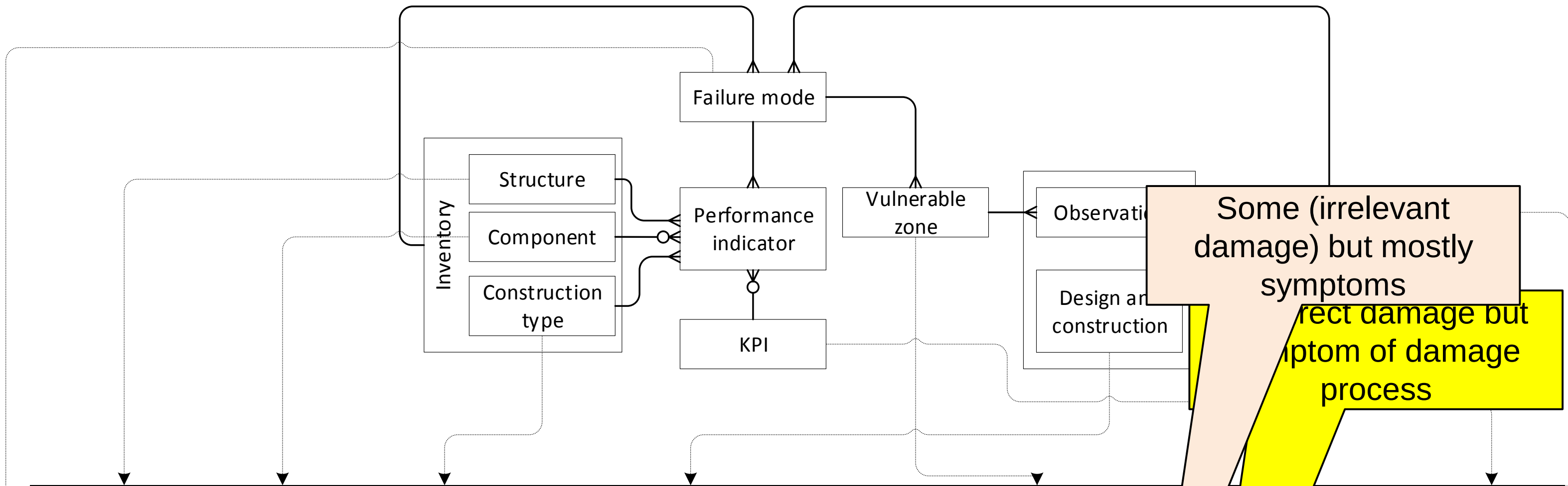
HMS-high suging moment zone	orange circle	ductile
HMH - high hoging moment zone		
HSS - high shear zone	red circle	britle

Vulnerable zone - flooding



Inspection - findings

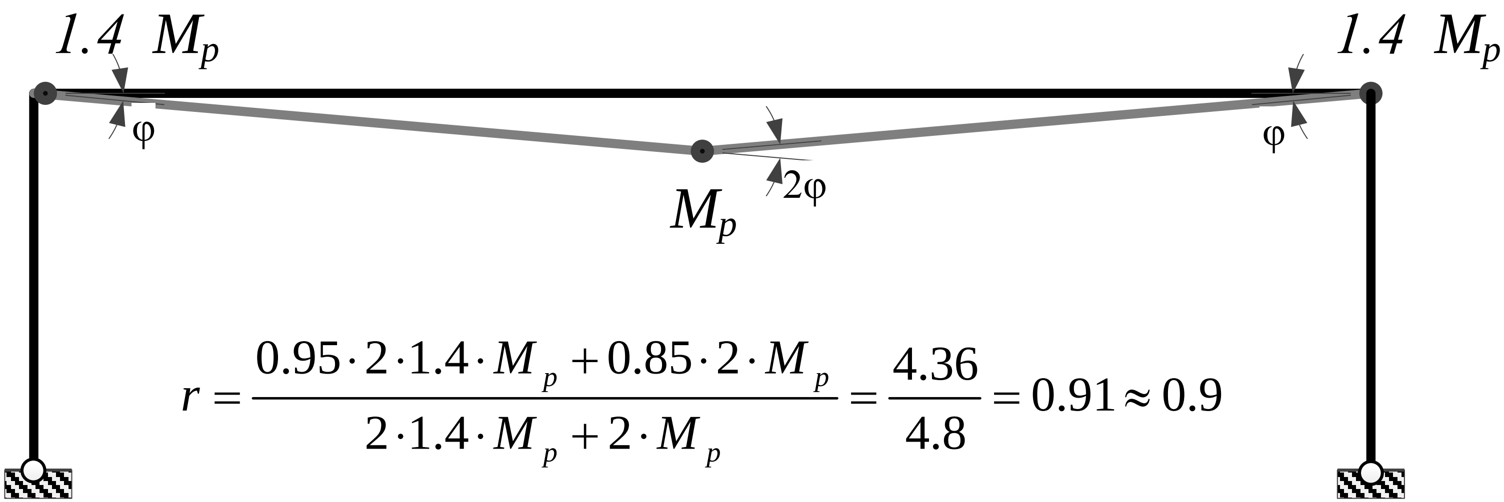




Frame bridge	Deck (old)	Reinforced concrete	1963	Bending failure mode	HMS	Corrode[illegible]ment	Reliability (Structure safety)
	Deck (new)	Reinforced concrete	1977			Corrod[illegible]rei[illegible]ement	
	Deck (old)	Reinforced concrete	1963			[illegible]spa[illegible]	
	Deck (new)	Reinforced concrete	1977			Spa[illegible]g	
	Deck (new)	Reinforced concrete	1977		HMH	Corro[illegible]ed r[illegible]forcement	
	Deck (old)	Reinforced concrete	1963			Corroded r[illegible]nforcement	
	Deck (new)	Reinforced concrete	1977			Sp[illegible]lling	
	Deck (old)	Reinforced concrete	1963			S[illegible]alling	
	Deck (new)	Reinforced concrete	1977			Efflorecences	
	Deck (old)	Reinforced concrete	1963			Efflorecences	
	Deck (old)	Reinforced concrete	1963	Shear failure mode	HSS	Crack	
	Deck (old)	Reinforced concrete	1963	Falling chunks		Spalling	Safety (Life and limb)
	Deck (new)	Reinforced concrete	1977			Spalling	
	Railings	Steel	1977	Falling of the bridge		Broken	

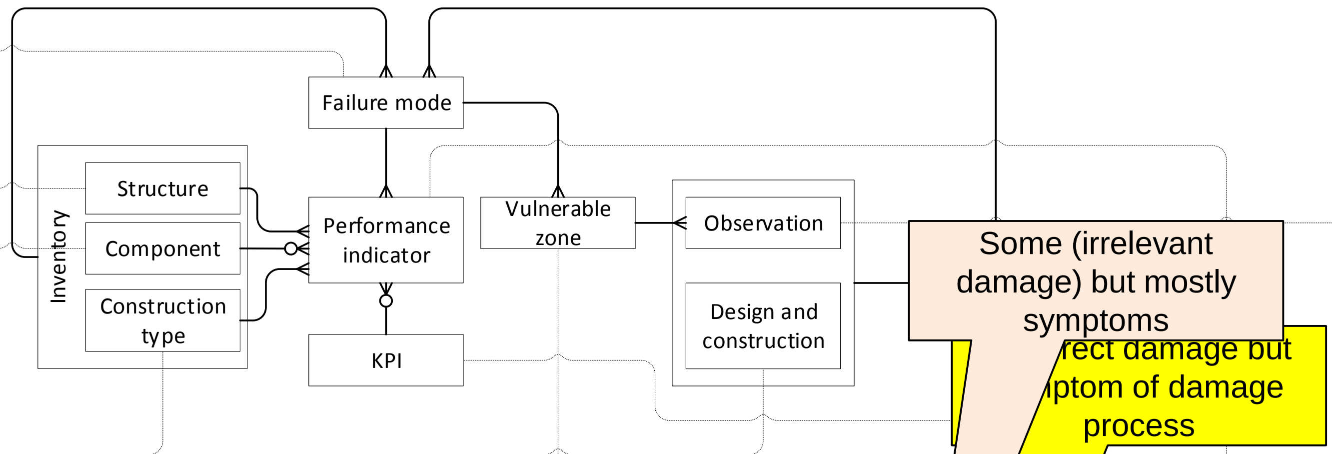
Impact of damages

- Resistance is essentially internal dissipation rate that decrease with each damage.
- Resistance decrease in midfield 15% and over the column 5%



$$r = \frac{0.95 \cdot 2 \cdot 1.4 \cdot M_p + 0.85 \cdot 2 \cdot M_p}{2 \cdot 1.4 \cdot M_p + 2 \cdot M_p} = \frac{4.36}{4.8} = 0.91 \approx 0.9$$

Reliability assessment of damaged bridge



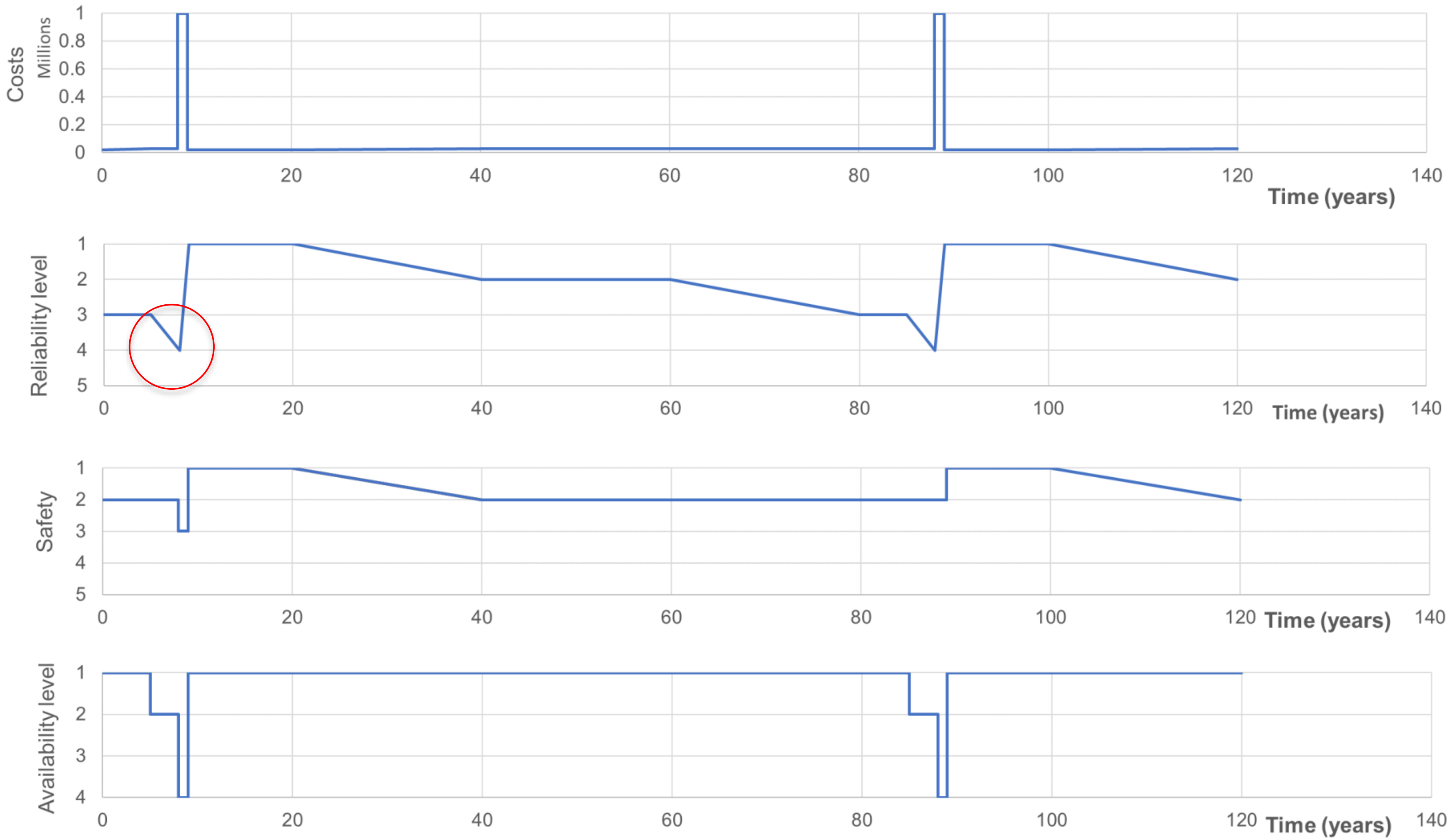
	Deck (old)	Reinforced concrete	1963			Corroded reinforcement			
	Deck (new)	Reinforced concrete	1977		HMS	Corroded reinforcement			
	Deck (old)	Reinforced concrete	1963			Spalling			
	Deck (new)	Reinforced concrete	1977			Spalling			
	Deck (new)	Reinforced concrete	1977	Bending failure mode		Corroded reinforcement			
	Deck (old)	Reinforced concrete	1963			Corroded reinforcement	Reliability (Structure safety)	3	3
	Deck (new)	Reinforced concrete	1977		HMH	Spalling			
	Deck (old)	Reinforced concrete	1963			Spalling			
Frame bridge	Deck (new)	Reinforced concrete	1977			Efflorecences			
	Deck (old)	Reinforced concrete	1963			Efflorecences			
	Deck (old)	Reinforced concrete	1963	Shear failure mode	HSS	Crack		2	
	Deck (old)	Reinforced concrete	1963	Falling chunks		Spalling			
	Deck (new)	Reinforced concrete	1977			Spalling	Safety (Life and limb)	2	2
	Railings	Steel	1977	Falling of the bridge		Broken		2	

Planning

- For different maintenance scenarios (strategies) one has to estimate
  - Reliability (or structural safety and serviceability margins)
  - Safety (loss of life and limb not included in structural failures)
  - Availability
  - Costs
  - Environmental impact

  over time.
- To this end one has to forecast reliability and safety development over time.
- The current models for condition development can be used to this purpose.

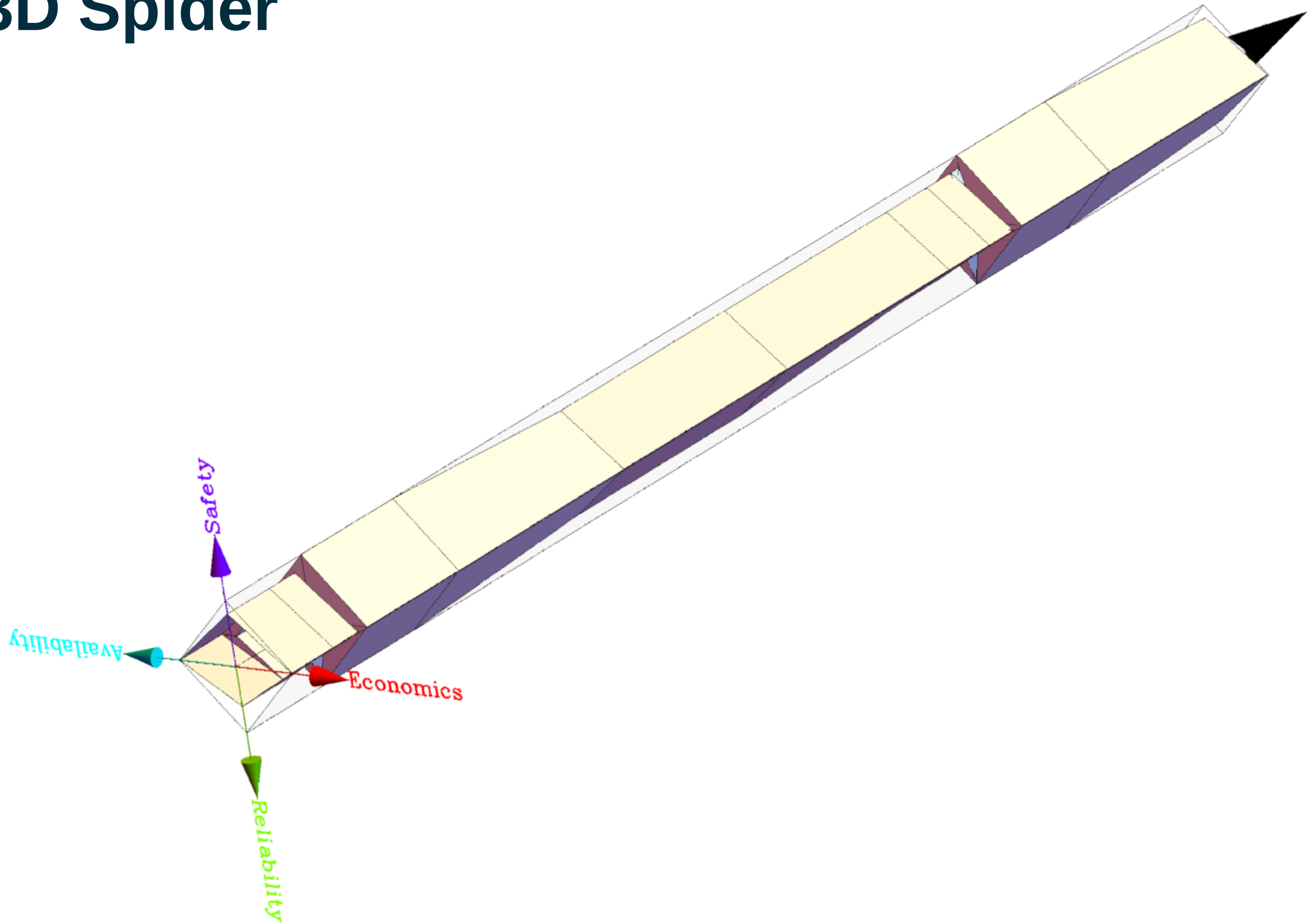
Example of maintenance scenario



Comparing scenarios

- In this COST Action this approach was not chosen in order to let owners to develop their own decision approaches
  - Weighted sum
  - MAUT
  - Utility theory
- Future alternative: Monetization
  - Cost are already monetized
  - Availability can be easily monetized
  - Reliability can be only monetized together with the consequences of “failure” -> Risk
  - Safety can be only monetized together with the consequences for “life and limb” -> Risk
- The monetization is widely adopted method in research community.

3D Spider



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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

Joseph Bridge over the Jordan river - Israel Case study - Steel truss road bridge

WG4

Amir Kedar – WG4 Leader , Kedmor Engineers Ltd., Israel

Mor Machlev – Kedmor Engineers Ltd., Israel

KEDMOR

22nd November 2018
Bergisch Gladbach, Germany

Content:

1. Preparing a case study
2. General data on the bridge
3. Technical condition
4. Potential failure modes
5. Additional investigations
6. KPI and QCP

Preparing a case study

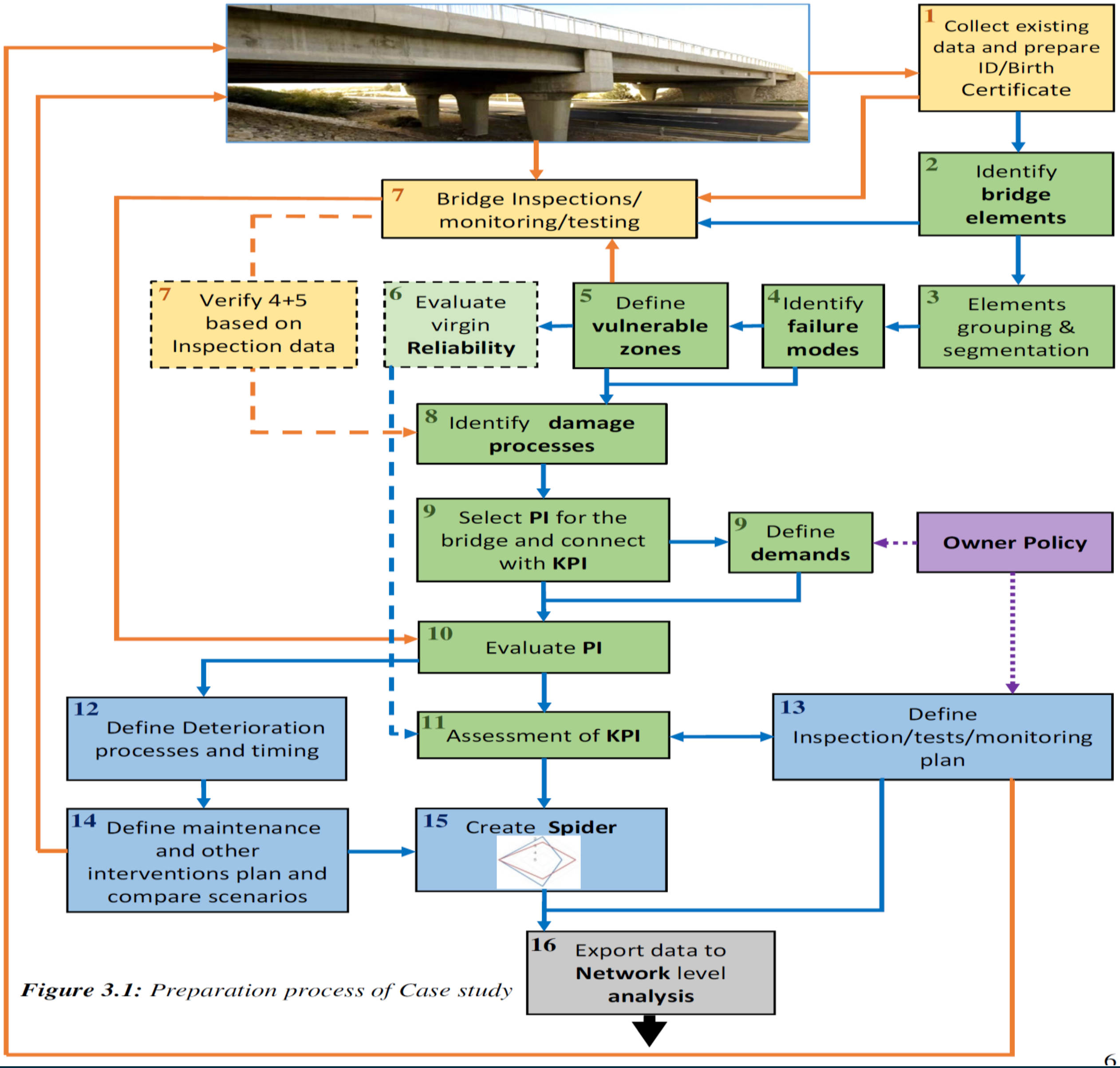
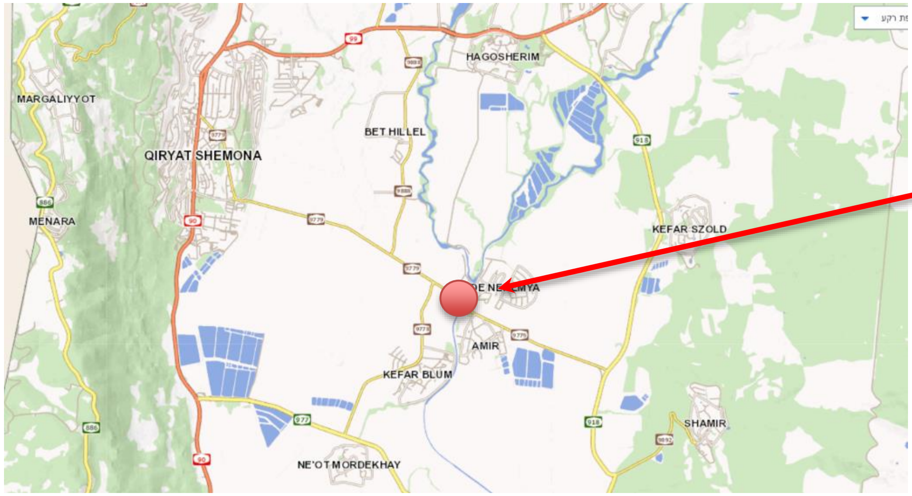
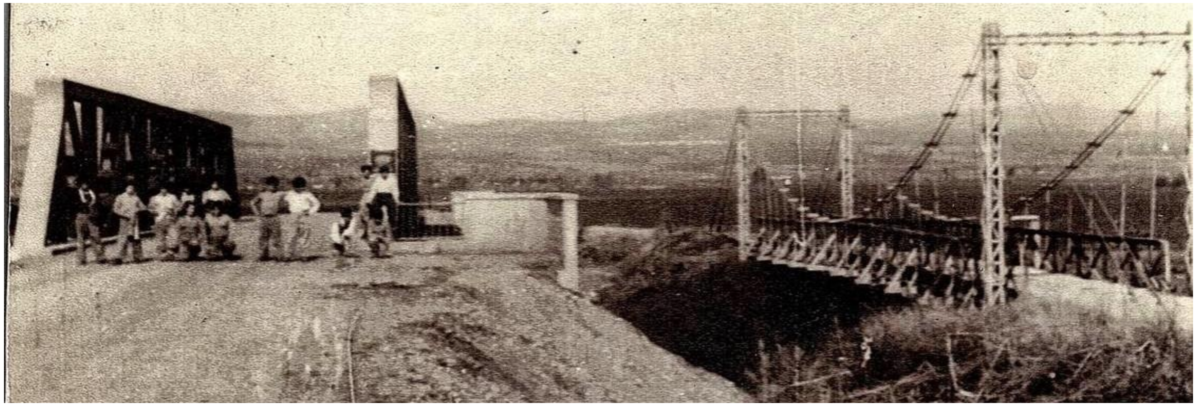


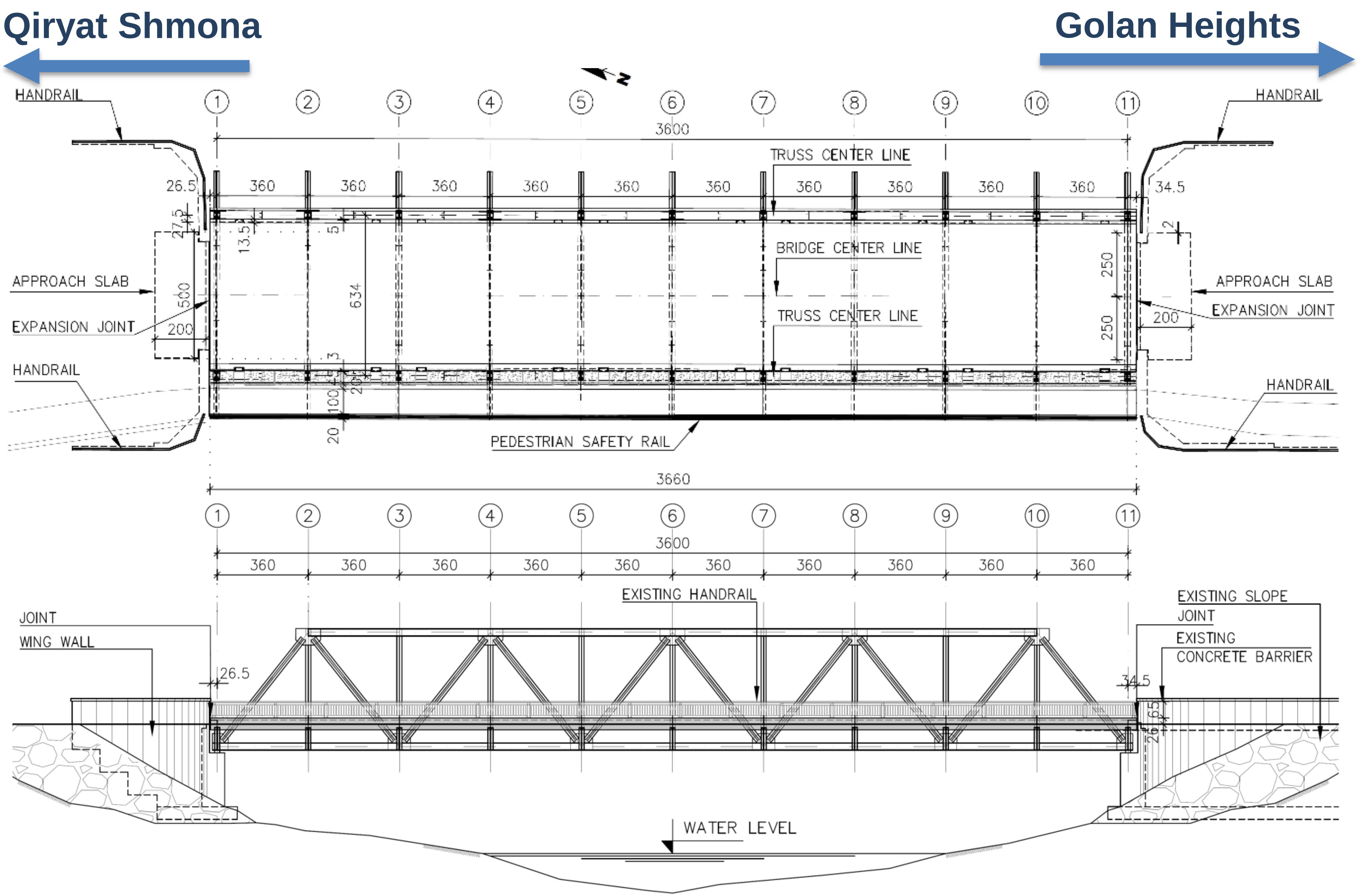
Figure 3.1: Preparation process of Case study

General data on the bridge:



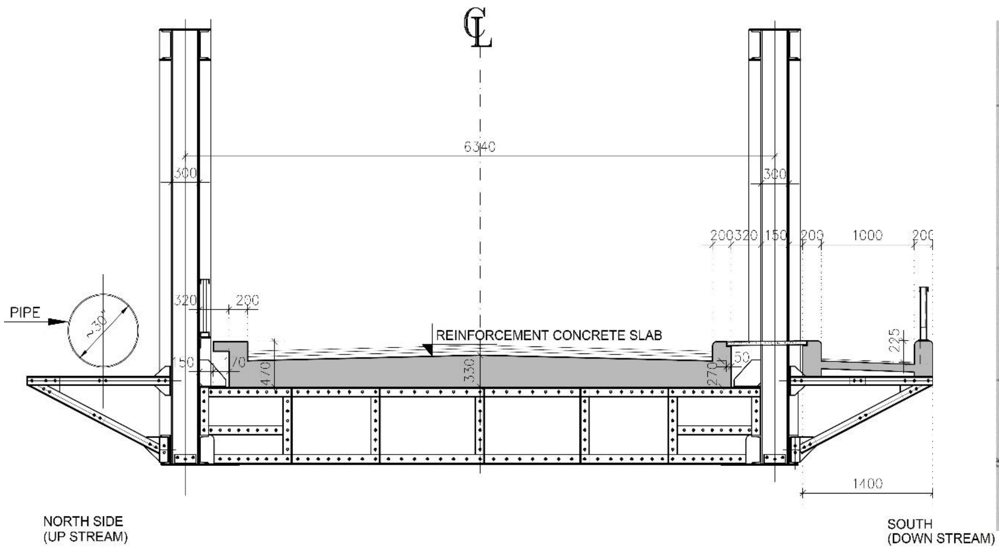
- Built 1956
- 36 meter single-span half-through steel truss bridge
- Riveted steel plates, angles and U shape steel profiles
- reinforced concrete slab
- The bridge carries road no. 9779 across the Jordan river between north of Galilee and the Golan heights

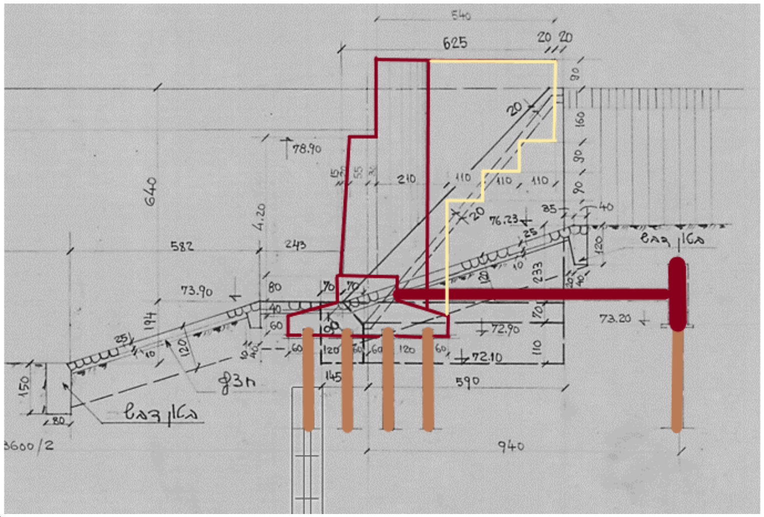




Qiryat Shmona
Golan Heights
HANDRAIL
APPROACH SLAB
EXPANSION JOINT
PEDESTRIAN SAFETY RAIL
TRUSS CENTER LINE
BRIDGE CENTER LINE
3600
3660
360
26.5
34.5
200
250
634
EXISTING HANDRAIL
EXISTING SLOPE
JOINT
WING WALL
EXISTING
CONCRETE BARRIER
WATER LEVEL

- Average annual daily traffic : **6800** (2012)
- Number of heavy cars / 24h : **unknown**
- The bridge is frequently crossed by heavily loaded army vehicles (**MLC 120**).
- Foundation are inaccessible
- Massive RC Abutments
- 4 rows of hammered piles with rear deadman anchor





Substructure:

Abutments made from reinforced (discovered during investigations) massive concrete with deadman block at the back tied by buried tension girders.

Superstructure:

- 36 meters long half through riveted steel truss.
- Reinforced concrete slab of 10 bays each 3.6 meter long.
- 2 parallel trusses with centerline distance of 6.34 meter.
- 11 rigid transvers cross girders with 810mm depth forming a U shape rigid deck structure.
- Reinforced concrete deck with variable depth of 330mm to 270mm and constant width of 5570mm connected rigidly onto the transvers girders.
- 10" high pressure sewage water pipe is supported by steel cantilever brackets original designed for 30" waterpipe.
- pedestrian concrete walkway is supported in a similar way.

Equipment:

- 60mm Asphalt pavement
- Reinforced concrete slab pedestrian walkway
- Safety barrier made from steel
- Pedestrian walkway handrail made from steel
- Old buried expansion joints (not designed as buried)
- Fixed (rotation free) bearing on east side
- Roller bearing on west side

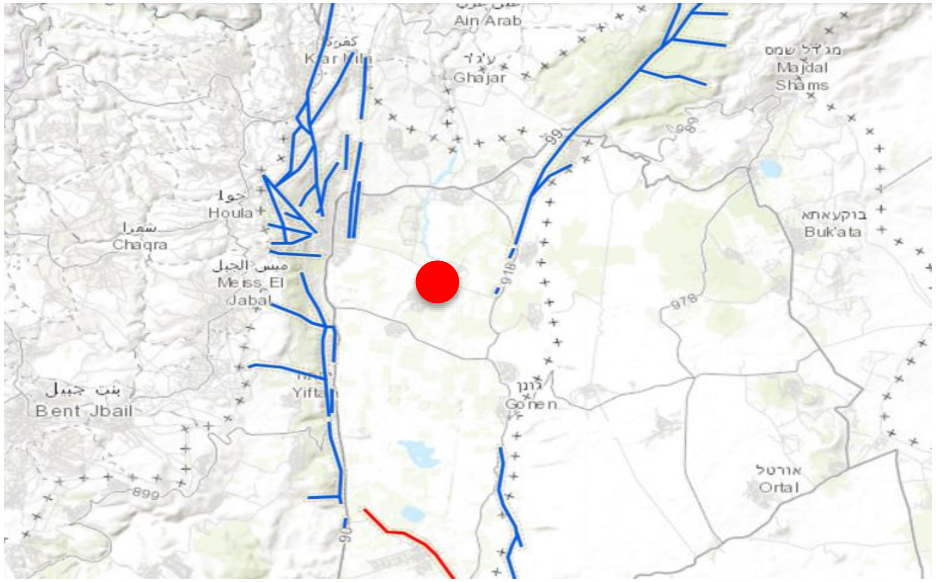
Current performance Indices in use:

According to the Israeli bridge condition rating system the status is:

CPI_{av}=72 meaning the structure is in poor to fair condition with moderate to severe damages and possible severe influence on one or more of the bridge or element performance.

CPI_{crit}=55 meaning possible failure of an element with severe defect or damage reducing the load carrying capacity. (taking into account the NDT done later, this score will be further reduce to 28)

SVIb = 66 The **Seismic vulnerability index** is classified as second grade meaning an action should be taken in the near future for seismic retrofitting of the bridge.



Potential failure modes:

ULS:

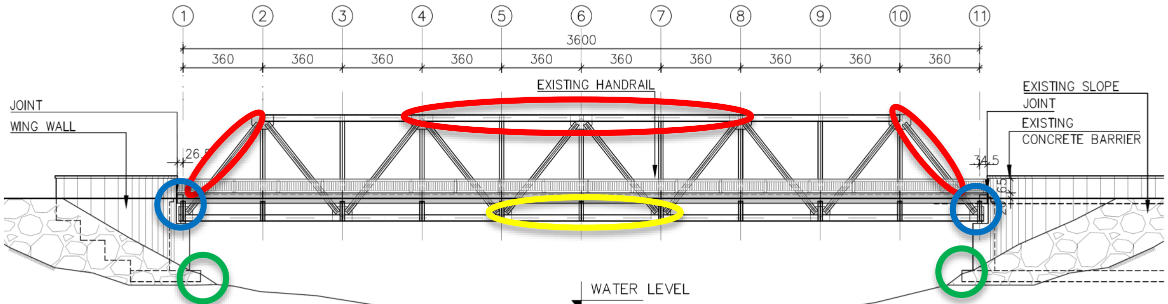
- **Truss failure** – Local failure of truss members and riveted section disintegration due to sheared rivets (fatigue).
- **Truss failure** – global bridge failure due to loss of stability of the truss and lateral buckling under heavy live load as a result of transvers girder to truss connection rivet failure (Limiting the sway restrain of the main truss by the transvers girders)
- **Truss failure** – local failure of truss vertical and diagonal members due to accidental load from heavy load transportation vehicle.
- **Transverse girder bending/shear failure** – Due to excessive dynamic effect of heavy vehicles crossing the bridge.
- **Failure due to Seismic loading** (The bridge is located at high seismic zone) SVIb value is low.

Potential failure modes:

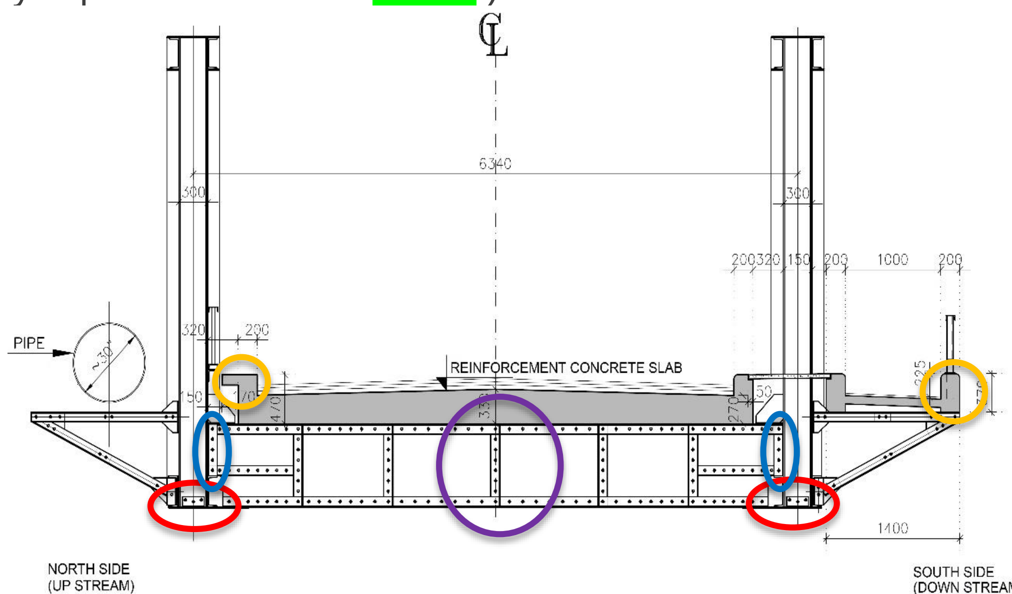
SLS:

- **Main Safety Barrier failure** – Due to accidental load from heavy load transportation vehicle
- **Pedestrian Safety handrail failure** – Due to increased corrosion at the edge and soffit of the pedestrian concrete pathway and loss of anchoring of the handrail vertical members
- **Bearing failure** – Loss of functioning of the roller bearing and rotation of the fixed bearings due to corrosion and accumulation of debris
- **Asphalt pavement failure** – Due to nonfunctioning Joints and drainage.
- **Concrete curb failure** – Possible falling of concrete chunks over the Jordan river where tourists are using boats.

Identifying Vulnerable Zones:



Vulnerable zones – main truss (Red=high compression zones, Yellow=high tension zone, Blue=Bearing area, Area possibly exposed to Scour = Green)



Vulnerable zones – Cross Girder to deck connection (Red= compression zones, Blue=Bearing area, Orange= Slab edge, Purple= Cross girder sagging)

Technical condition of the bridge:

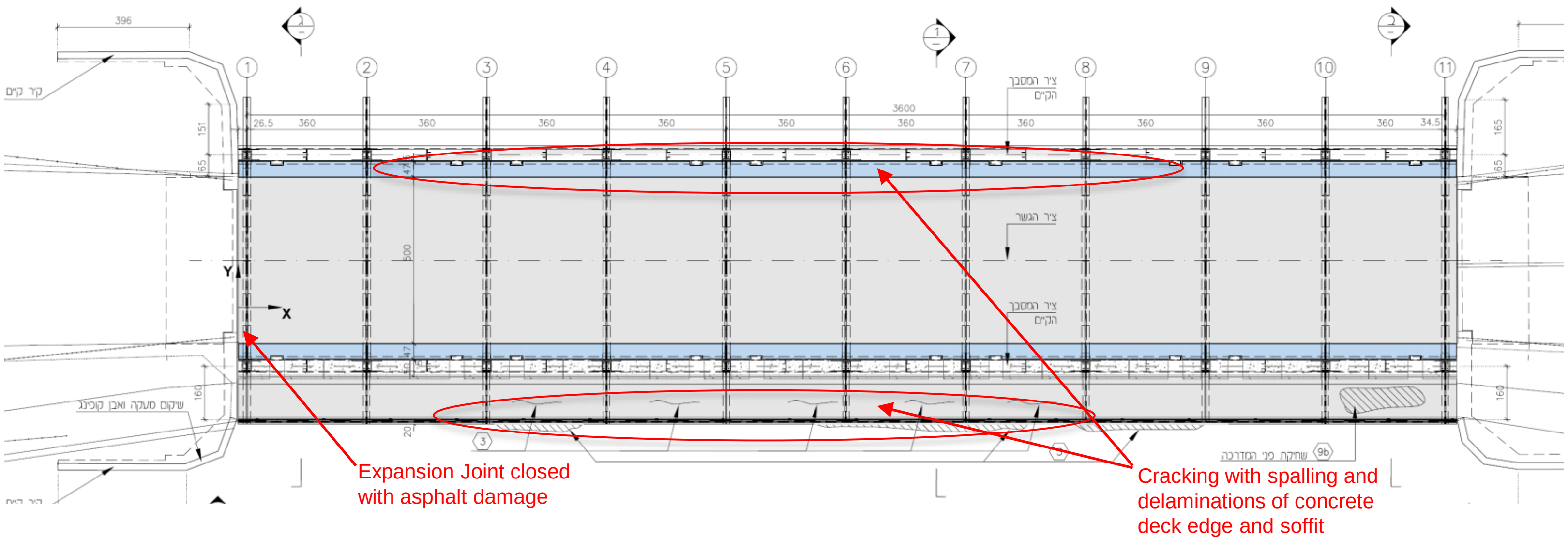
The main types of defects discovered on the bridge inspection are:

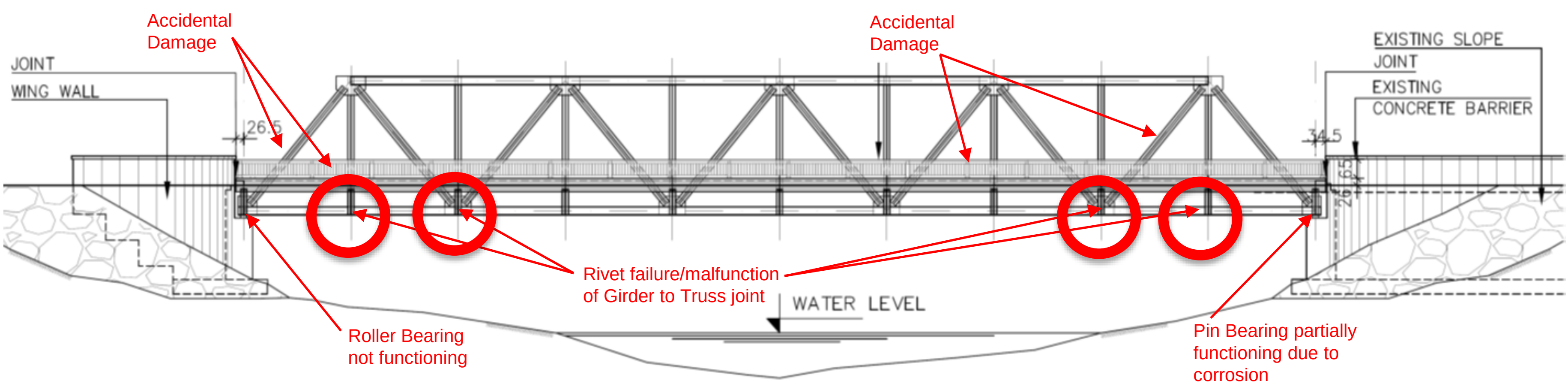
1. **Increased vibration of the bridge during vehicle passing.**
2. **Mild corrosion of structural steel.**
3. **Excessive relative movement of rivet head in many locations.**
4. **Out of plane deformation of steel plates at the bottom girder to truss connections.**
5. **Concrete deterioration mainly at the deck slab edges and in some locations at the wing walls and abutments.**
6. **Deterioration of the concrete closing wall behind the roller bearings at abutment A.**

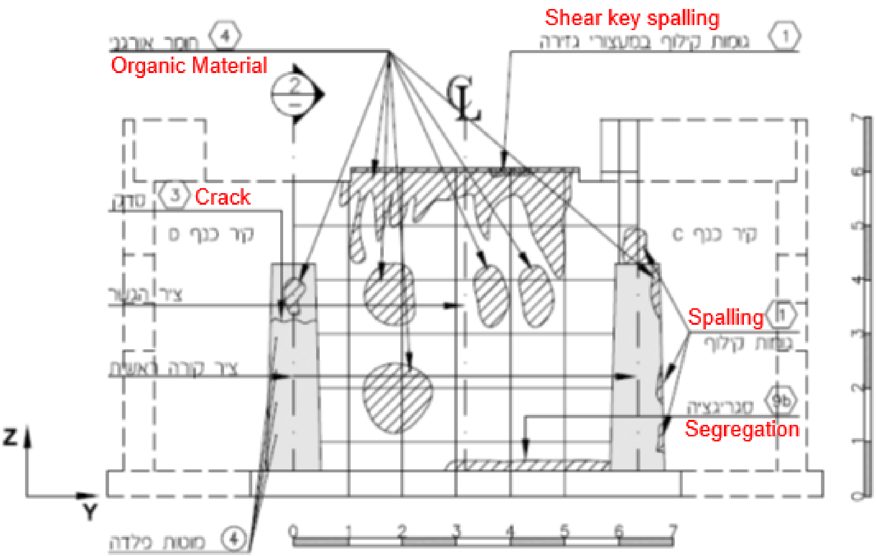
Technical condition of the bridge:

7. **Accidental damage** due to collision of vehicles with main truss vertical and diagonal members.
8. **Defects of pavement** mainly near the expansion joints.
9. Deck **waterproofing not functioning** (or missing).
10. **Inefficiency of deck drainage**.
11. **Deterioration of the steel handrailing** and collision damages at the north side.
12. **Nonfunctioning roller bearings**.
13. **Limited rotation** of the pin bearings due to corrosion damages.
14. **Horizontal cracking** in layers at Abutment A.

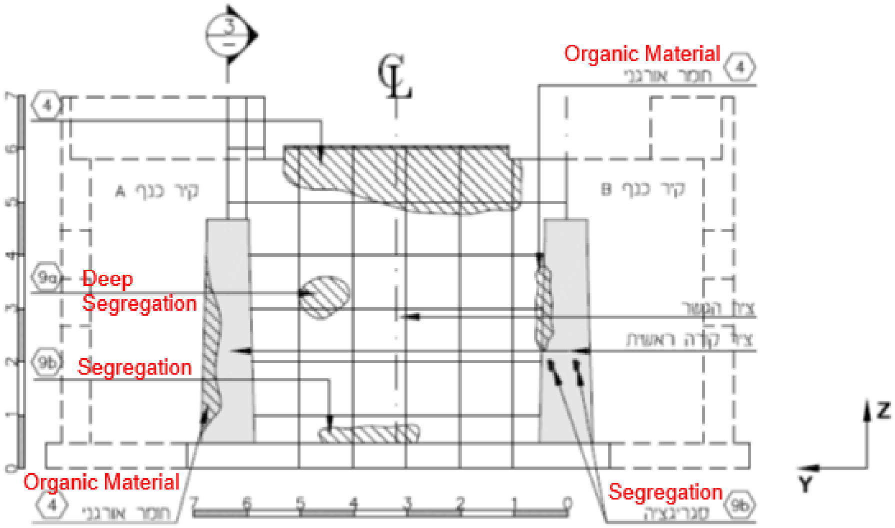
Technical condition of the bridge:



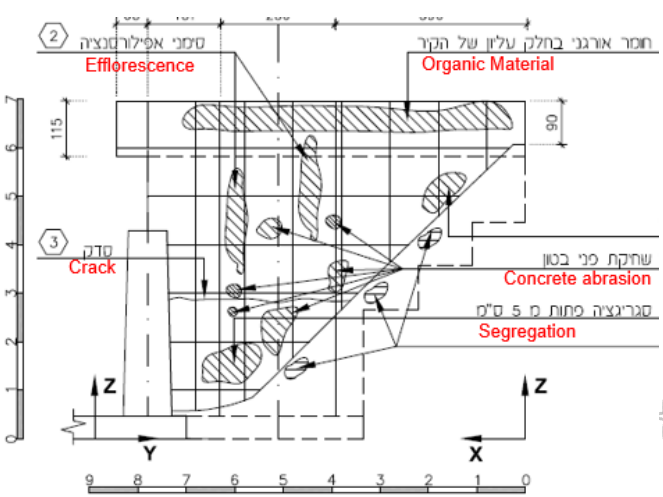




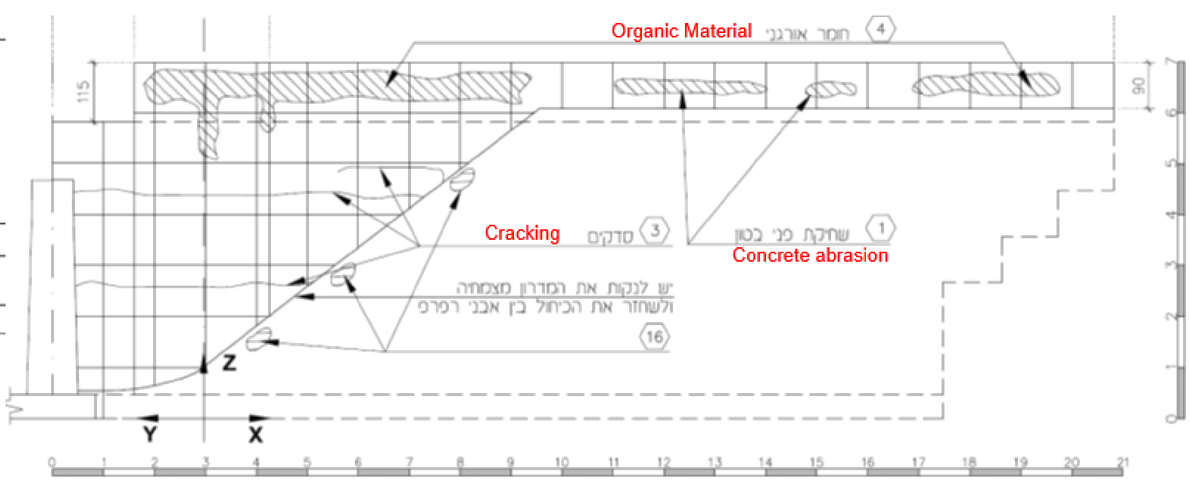
Shear key spalling
Organic Material
Crack
Spalling
Segregation



Organic Material
Deep Segregation
Segregation
Organic Material
Segregation



Efflorescence
Organic Material
Crack
Concrete abrasion
Segregation



Organic Material
Cracking
Concrete abrasion

Technical condition of the bridge:

Steel truss defects

Fig. 21 Local collision damage to members few locations

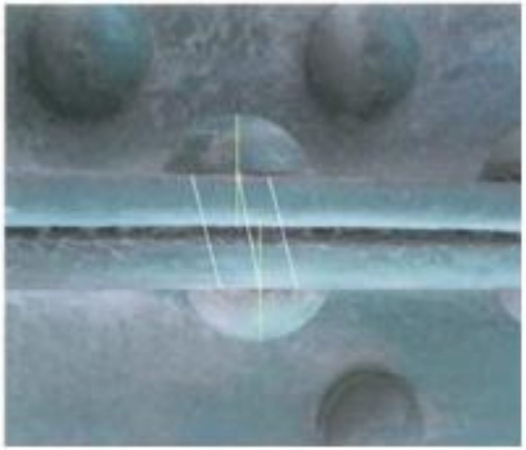


Fig. 22 rivet relative movement

Fig. 23 Sheared rivet due to excessive dynamic loading

Fig. 24 Out of plane deformation at the bottom plates of the truss-girder connection

Fig. 25 Construction welding broken due to fatigue

Fig. 26 Corrosion of truss member (typical condition) Corrosion between riveted angels and plates

Technical condition of the bridge:
Concrete slab and Abutments defects

Fig. 27 Spalling and delaminations along the deck slab edge (typical along the edges)

Fig. 28 Corrosion at the connection between transverse girder and the deck slab with efflorescence due to water penetrating in between the girder upper

Fig. 32 damage to closing wall near supports at massive abutment

Fig. 30 concrete spalling at massive abutments

Fig. 31 Concrete surface abrasion at massive abutments

Technical condition of the bridge:
Bearings, Safety Barrier and Asphalt defects


Fig. 33 Nonfunctioning roller bearing


Fig. 34 Corrosion damage at fixed bearing


Fig. 37 Asphalt defects near and over joints

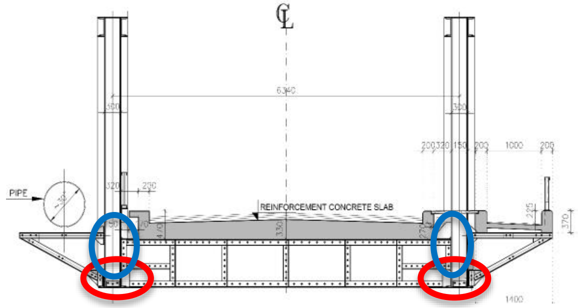

Fig. 35 safety barrier collision damage

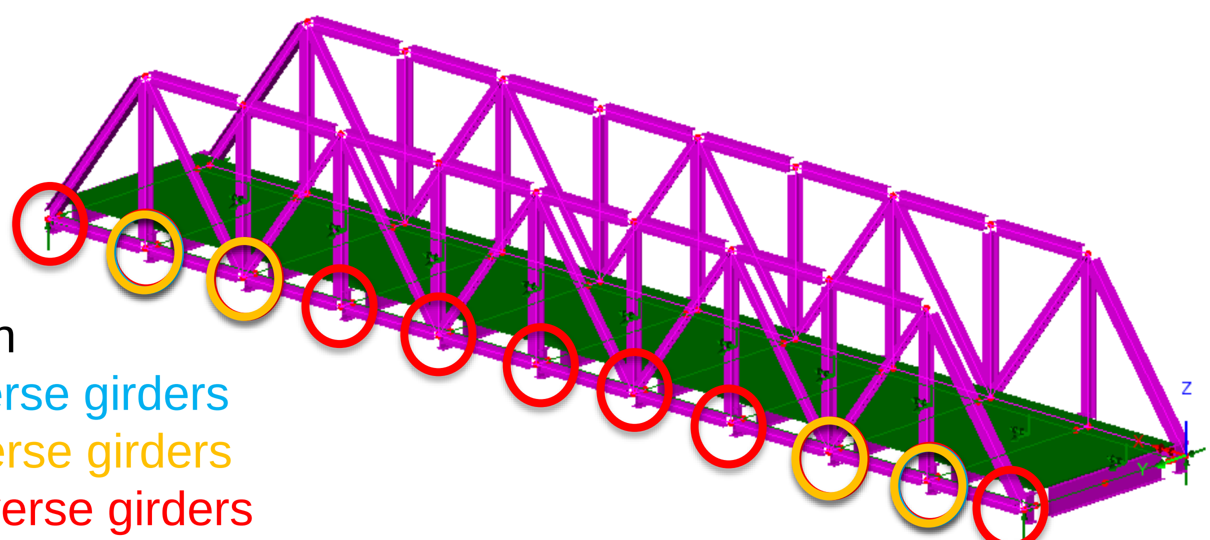

Fig. 36 Safety barrier collision damage


Fig. 38 Asphalt defects near and over joints

Load capacity:

- Excessive dynamic response to vehicles crossing the bridge.
- Load capacity immediately reduced to 40 ton as a safety precaution.
- Traffic detour problems for heavy vehicles.
- Theoretical capacity was checked according IS1227 for HA, HB & HC loads and found to be satisfactory.
- Integrity of the riveted lower connection of the transverse girders with the main truss bottom chord and truss vertical elements.
- FEM calculation model was set and the model was checked for 4 main cases:





- Case A - monolithic connection
- Case B - releases in 2 transverse girders
- Case C - releases in 4 transverse girders
- Case D - releases in all transverse girders

	Case A	Case B	Case C	Case D
Safety Factor (Buckling analysis)	3.5	3	2.5	0.6
Upper chord lateral sway at mid span according to HC load (1500KN)	8.25 mm	40 mm	48.5 mm	65 mm
Upper chord lateral sway at mid span according to 600KN Truck load	3.4 mm	3.45 mm	4.5 mm	6 mm

overall stability of the truss is related directly to the degree of the fixing of the lower cross girder connection with the truss.

Dynamic measurements of load testing:

Fundamental frequency = 3.8Hz $\pm$0.05 (on vertical direction) < Calculated= **3.93Hz**
Fraction of critical damping ζ= 0.012$\div$0.014 (1.2% - 1.4%)
Lateral fundamental frequency of the truss in some cases was 10Hz.

Additional NDT testing:

Fig. 39 Results of defect rivet

Fig. 40 Ultrasonic testing of rivets

405 tested at specific locations
9 Class III (Sheared)
44 Class II (Suspected)
352 Class I (OK)

Key Performance Indicators and QC Plan:

Structure type	Group	Component	Material	Design & Construction	Failure mode	Location/ Position	Damage /Observation	Damage process	KPI	Performance Indicator component level		Performance value R (max)	Performance value S (max)	Estimated failure time [years]
TB	Structural elements	Main Trusses	Steel	1954	Truss Bending failure mode	Upper chord compression zone	Corroded plates	Corrosion	Reliability (Structure safety)	2.3	4.1	4.1	2.1	**40**
							Corroded rivet	Corrosion		2.3				**40**
						Lower chord tension zone	Corroded plates	Corrosion		2.3				**40**
							Corroded rivet	Corrosion		2.3				**40**
					Truss Shear failure mode	Diagonals	Corroded plates	Corrosion		2.3				**40**
							Corroded rivet	Corrosion		2.3				**40**
							Accidental damage	Impact		2.0				**20(?)**
					Global buckling of truss upper chord	Connection of truss verticals with deck cross girder	sheared rivet	Fatigue		4.1				**15**
							Out of plane movement of lower connection plate	Fatigue		4.1				**20**
		Cross girders	Steel	1954	Bending	High sagging area	Shear connection with deck corroded	Corrosion		2.1	4.1			**30**
					web plate buckling	Bearing area over main truss	Rivets are partially sheared	Fatigue		4.1				**20**
					Bending	Along the girder	Corroded rivet	Corrosion		2.1				**40**
		Deck slab	Reinforced concrete	1954	Bending	HMS/bottom	delamination	Corrosion	Reliability	2.1	2.1			**30**
				1954	Falling chunks	bottom	Spalling	Corrosion	Safety (Life and limb)	2.1	2.1			**30**
				1954	Bending	HMH	Efflorescence	Leaching	(Symptom)	(2.1)				
		Bearings	Steel	1954	Bearing Failure	Abutment 1 (west)	Corrosion	Corrosion	Reliability	2.0	4.0			**40**

Key Performance Indicators and QC Plan:

Structure type	Group	Component	Material	Design & Construction	Failure mode	Location/ Position	Damage /Observation	Damage process	KPI	Performance Indicator component level		Performance value R (max)	Performance value S (max)	Estimated failure time [years]
		Bearings	Steel	1954	Bearing Failure	Abutment 1 (west)	Bearing restrained no movement due to corrosion and debris	Corrosion	Reliability	4.0				20
		Bearings	Steel	1954	Bearing Failure	Abutment 11 (east)	Loss of rotation ability due to Corrosion	Corrosion	Reliability	3.0				20
		Abutment	Reinforced concrete	1954		Abutment 1 (west)	Spalling and delamination at closing wall	Joint leaking	Reliability	3.0	3.0			20
		Abutment	Reinforced concrete	1954	Bearing Failure	Abutment 1 (west)	closing wall with horizontal crack	Closing of joint	Reliability	3.0				20
		Wing wall	Reinforced concrete	1954		Wing wall	Horizontal cracking		Reliability	2.1	3.3			-
		Wing wall	Reinforced concrete	1954		Wing wall	Spalling	Corrosion	Reliability	3.3				-
		Wing wall	Reinforced concrete	1954		Wing wall	Surface abrasion	Abrasion	(Symptom)	3.3	-			
		Expansion Joint	steel	1954	Closing	EJ 1 (west)	Closing of EJ	Deck movement	Reliability	3.0	3.0			
		Pedestrian Deck slab	Reinforced concrete	1954	HMH	Over transvers supporting truss	Transvers cracks	Not active	Reliability	2.3	2.3			20
		Pedestrian Deck slab	Reinforced concrete	1954	Falling chunks	South Edge	Spalling	Corrosion	Safety (Life and limb)	3.3	3.3	-	3.3	20
	Equipment	Safety barrier	Steel	1954	Falling of the deck	Safety barrier	Broken, missing parts	Impact	Safety (Life and limb)	3.0	3.0			10 (?)
		Pedestrian Handrail	Steel	1954	Falling of the deck	Handrail anchoring	Corrosion of structural steel	Corrosion	Safety (Life and limb)	2.7	2.7			30
		Curb	Reinforced concrete	1954	Falling chunks	Curb side	Spalling, delaminations	Corrosion	Safety (Life and limb)	3.3	3.3			20
		Pavement	Asphalt	Estimated 2005	Sudden disturbance to driver	Expansion joints overlay	Open transvers cracks	Joint reflection cracking	Safety (Life and limb)	3.3	3.3			5

Key Performance Indicators and QC Plan– category definitions (WG3)

Reliability:

ULS - Table 12.1 Scale for KPI Reliability (structural safety) and urgency of intervention

Reliability scale	Quantitative scale (β)	Urgency of intervention
1	> 4.00	Regular inspection
2	3.25-4.00	Reassessment should be performed to update the period between inspections
3	2.50-3.25	Reassessment should be performed to plan an optimal time of an intervention
4	2.00-2.50	Reassessment and possible intervention shall be performed shortly after an inspection
5	< 2.00	Immediate action/intervention is required

SLS -Table 12.2 Scale for KPI Reliability (serviceability) and urgency of intervention

Reliability scale	Quantitative scale (β)	Urgency of intervention
1	> 2.50	Regular inspection
2	2.00-2.50	Reassessment should be performed to update the period between inspections
3	1.50-2.00	Reassessment should be performed to plan an optimal time of an intervention
4	1.00-1.50	Reassessment and possible intervention shall be performed shortly after an inspection
5	< 1.00	Immediate action/intervention is required

Key Performance Indicators and QC Plan

Reference scenario:

- The reference approach is lacking of any planed major repairs of the bridge component and accessories except for periodical pavement repairs.
- Interventions are triggered following defects development up to the Component failure.
- Inspection schedule increased in time

Preventive/Corrective scenario:

- One of few possible life cycle approaches.
- The bridge is going to be completely rehabilitated bringing its reliability index to the maximum possible target which is 'As new’.
- The intervention will take place in the next two years following design period.
- Preventive intervention regime is established with 10, 20 and 40 years.
- Inspection and testing schedule as defined in the regulations

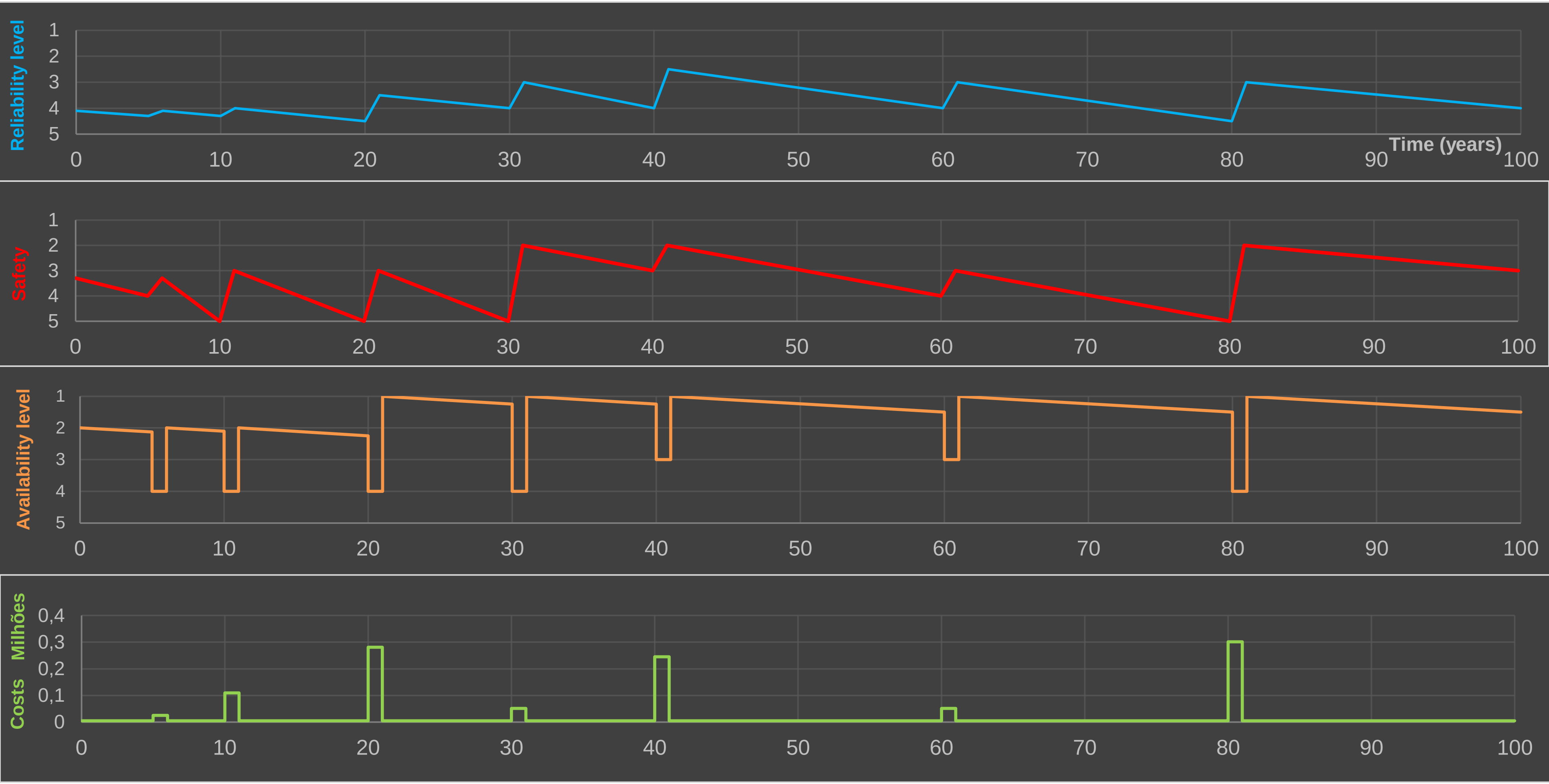
Key Performance Indicators and QC Plan – Reference scenario:

Component	Time (years)	Description	Repair cost	Comments
Expansion Joints	5	Expansion joints not functioning	24000	Replace expansion joints and pavement including waterproofing. Clean bearings
Asphalt overlay	5	Crack development over expansion joints and creation of potholes. Reduction of driving safety & increased probability for accidental impact load hitting the main truss members.		
Safety barrier Deck slab curbs	10	Collapse in 10 years due to possible accidental damage Deterioration of side curbs and ends of slab	110000	Replace safety barriers and rehab. Slab edges - (10y instead of 20y)
Concrete slab	15-20	Edge spalling and soffit delaminations is predicted to develop into unsafe condition to the users of the boat service passing below the bridge.		
Truss - girder connection	20	Fatigue induced fracture of rivets lead to connection failure and global truss failure	280000	Gradual reduction of global F.O.S
Abutment	20	Failure of closing wall		Rehab. closing wall
Bearings	20	Bearings failure due to corrosion		Replace with elastomeric

Key Performance Indicators and QC Plan – Reference scenario:

Component	Time (years)	Description	Repair cost	Comments
Handrail anchors	30	Anchoring of pedestrian handrail is deteriorating due to corrosion	50,000	Rehab. handrails Replace additional rivets by Bolts
Steel cross girders	30	Fatigue of rivets and shear connectors		
Deck slab	30	Deterioration of reinforced concrete		
Truss members	40	Truss failure due to Corrosion in 30 to 40 years' time based on the site climate and the current condition	244000	Rehab. All steel members of truss and cross girders
Expansion Joints		Expansion joint full deterioration		
Pavement		Asphalt and waterproofing deterioration		Replace asphalt and waterproofing

Key Performance Indicators and QC Plan – Reference scenario:



Key Performance Indicators and QC Plan – Preventive/Corective scenario:

Immediate bridge rehabilitation (€365000)

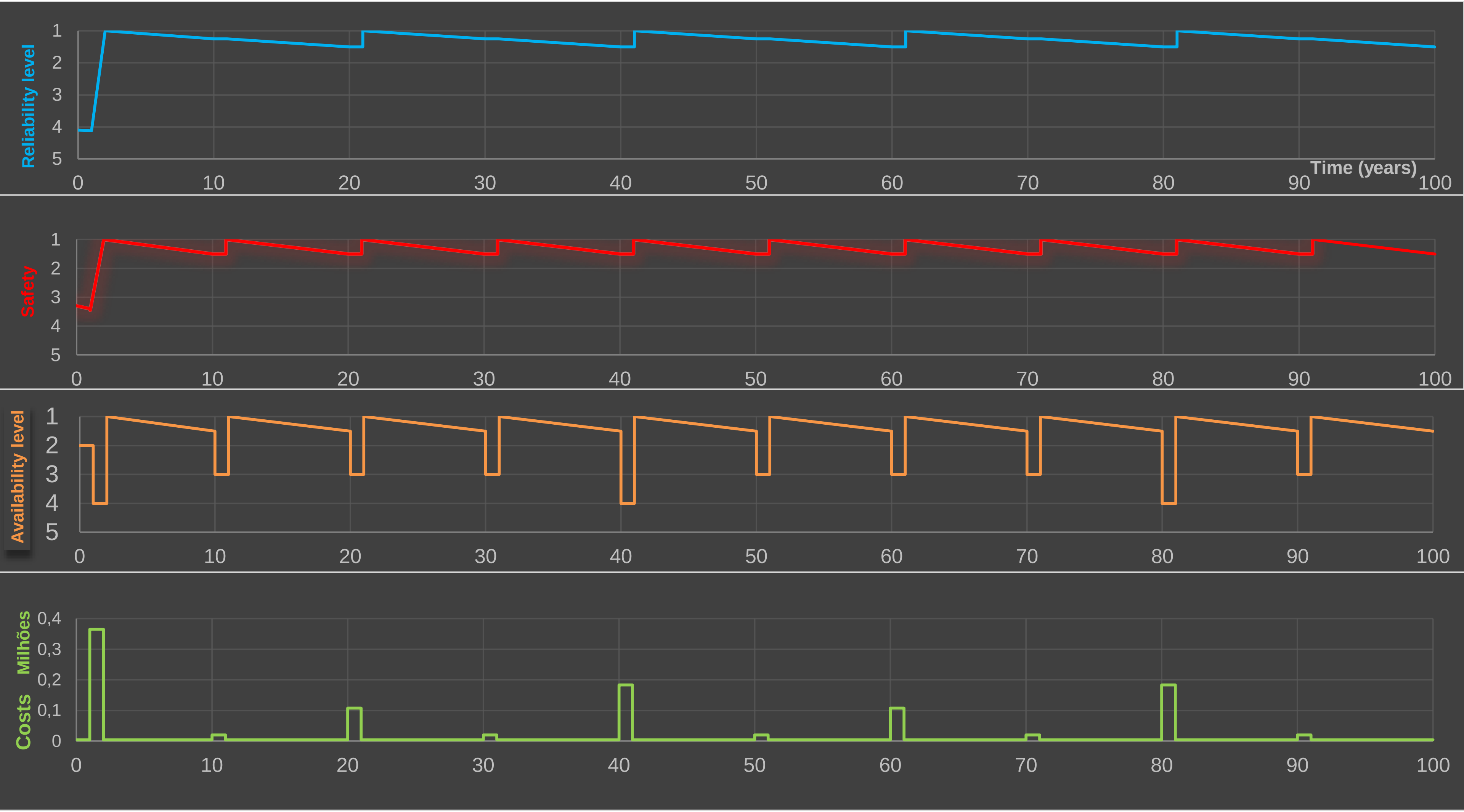
Component	Time (years)	Description	Repair cost
Abutments + Slab	1	Complete concrete elements repair	74800
Curb	1	Concrete curb replacement	10400
Truss - girder connection	1	Joints connection repair including about 400 rivets replacement and plate replacement	89300
Truss + Girders	1	Local rivet replacement, Local member strengthening, Overall bridge painting	71164
Expansion Joints	1	Expansion joints replacement	14200
Bearings	1	Bearing rehabilitation	17750
Safety barrier	1	Replacing safety barrier with new one including end blocks	65550
Handrails	1	Rehabilitation of the pedestrian handrails	9000
Pedestrian slab	1	Pedestrian deck overlay	3120
Deck overlay	1	New waterproofing and asphalt overlay.	11200

Key Performance Indicators and QC Plan – Preventive/Corective scenario:

Scheduled interventions Budget

Treatment	yearly	10y	20y	40y
Yearly maintenance (cleaning)	1020	1020	1020	1020
Inspection (every 2 years)	2040	2040	2040	2040
Asphalt		6100	6100	6100
Safety Barrier		6100	6100	6100
Overall paint (steel)			41850	41850
Concrete treatments			27500	27500
NDT and special testing			10460	10460
Expansion joint replacement			13080	13080
Rivet replacement				48000
Bearing replace/rehab.				22300
Waterproofing				5500
Total	**3060**	**15260**	**108150**	**183950**

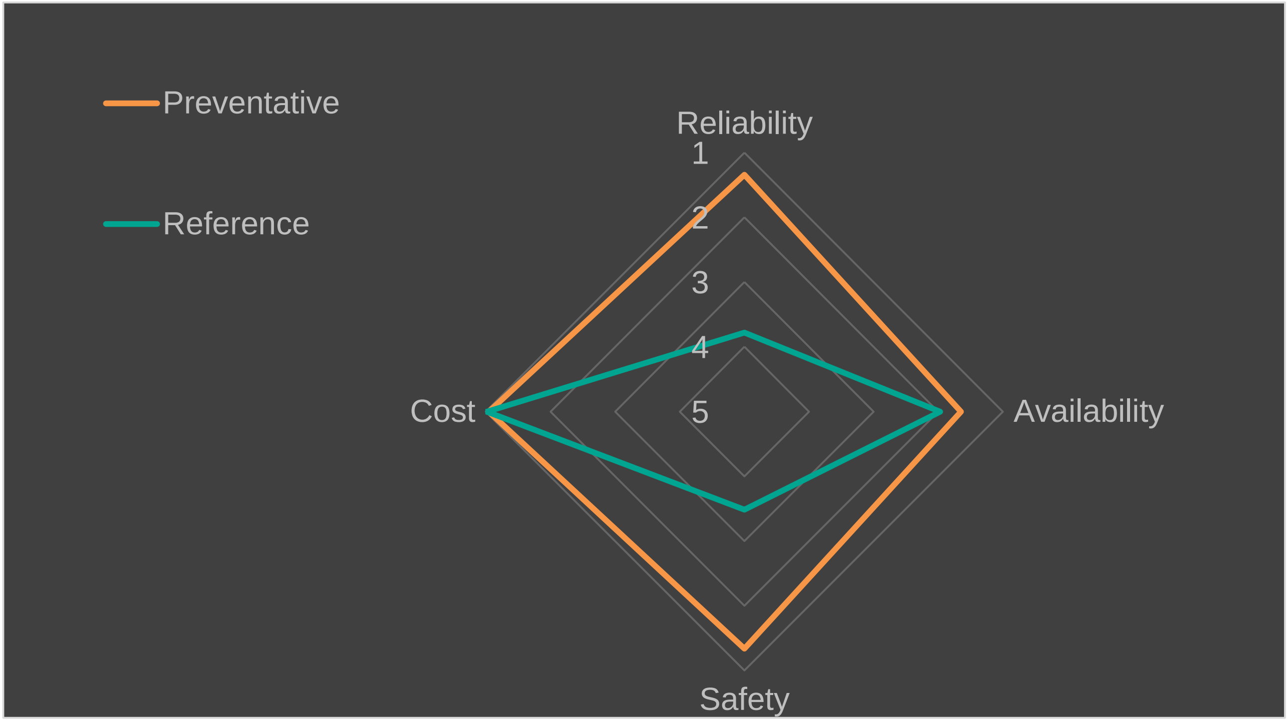
Key Performance Indicators and QC Plan – Preventive scenario:



Key Performance Indicators and QC Plan – Comparing scenarios:

Preventative approach is clearly more appropriate for this truss bridge

- The cost is little more but all other indicators shows more favorable results for all aspects.
- The reliability and safety are kept in higher levels all over the period.



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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

Arch concrete bridge in Guarda, Portugal

Marija Docevska – University Ss. Cyril and Methodius-Skopje, R. Macedonia
Jose Campos e Matos – University of Minho, Campus de Azurem, Portugal

ГРАДЕЖЕН ФАКУЛТЕТ
Универзитет Св. Кирил и Методиј

University of Minho
School of Engineering

22nd November 2018
Bergisch Gladbach, Germany

Outline

- Selecting a case study bridge
- Collection of existing data
- Failure modes and vulnerable areas
- Evolution of virgin reliability
- Maintenance scenarios
- Conclusion

Selecting a case study bridge

1. One of the defined common prototype of road bridges
- **Girder bridge –** Concrete, Composite
- **Arch bridge – Concrete**, Steel, Masonry
- **Frame bridge –** Concrete, Steel

2. The bridge was built and maintained by a highway authority
- **Infraestruturas de Portugal**
- **Construction year: 1940**

3. Inspection history:
- **two inspections (1st:2007 / 2nd:2015) and one repair work (2010)**

4. Data of NDT exists
- **concrete cover; depth of carbonation; moisture content in the concrete; petrographic analysis**

Collection of existing data

1. Bridge location

- **Sabugal, Guarda district – Portugal; bridge over a river Cró**

2. Structural system and bridge elements

- **Simple supported deck arch (arch type acc. to WG3: open spandrel)**

3. Defects on the main structural elements identified during inspections

- **Spalling, hairline cracks, calcium leaching, brown spots, direct wetting of concrete, corroded steel bars…**

Collection of existing data

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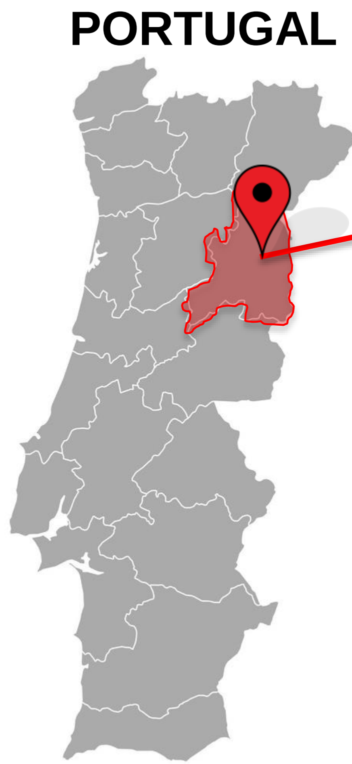

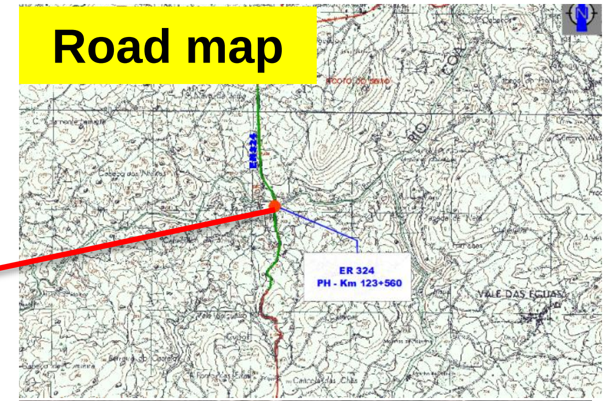

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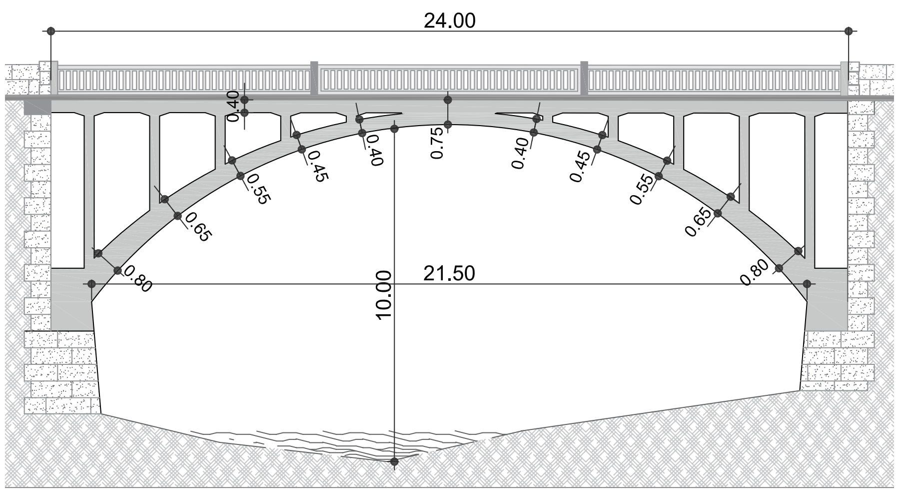

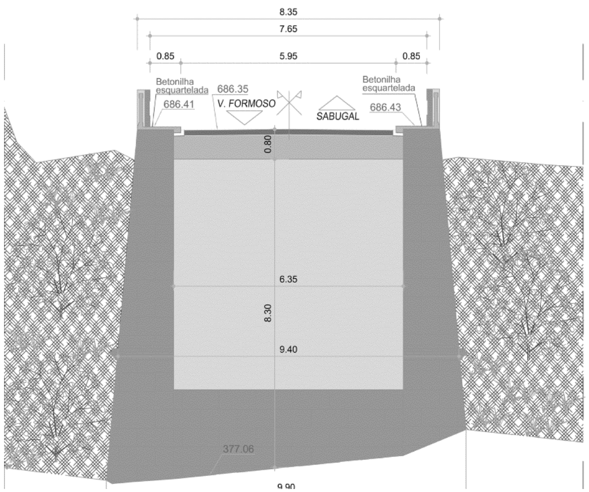

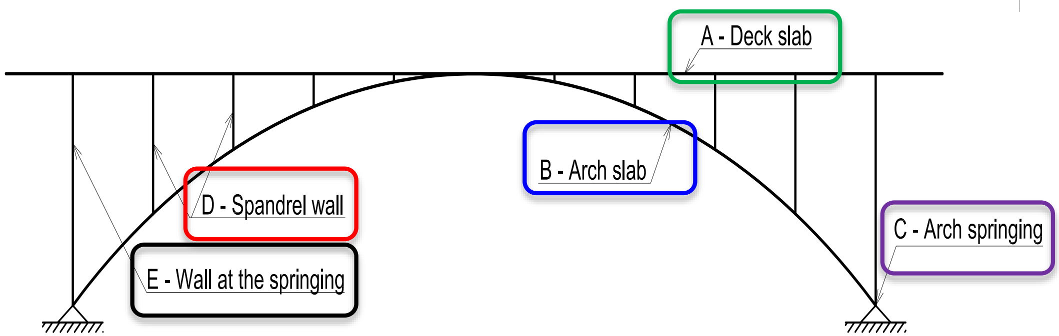

Bridge elements:

A – Deck slab
B – Arch slab
C – Arch springing
D – Spandrel wall
E – Wall at the springing

Collection of existing data

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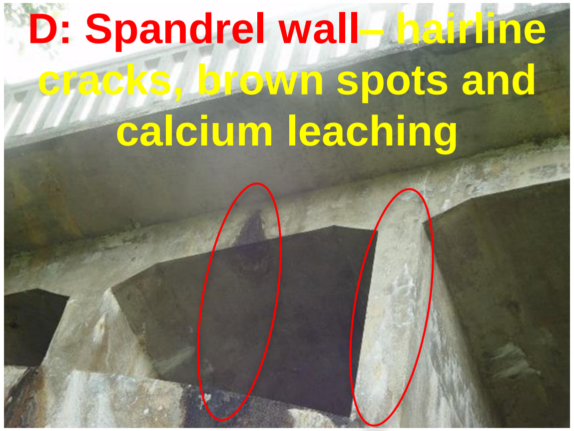
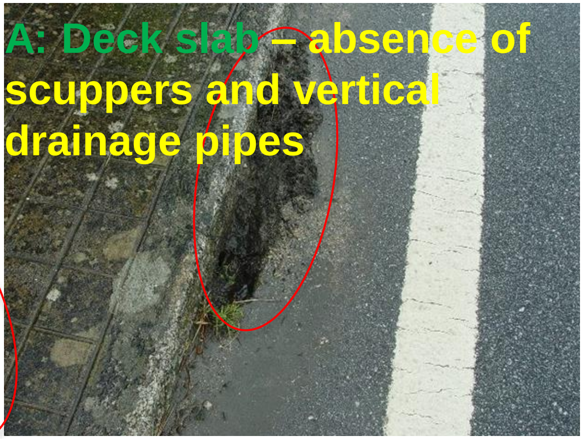
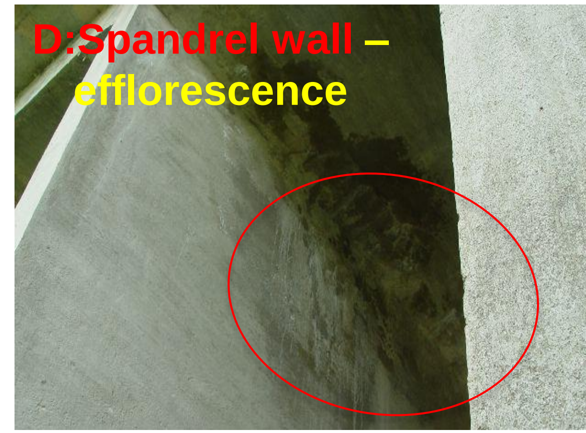
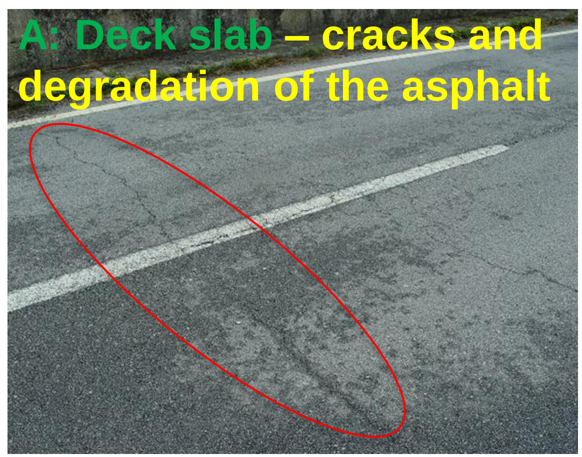


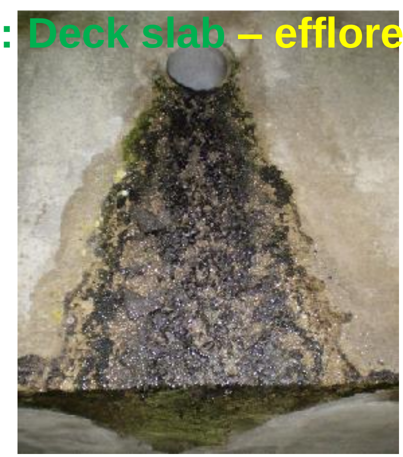


Collection of existing data

3. Defects on the main structural elements identified during inspections

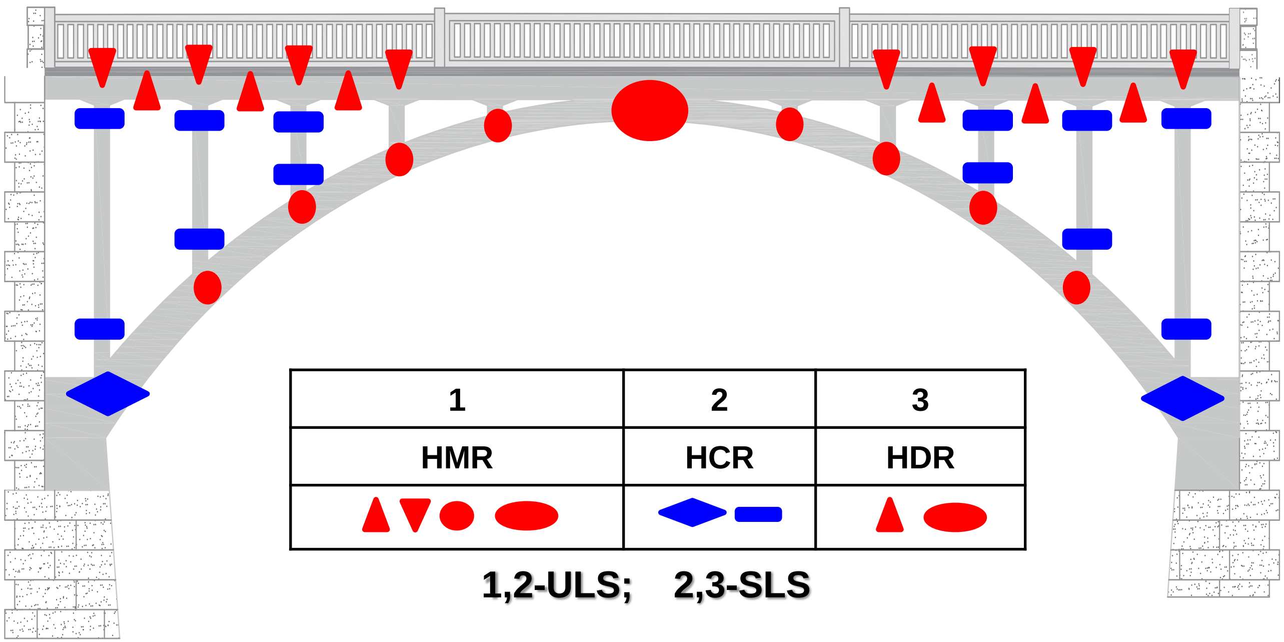






Failure modes and vulnerable areas

- Definition of the failure modes for the actual structural system and corresponding vulnerable areas



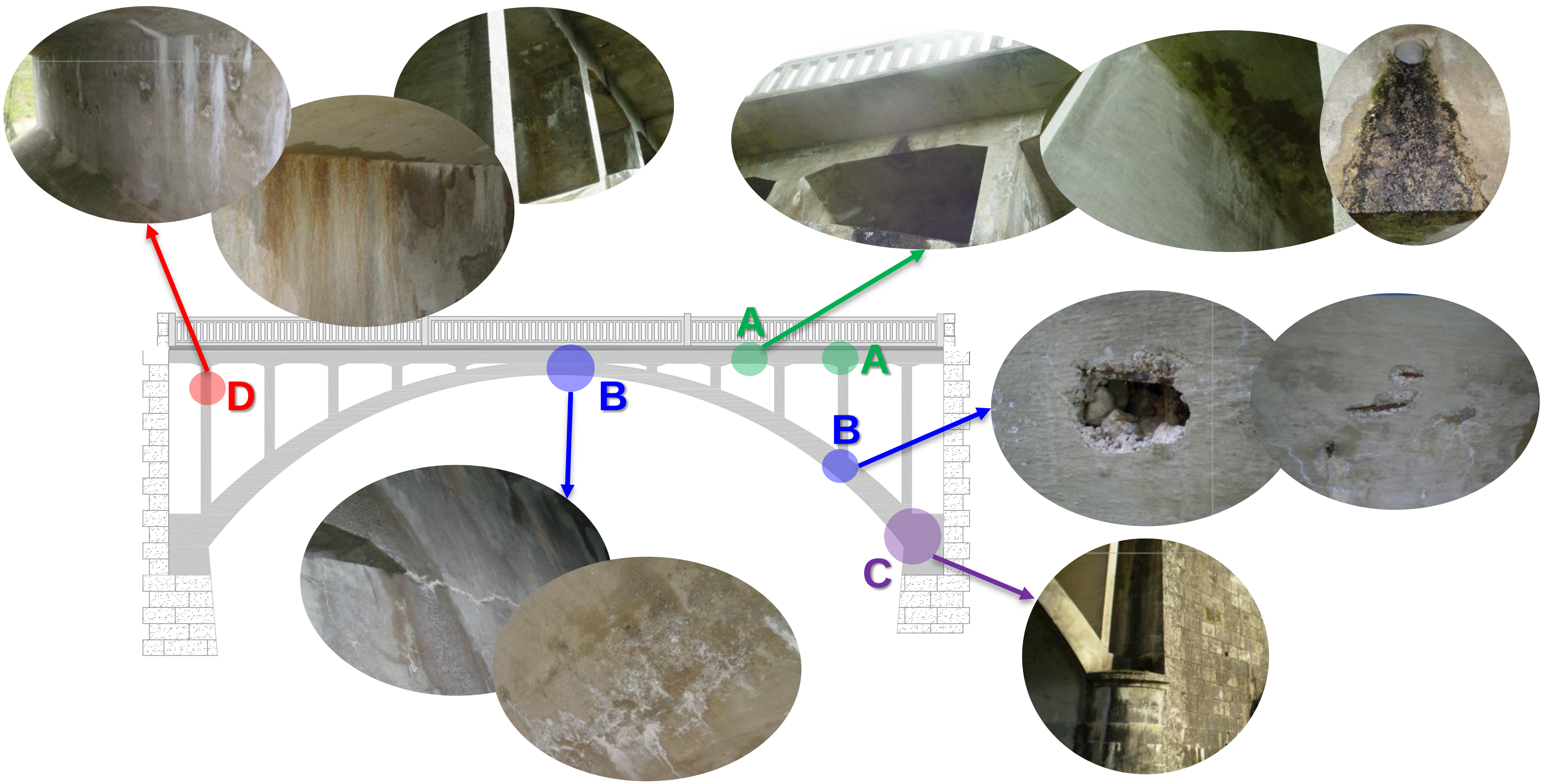
1	2	3
HMR	**HCR**	**HDR**

1,2-ULS; 2,3-SLS

HMR - High **M**oment **R**egion
HCR - High **C**ompression **R**egion
HDR - High **D**eflection **R**egion

Failure modes and vulnerable areas

- Link between vulnerable areas and observed defects



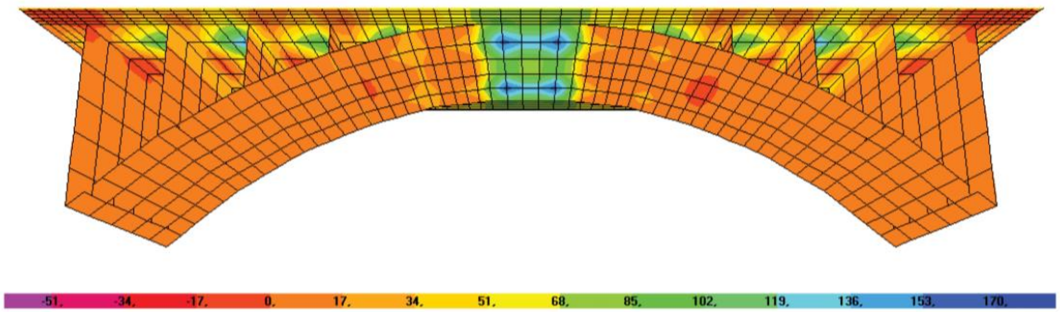
Failure modes and vulnerable areas

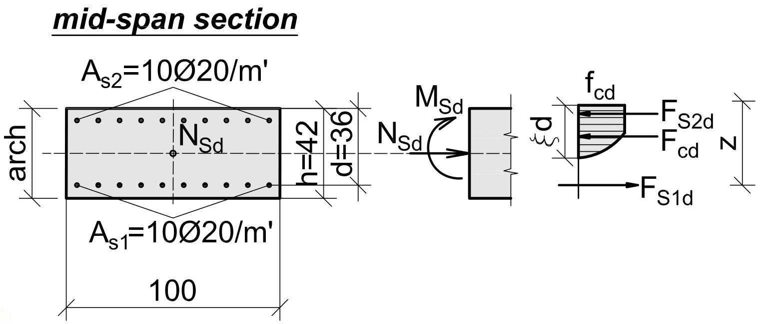
- The QC protocol

Failure mode	Vulnerable area	Element	Damage observations	Damage process	KPI	Performance value (1-5)	Overall rating
Bending failure	A	Deck	Efflorescence	Leaching	Symp.	/	**R=4 S=2**
		Deck	Wet spots	-	Symp.	/	
	B	Arch	Surface cracks	Corrosion	R	3	
		Arch	Spalling	Corrosion	R	1	
		Arch	White spots	Carbonization	R	3	
	A	Deck	Efflorescence	Leaching	Symp.	/	
		Deck	White spots	Carbonization	R	3	
	B	Arch	Longitudinal crack	Structural damage	R	3	
		Arch	Surface cracks	Corrosion	R	3	
Compression failure	C	Arch	No damage	/	/	/	
	D	Walls	Surface cracks	Corrosion	R	4	
		Walls	Brown spots	Corrosion	R	3	
Falling from the bridge	/	Railing	Spalling	Corrosion	S	2	
	/	Railing	Cracks	Corrosion	S	2	

Evolution of virgin reliability

- Analytical assessment



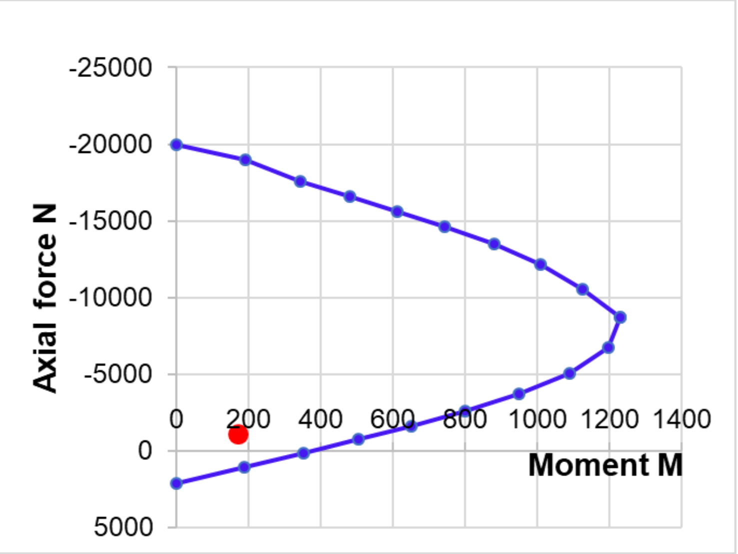


$$M_{Sd}(\gamma_G,\gamma_Q) \leq M_{Rd}(\gamma_C,\gamma_S)$$

$$N_{Sd}(\gamma_G,\gamma_Q) \leq N_{Rd}(\gamma_C,\gamma_S)$$

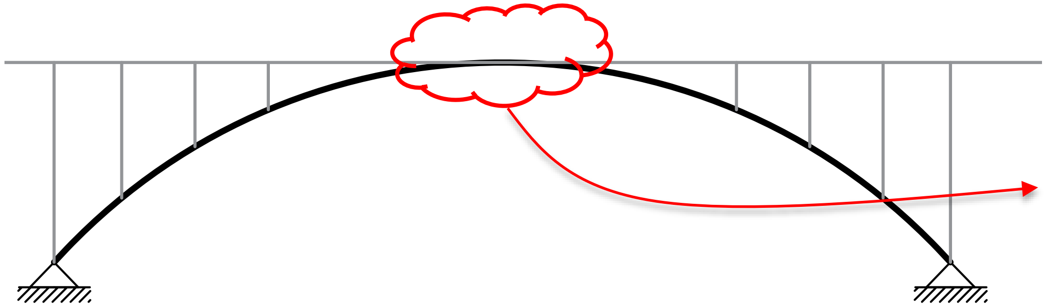
$$n = M_{Sd}/M_{Rd}(or\ N_{Sd}/N_{Rd})$$

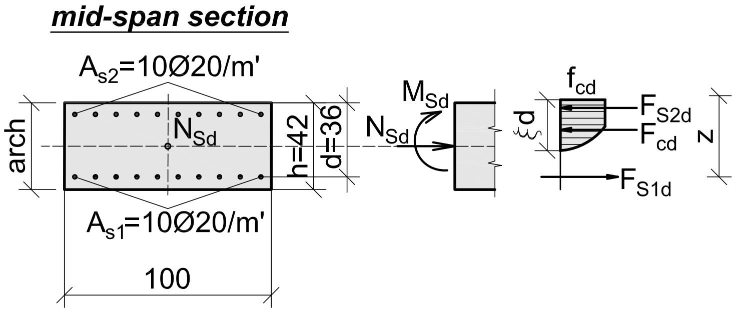
section	M_{Sd}	M_{Rd}	n	N_{Sd}	N_{Rd}	n
Mid-span	171.91	221.32	**0.77**	1144.91	20000	**0.06**
Support	/	/	/	/	/	/



Evolution of virgin reliability

- Reliability index





$$\textit{Limit state function}: \; g(R,S) = R - S = 0$$

$$R = M_{Rd} = F_{cd} \times z + F_{sd2} \times (d - a_2) - N_{sd} \times \left(\frac{h}{2} - a_1\right)$$

$$S = M_{sd} = 159.18kNm; \; N_{sd} = 1060.10kN$$

Monte Carlo simulation

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} = -\Phi^{-1}(P_f)$$

Overall bridge reliability – Parallel systems

$$P_f = 1 - \prod_{i=1}^{2} [1 - P_{fi}]$$

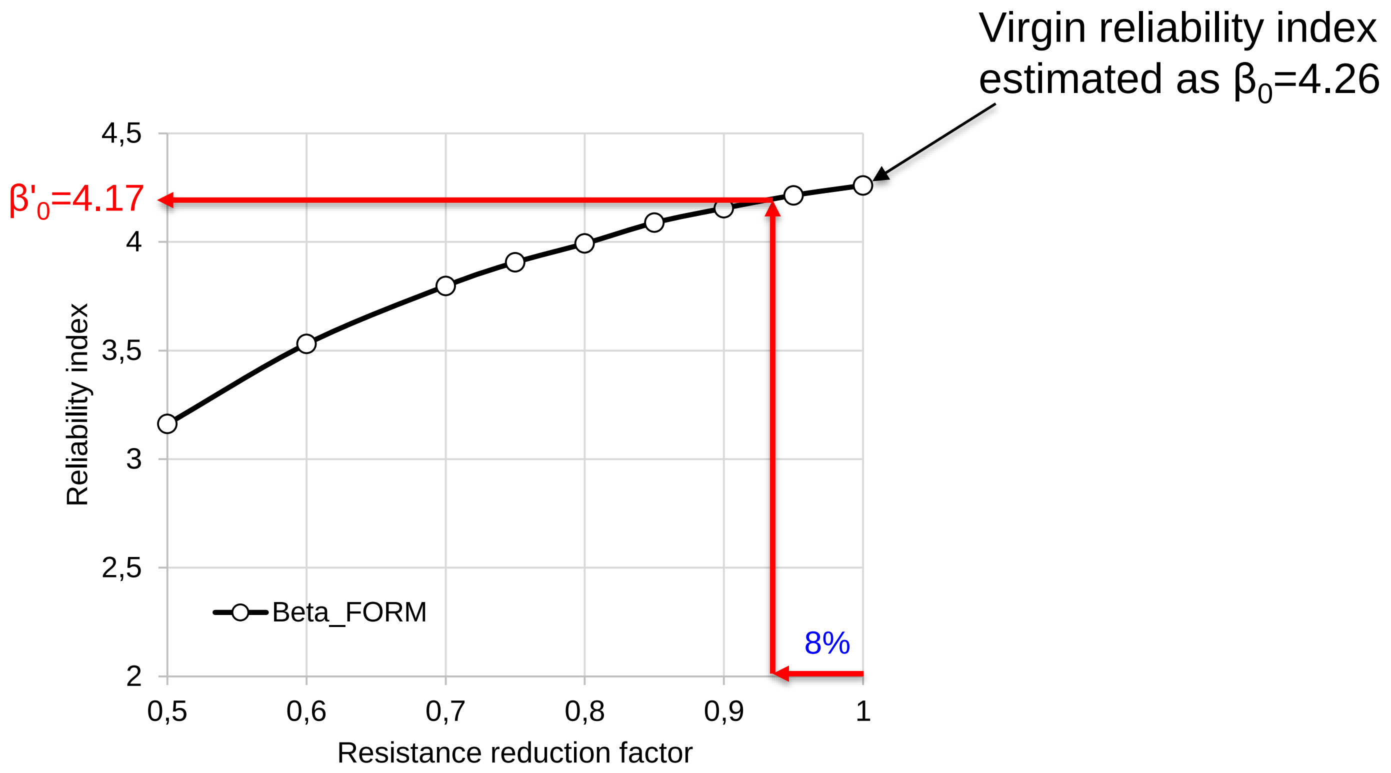
Since the bridge is simple supported arch, the overall bridge reliability is equal to the reliability of mid-span section

$$\beta_0{}^{bridge} = \beta_0{}^{mid-span} = -\Phi^{-1}(P_f)$$

$$\boldsymbol{\beta_0{}^{bridge} = 4.26}$$

Evolution of virgin reliability

- Influence of a resistance reduction on reliability index



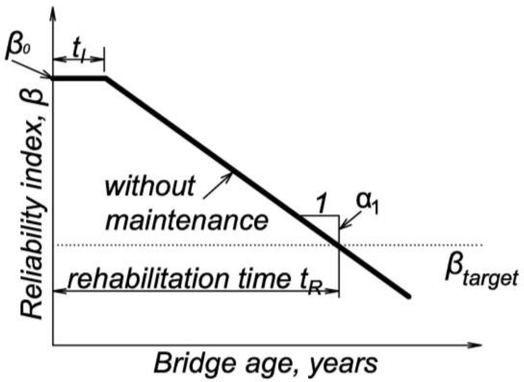
8% qualitatively assumed resistance reduction based on the observed defects during the last inspection

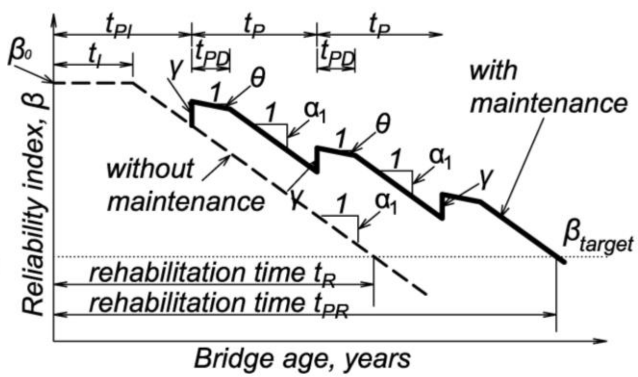
Maintenance scenarios

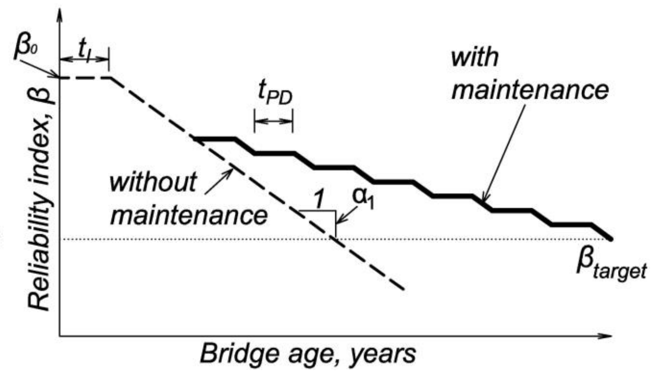
NO MAINTENANCE
'Do-nothing and rebuild'

CORRECTIVE

PREVENTIVE







α_1 — **degradation rate**

t_i — **time of initiation of damage**

γ — **reliability improvement**

θ — **decrease in degradation rate**

t_{pD} — **duration of maintenance effect**

t_p — **time of reapplication of the actions**

t_{pD} — **delay of degradation process**

$\delta = \alpha_1 - \theta$

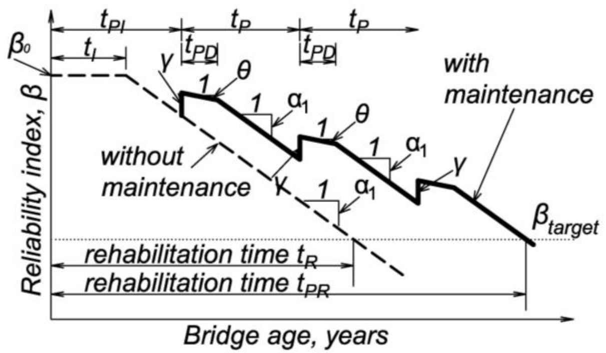
Degradation model:

$$\beta(t) = \begin{cases} \beta_0 & \text{if } 0 \leq t \leq t_I \\ \beta_0 - (t - t_I)\alpha & \text{if } t_I < t \leq t_{PI} \\ \beta_1 - (t - t_{PI})\theta & \text{if } t_{PI} < t \leq t_{PI} + t_{PD} \\ \beta_1' - [t - (t_{PI} + t_{PD})]\alpha & \text{if } t_{PI} + t_{PD} < t \leq t_{PI} + t_P \\ \beta_n - \{t - [t_{PI} + (n-1)t_P]\}\theta & \text{if } t_{PI} + (n-1)t_P < t \leq t_{PI} + (n-1)t_P + t_{PD} \\ \beta_n' - \{t - [t_{PI} + (n-1)t_P + t_{PD}]\}\alpha & \text{if } t_{PI} + (n-1)t_P + t_{PD} < t \leq t_{PI} + nt_P \end{cases}$$

Maintenance scenarios

- Choosing parameters for degradation models – based on experts opinion

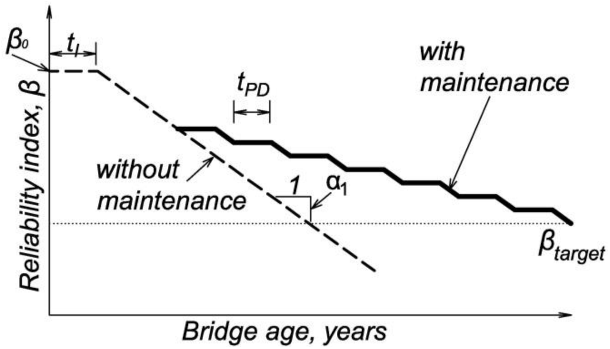
CORRECTIVE



$\delta = \alpha_1 - \theta$

Action	td [years]	δ [years^{-1}]	γ [/]
Crack sealing	[0.5 1.5 3]	[0.7 0.8 0.9]	[2 1 1]
Depth conc. repair	-	-	[1 0 0]
Waterproofing	[2 3 3]	[0.75 0.8 1.0]	-
Bearing replacement	-	-	[2 2 2]

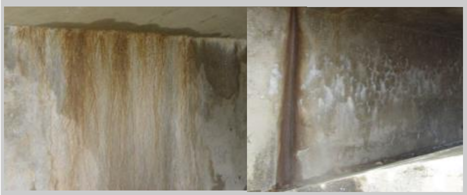
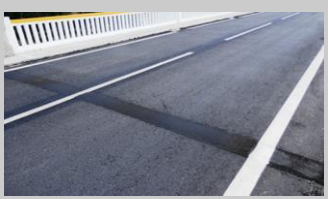
PREVENTIVE



Action	td [years]	δ [years^{-1}]	γ [/]
Deck washing	[1 1.5 2]	-	-
Minor spall repairs	[1.5 2 3]	-	-
Concrete spot painting	[4 6 8]	[0.3 0.4 0.5]	-
Bearing cleaning	[0.5 1 2]	-	-

min avg max

CORRECTIVE

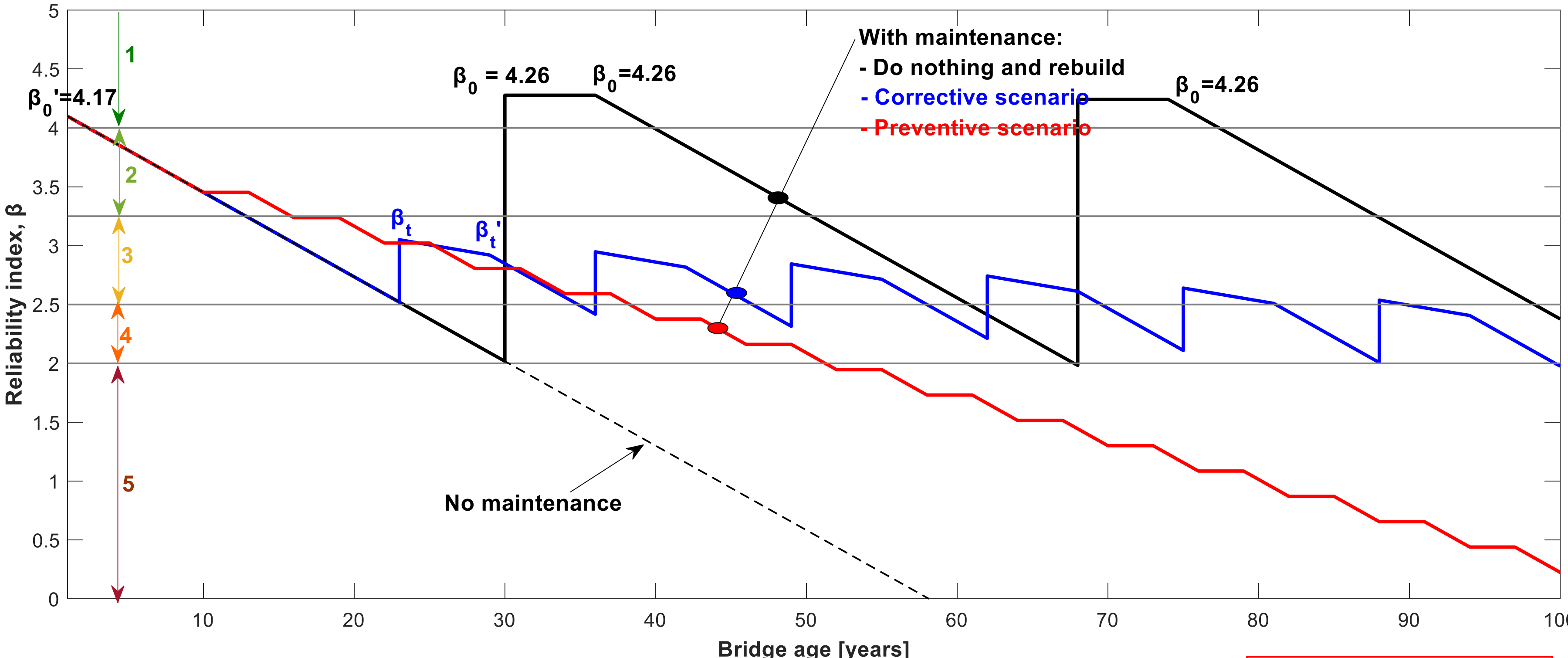
No.	Picture	Defect description	Corrective action	Cost
1		Three to four isolated moderate spalls and delamination of the pavement, moderate riding quality.	Repairing the asphalt wearing surface (1), applying thin overlay and anti-slip pavement (2).	(1) 50EUR/m2 (2) 40EUR/m2
2		A lot of cracking due to corrosion of reinforcement	Replacement of the concrete railing	50EUR/m’
3		Over 50% of the walls have cracks, brown spots and leakage	Repair the walls	250EUR/m3
4		Localized areas of white and wet spots, surface cracks	(1) Rehabilitation of the concrete deck slab; (2) Improvement of drainage system (3) waterproofing placement	(1) 200EUR/m2 (2) 100EUR (3) 50EUR/m2 + 10EUR/m’
5		Failure of the sealer material. Water and debris can freely enter the opening and damage the bridge elements below.	Repair / Replacement of the expansion joints including surrounding concrete (‘viajoint’)	200EUR/m’

PREVENTIVE

No.	Picture	Defect description	Prevent. action	Cost
1		Reduced diameter of the sinks	Cleaning the scuppers	/
2		Vegetation and deterioration	Cleaning and Repairing the sidewalks (execution of new RC sidewalk)	50EUR/m2
3		Over 50% of the walls have cracks, brown spots and leakage	Cleaning and surface repair of concrete (<30mm) in localized areas, removing degraded concrete, cleaning and protecting the reinforcement	30EUR/m2
4		Localized areas of white and wet spots, surface cracks	Cleaning and concrete deck sealing (1); filling or sealing of cracks with width >0.30mm (2)	(1)100EUR/m’ (2) 50EUR/m’
5		Three to four isolated moderate spalls and delamination of the pavement, moderate riding quality.	Clean the bridge, sealing the cracks in the asphalt, apply overlayers	20EUR/m2

Maintenance scenarios

- Semi-quantitative evolution of reliability index over time



"Do nothing and rebuild"

α=0.07 years⁻¹
γ=4.26-2=2.26
tpi=30 years
tpD=6 years

Corrective

α=0.07 years⁻¹
γ=0.53
δ=0.02 years⁻¹
tpi=23 years
tpD=6 years
tp=13 years

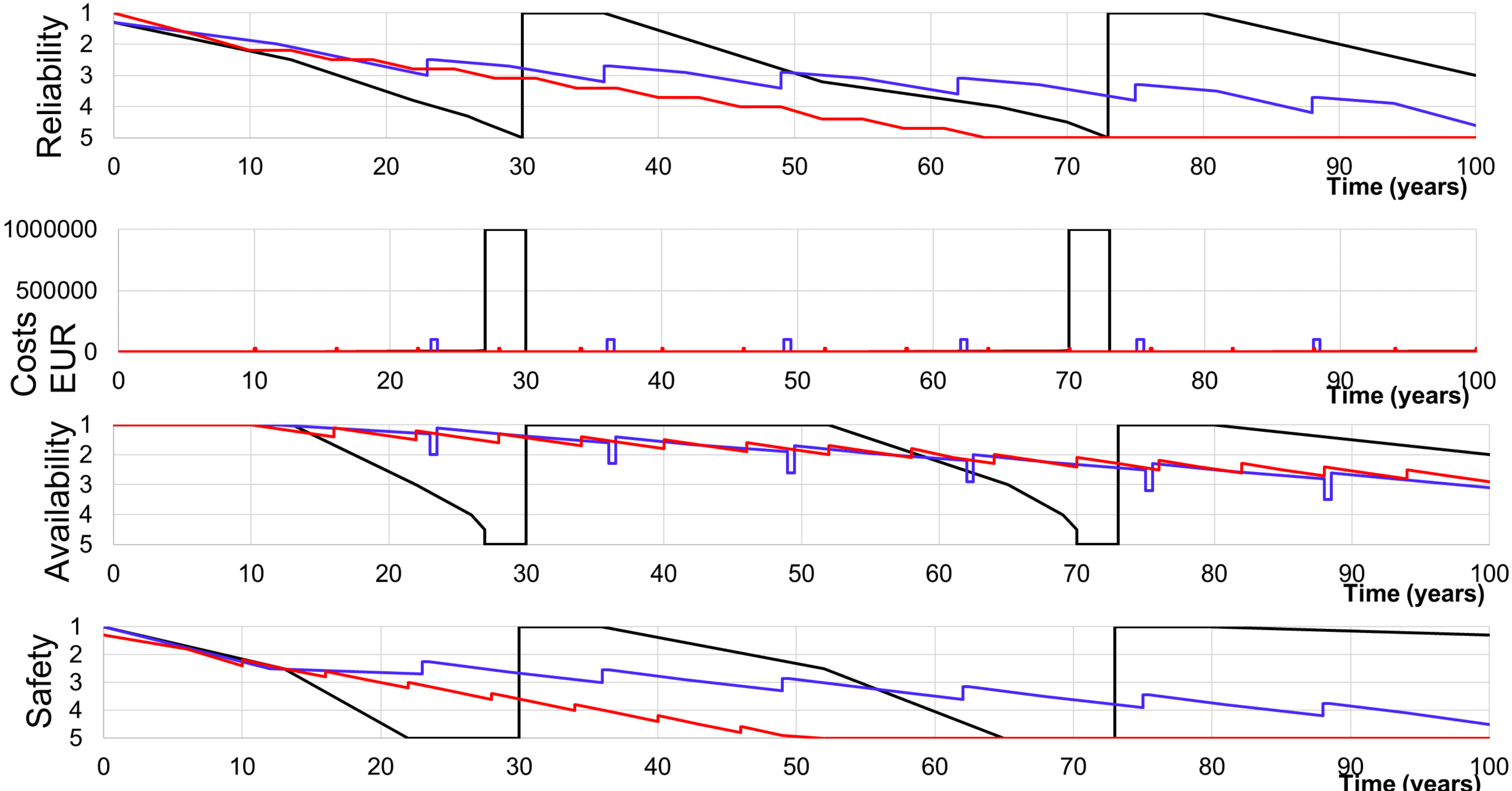
Preventive

α=0.07 years⁻¹
γ=0.00
θ=0.00 years⁻¹
tpi=10 years <23 years
tpD=3 years
tp=6 years

Maintenance scenarios

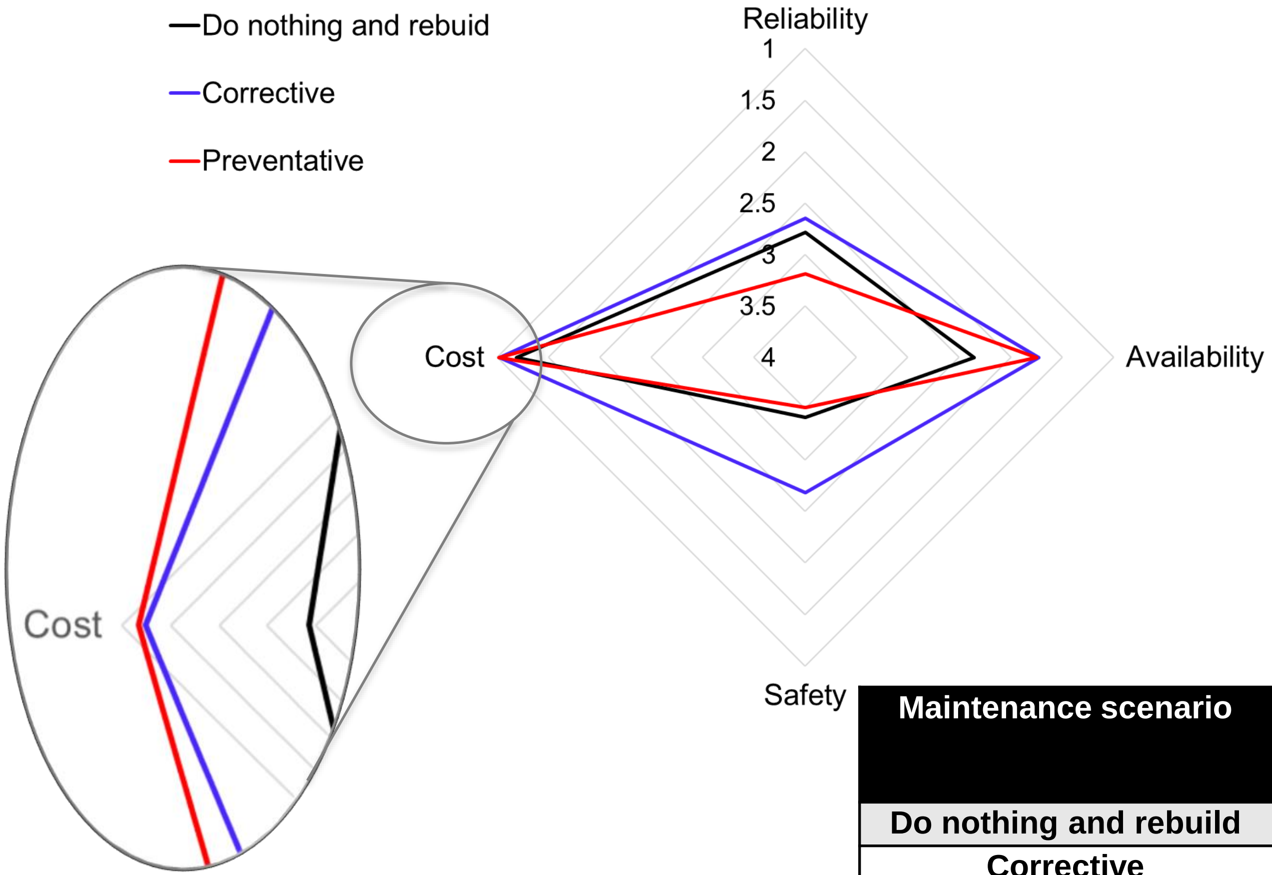
- Qualitative evolution of KPIs over time

LEGEND:
"Do nothing and rebuild" **Corrective** **Preventive**



Maintenance scenarios

- Comparison



Maintenance scenario	Spider Area [/]	In terms of Do nothing and rebuild
Do nothing and rebuild	12.24	/
Corrective	16.89	38%
Preventative	11.94	2.45%

Conclusion

- With the applied quality control plan, ‘virgin‘ reliability, anticipated failure modes and related vulnerable areas were taken into account, bringing some adventages in terms of other element-oriented quality control methodologies. With such a holistic approach, preventative maintenance and possible rehabilitation can be planned and optimized.

- Established methodology is applicable also in the quantitative manner, which is the aim of the further research.

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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

Girder beam bridges - Sub group B1 Strymonas river bridge case

Panagiotis Panetsos – Egnatia Odos A.E., Greece

ΕΓΝΑΤΙΑ ΟΔΟΣ Α.Ε.

22nd November 2018
Bergisch Gladbach, Germany

STRYMONAS RIVER BRIDGE SELECTED FOR GIRDER BEAM USE CASE

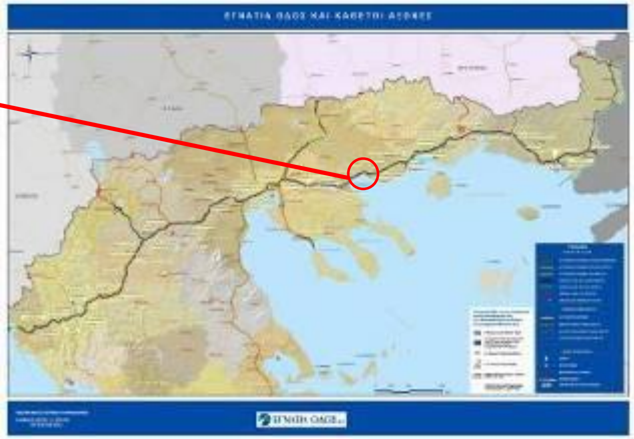
The Strymonas river bridge is a 8 span bridge, built by pre-stressed concrete, founded on the river bed of the Strymonas river, with multi column piers through piles.

The total length of the bridge is 240m, its pavement width -including sidewalks-is 12.00 m, providing two traffic lanes.

All 8 main spans over the entire river bed are 30 m long each, built by 5 precast pre-stressed concrete T beams. All spans are simply supported, through elastomeric bearings on the multi column bents.

The age of the bridge is estimated some 30 years old.

Year of construction: 1987
Deck: 5 prestressed concrete beams
Bridge length: 237.60m
Span no: 8 (×30.00m long)
Joint type: Elastomeric expansion joint (anchored) T50
Bearing type: Elastomeric orthogonal Type NB1

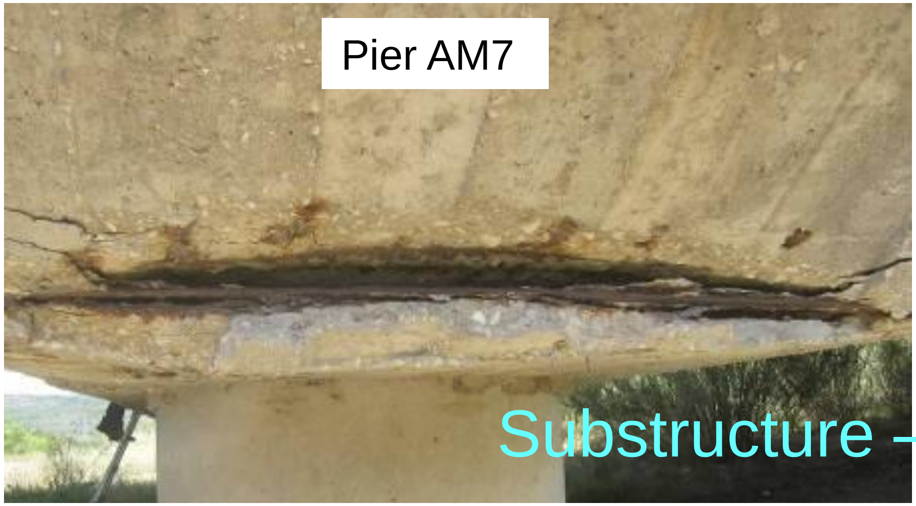


DEFECTS DETECTED DURING INSPECTIONS

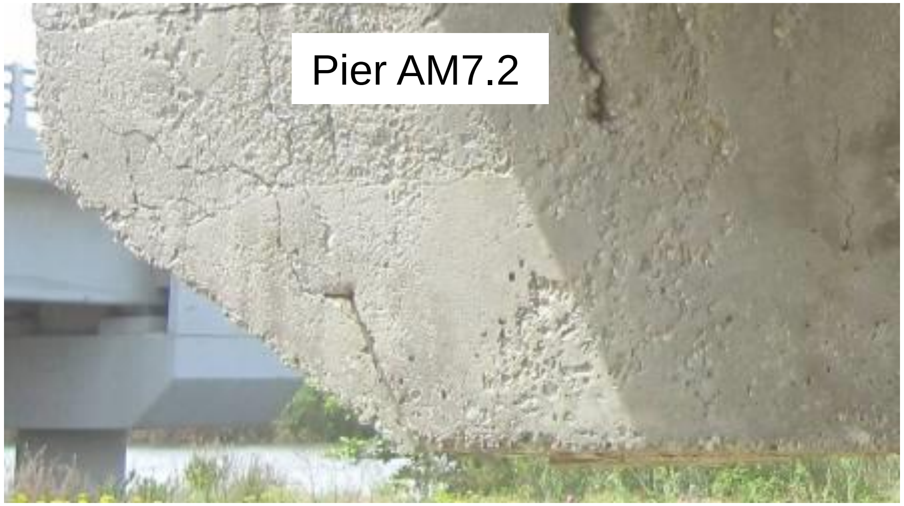

Substructure – Abutment AA0

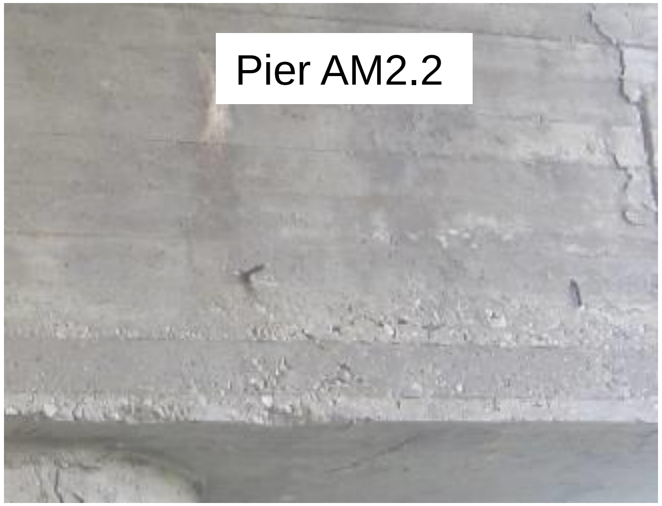

- Wet spots / moisture or wetting areas mainly at the ends of the abutment due to the incapacity of the superstructure’s expansion joint.
- Light efflorescence on the surface of the concrete.

Substructure – Piers

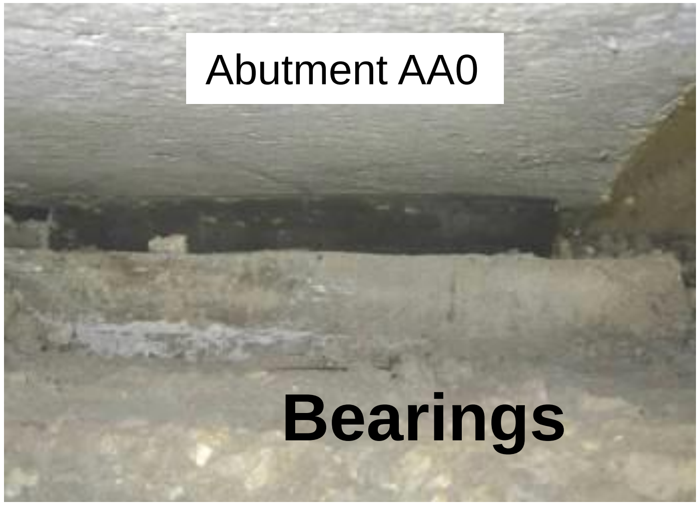


Wetting of concrete’s surfaces, heavy spalling of concrete, exposed and totally corroded steel bars.





Areas with voids all over the surface of piers.



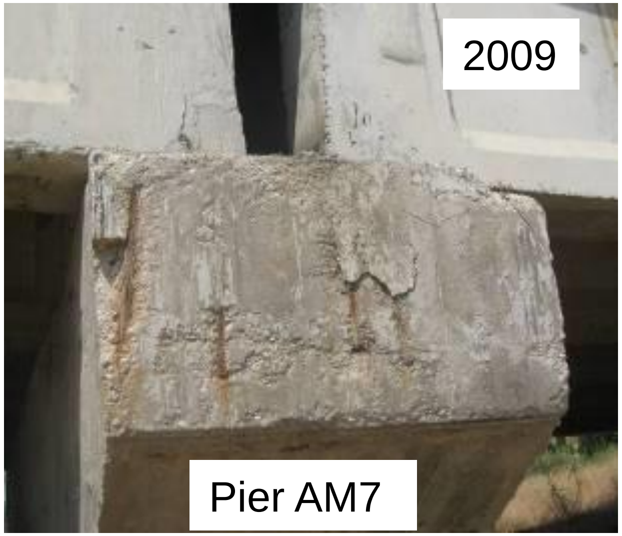
Type 1 bearings of acceptable condition on the abutments. Poor condition of concrete bottom plInths

Superstructure – north side view

Superstructure – south side view

Absence of vertical drainage pipes. Direct wetting of concrete, efflorescence, heavy spalling, exposed and serious corroded mild steel bars, exposed and corroded external covering of tensioning ducts and strands.

Damage evolution vs time



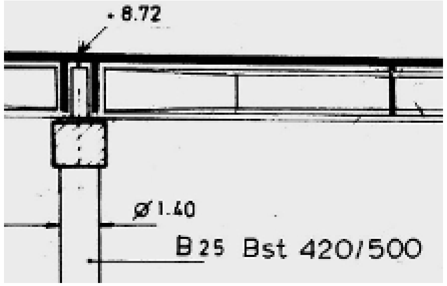
Catastrophic testing for identifying the actual properties of the bridge

Concrete's compress strength assigned to 20MPa, and yield stress of steel bars assigned to 420MPa, according to the design.

For the assessment calculations, laboratory strength and specimen testing were carried out.

Δοκίμιο	Μήκος L_0 (mm)	Διάμετρος d_0 (mm)	Διατομή f (mm^2)	Φορτίο διαρροής P_δ (kg)	Φορτίο θραύσης P_θ (kg)	Τάση διαρροής σ_δ (MPa)	Τάση θραύσης σ_θ (MPa)
1	60	12,1	114,990	5000	8250	434,8	717,5
2	60	12	113,097	5000	8100	442,1	716,2
M.O.						**438,5**	**716,8**

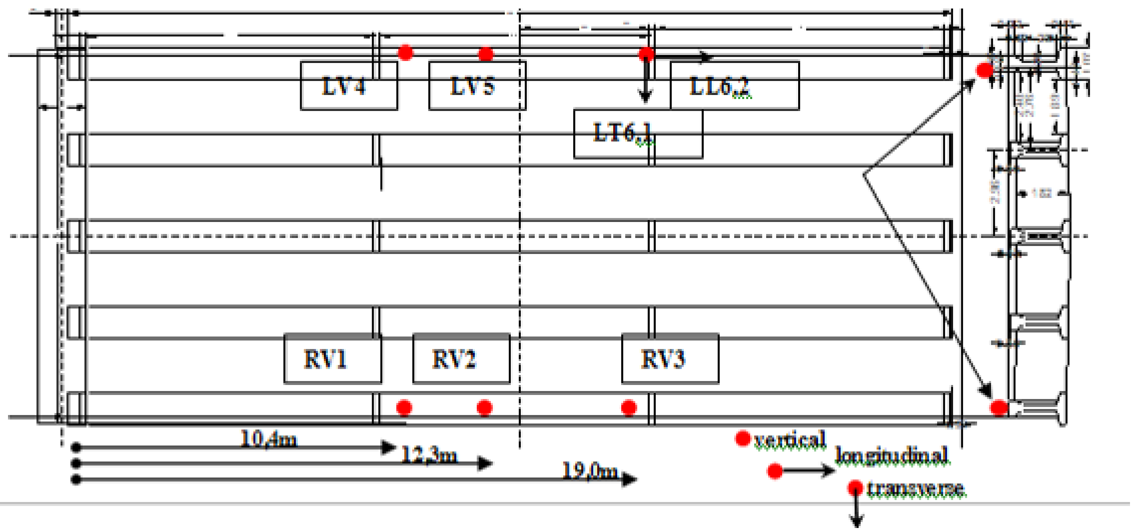
Yield stress of steel bars

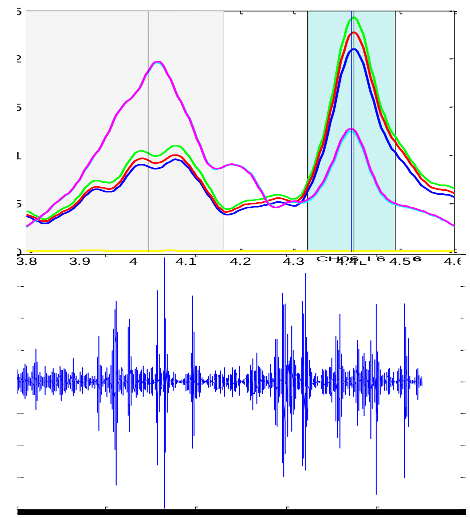


Δοκίμιο	Φορτίο (kN)	**Αντοχή πυρήνα** (MPa)	L1	L2	L4	**Ισ.αντοχή κυλίνδρου** (MPa)	L3	**Ισ.αντοχή κύβου** (MPa)
K1	182,5	24,29	0,852	0,958	1,03	20,4	1,208	24,7
K2	119,3	15,88	0,855	0,958	[illegible]	[illegible]	1,246	16,7
K3	134,6	17,92	0,855	0,958	1,03	15,4	1,238	18,7
K4	96,8	16,11	0,857	0,958	1,03	13,6	1,246	17,0
K5	120,6	16,05	0,857	0,958	1,03	13,6	1,246	16,9
K6	142,8	19,01	0,855	0,958	1,03	16,0	1,233	19,8
M.O.		**17,0**				**14,3**		**17,8**

Compress strength from drilling cores

Ambient vibration Monitoring

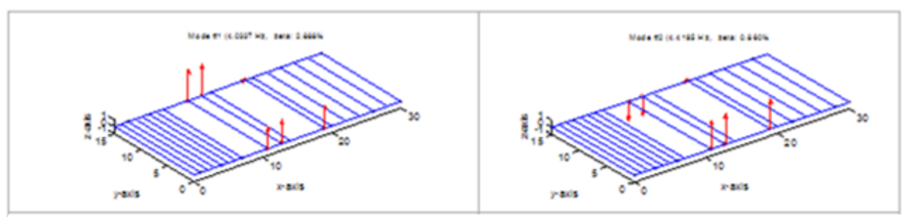




Uniaxial FB Accelerometers arrays installed on the bottom of the beams

Identified modeshapes, frequencies and modal damping rations of Strymonas river bridge

Identified frequencies		measured	measured	Model predicted
No	Type of modes	Modal Frequencies (Hz)	Modal damping ratios (%)	Modal Frequencies (Hz)
1	1st bending	4.03	2.89	4,15
2	1st rotational	4.42	0.86	4.45
3	2nd rotational	13.04	0.31	12.96
4	2nd bending	13.18	0.51	14.99

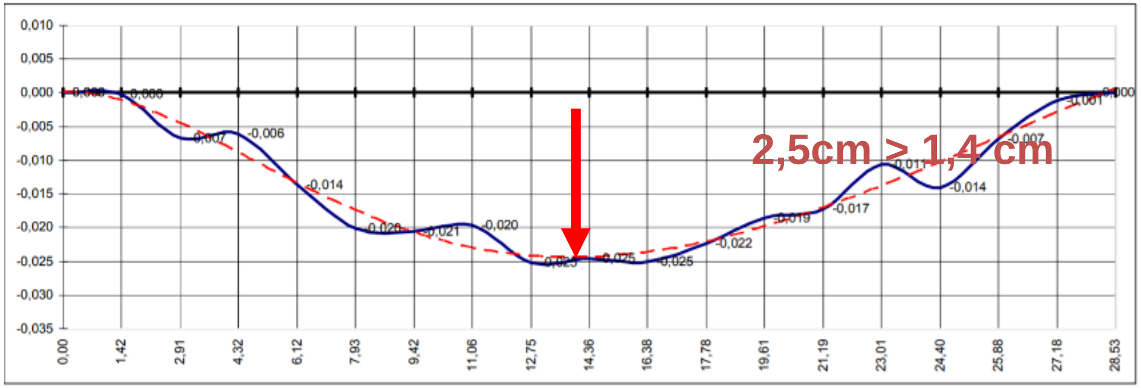


Identified modeshapes a) 1st bending mode (4,03Hz) ,b) 1st rotational mode (4,42Hz)

Conclusions based on 2 sequential vibration measurements (2007 and 2017):

1. **Frequencies lower than the model predicted.**
2. **Frequencies do not change vs time**

Deflection monitoring of post-tensioned beams



Δ5-M6M7

Actually measured deflections are bigger than the model predicted (considering creep)

Chemical properties testing

Laboratory chemical properties included Cl -, SO4-2, NO3-and PH determination at the outer surface of the concrete (usually > 7 cm depth from the outer surface).

Core	Salts (%)						PH	
	Cl^-		SO_4^{-2}		NO_3^-			
	upper 3cm	lower 3cm	upper 3cm	lower 3cm	upper 3cm	lower 3cm	upper 3cm	lower 3cm
1	0.44	0.13	0.66	0.53	0.02	n/d	11.8	11.9
2	0.32	0.26	0.34	0.72	0.01	0.01	11.9	12.1
3	0.20	0.14	0.47	0.49	0.01	0.01	11.8	11.9
4	0.07	0.14	0.39	0.49	0.01	n/d	11.9	12.0
5	0.32	0.25	0.50	0.62	0.01	n/d	11.6	11.8
6	0.33	0.27	0.37	0.66	n/d	n/d	11.8	11.9
7	0.35	0.32	1.50	0.92	0.04	n/d	11.6	12.0
8	0.13	0.06	0.59	0.46	n/d	n/d	12.3	12.4

- **Separate definition of PIs for 4 components of the bridge:**
  Superstructure, Piers, Abutments, Pavement

- **Selection of 4 KPIs :**
  Reliability,
  Availability,
  Safety
  Agency Costs (Costs of maintenance)

Failure modes triggered due to the deterioration mechanisms

Abutment : No failure is expected in next 25 years

Piers : Failure of the pier cap external cantilever under vertical loads (due to corrosion) .

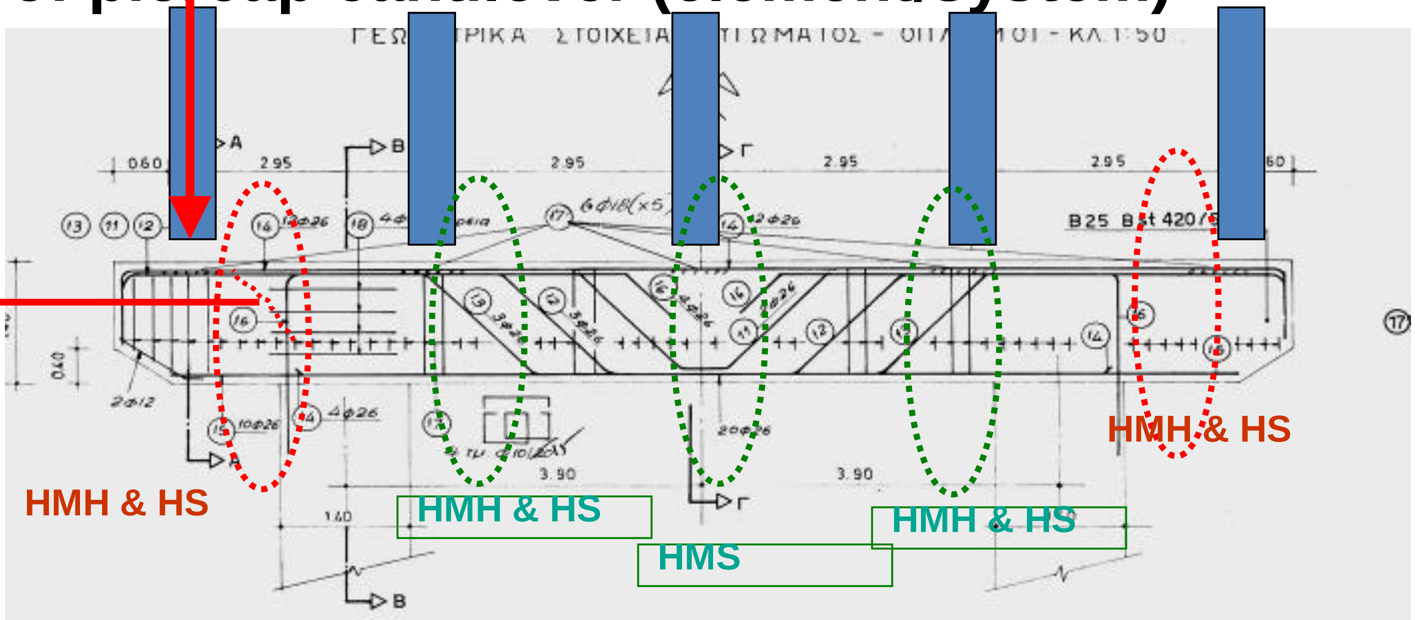
Prediction : t=47 or after 15 years

Superstructure : Failure of the post-tensioned beams under vertical loads (outer beams due to corrosion)

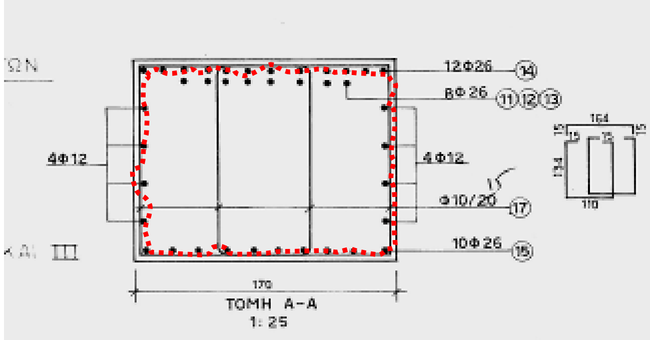
Prediction : t=52 or after 20 years

Failure modes triggered:
Failure of piercap cantilever (element/system)

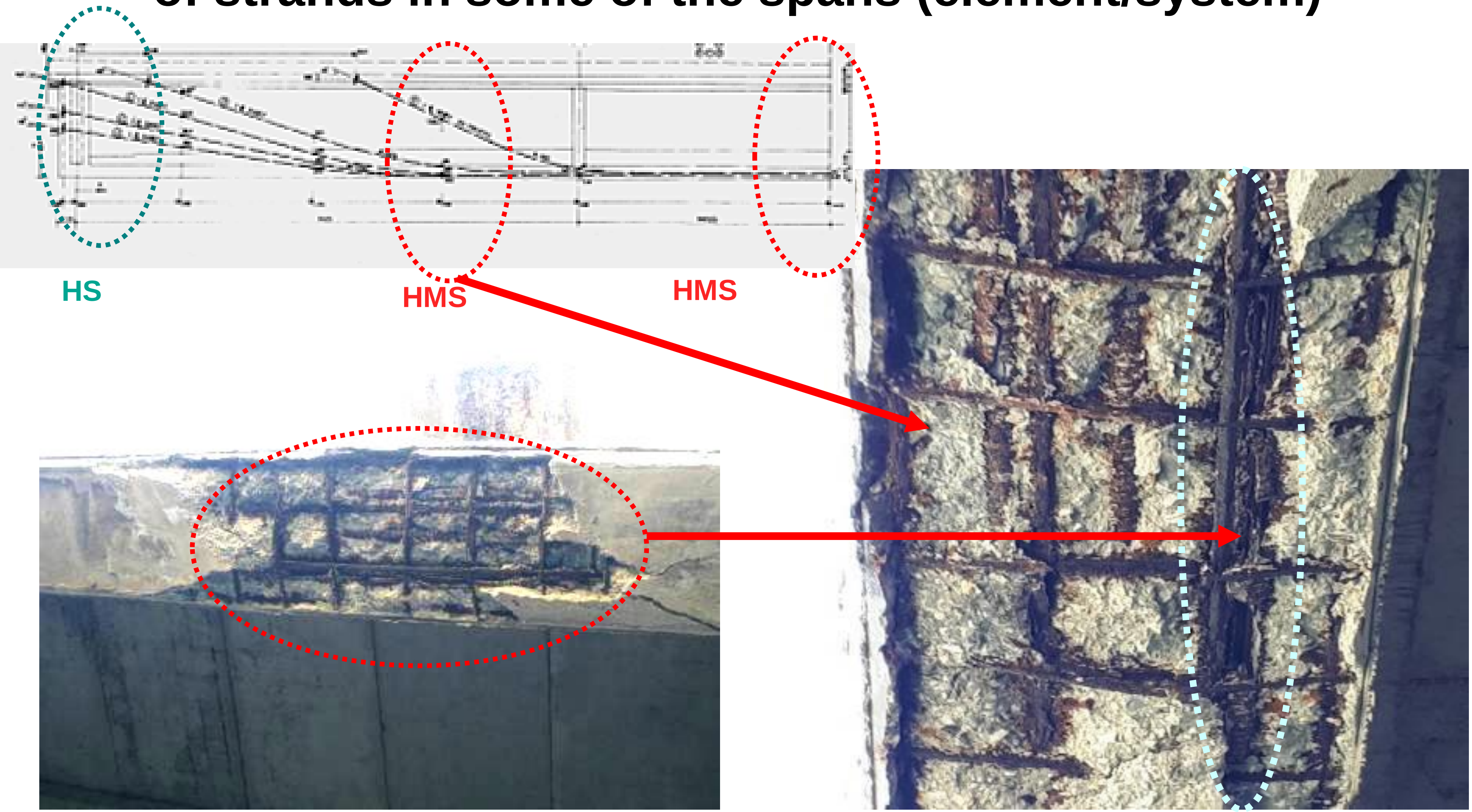
Hairline shear cracks



Delamination/spalling/
10% steel bar diameter loss



Failure modes triggered due to the corrosion initiation of strands in some of the spans (element/system)



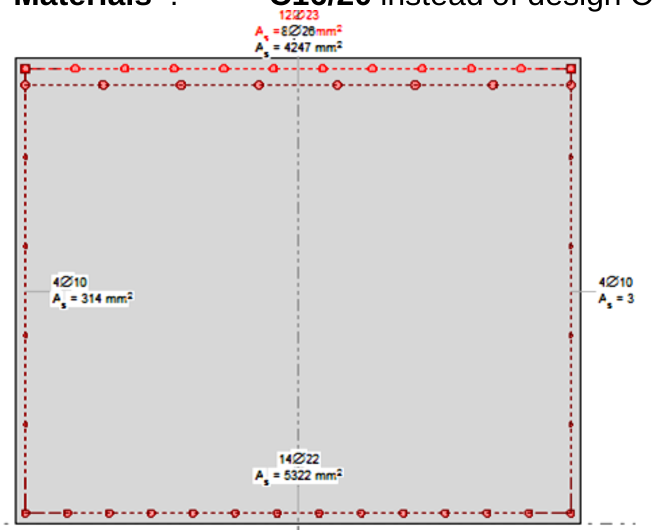
Failure modes triggered: Failure of piercap cantilever (element/system)

Calculation of the remaining bending moment capacity of the pier <u>head support</u>

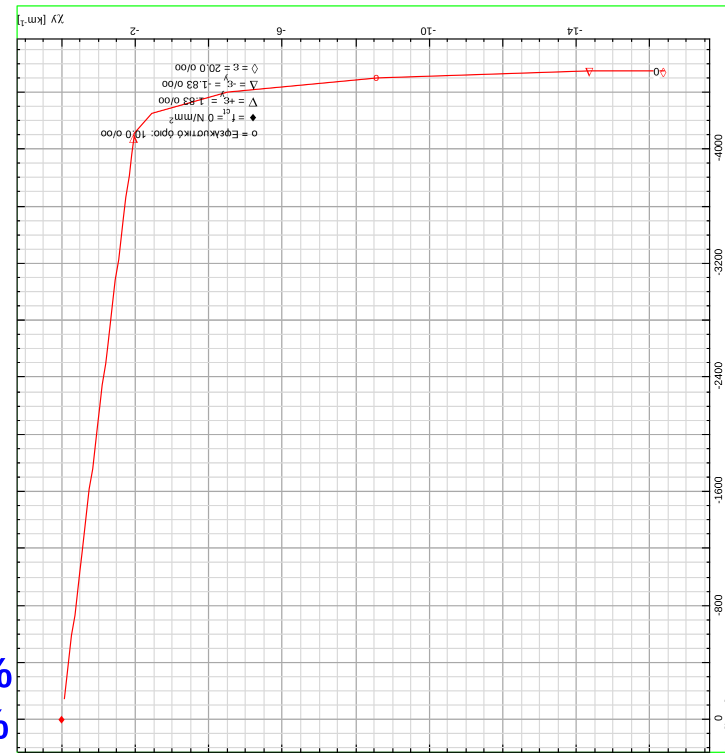
Considerations: upper layer **12 Φ23 remaining from initial 12 Φ 26**

Second layer **8 Φ26** /**Stirrups** : 4x Φ9/15+Φ16/30 instead of **4x Φ10/15+Φ18/30**

Materials : **C16/20** instead of design C20/25 and **S420**



Reinforcement arrangement of the pier head support cross section, considering the diameter loss due to corrosion



Bending Moments: ***Reduce of safety factor*** **-17,88%**

Shear Forces : ***Reduce of safety factor*** **-21,62%**

Prediction of the pitting corrosion penetration in reinforcement bars (top layer)

Corrosion penetration is given by : $x_u = C_1(T - T1)C_2$ ***(1)*** (Paik et al. 2004)

where: x_u = corrosion penetration in unprotected steel in *μm*

T = **age** of the bridge,

T1= the **time from the exposition of the reinforcement bars**

C_1= coefficient indicative of the **annual corrosion rate**

C_2 = coefficient indicative of the **trend in corrosion propagation**

Values of C_1 and C_2 were considered conservatively as of marine environment *C1=70,6, C2=0,79.*

The yearly penetration is resulted equal to 55,774μm

1. *The additional loss of stirrups' diameter, that would reduce the safety factor to 1, approximately corresponds to* ***1*** *mm diameter loss.*

To get such a diameter loss we need some **18** years of exposition and of non protection/repair of the already corroded stirrups to the corrosive environment

2. *The additional loss of top layer bars, that would reduce the bending moments safety factor to 1 approximately corresponds to* ***1,2*** *mm diameter loss.*

To get such a diameter loss we need some **20** years of exposition and of non protection/repair of the already corroded stirrups to the corrosive environment

The conservative prediction of the shear failure of the piercap of the bridge piers in the next 15 years is considered herein

35 PIs are set for Reliability, 12 PIs for Safety, 11 PIs for Availability. Costs represents the yearly cost.

The importance of PIs to each KPI are defined

35 PI

Importance of PIs for the Reliability of Superstructure

PI Weighting factors for Reliability

Analytical Hierarchy Process

crack width (longitudinal, due to retr	3	0.75	0.75	1.5	0.15	0.2	132	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.007576
Flexular structural cracks (width)	8	2	2	4	0.4	0.5333333	49.5	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202
Calcium leaching (area)	3	0.75	0.75	1.5	0.15	0.2	132	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.007576
Calcium leaching (intensity)	3	0.75	0.75	1.5	0.15	0.2	132	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.0075758	0.007576
Spalling depth (loss of concrete secti	7	1.75	1.75	3.5	0.35	0.4666667	132	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.017677
Loss of fl. Bars section (diameter)	10	2.5	2.5	5	0.5	0.6666667	56.571429	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.025253
loss of stirrups section (diameter)	10	2.5	2.5	5	0.5	0.6666667	39.6	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.025253
pitted corrosion	5	1.25	1.25	2.5	0.25	0.3333333	39.6	0.0126263	0.0126263	0.0126263	0.0126263	0.0126263	0.0126263	0.0126263	0.0126263	0.012626
rotation of the pier around horizonta	10	2.5	2.5	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0252525	0.0252525	0.0252525	0.0252525	0.025253
settlement of the pier	10	2.5	2.5	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0252525	0.0252525	0.0252525	0.0252525	0.025253
pier head residual horizontal displac	10	2.5	2.5	5	0.5	0.6666667	39.6	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.025253
sulfate content	7	1.75	1.75	3.5	0.35	0.4666667	39.6	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.0176768	0.017677
carbonation depth	10	2.5	2.5	5	0.5	0.6666667	56.571429	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.0252525	0.025253
chloride content	8	2	2	4	0.4	0.5333333	39.6	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202	0.020202
Safety factor for dead/traffic loads	40	10	10	20	2	2.6666667	49.5	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.10101
Traffic load carrying capacity factor	40	10	10	20	2	2.6666667	9.9	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.1010101	0.10101
delamination (in area)	15	3.75	3.75	7.5	0.75	1	9.9	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.037879
delamination (in depth)	13	3.25	3.25	6.5	0.65	0.8666667	26.4	0.0328283	0.0328283	0.0328283	0.0328283	0.0328283	0.0328283	0.0328283	0.0328283	0.032828
ductility of steel bars	15	3.75	3.75	7.5	0.75	1	30.461538	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.037879
ductility of prestressing strands	15	3.75	3.75	7.5	0.75	1	26.4	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.037879
Shear like structural cracks (width)	15	3.75	3.75	7.5	0.75	1	26.4	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.037879
damping	30	7.5	7.5	15	1.5	2	26.4	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.075758
frequency	30	7.5	7.5	15	1.5	2	13.2	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.0757576	0.075758
Seismic rating factor	20	5	5	10	1	1.3333333	13.2	0.0505051	0.0505051	0.0505051	0.0505051	0.0505051	0.0505051	0.0505051	0.0505051	0.050505
Concrete Strength (actual vers as des	15	3.75	3.75	7.5	0.75	1	19.8	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.037879
Steel Strength (actual vers as design	15	3.75	3.75	7.5	0.75	1	26.4	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.0378788	0.037879

t=32 years

PIs and **KPis** for bridge elements and for the System ***(Reliability)***

or directly for the system ***(Availabiity, Safety, Cost)***

are calculated for the current bridge condition (2017 or 32 years after construction)

The PIs are calculated for each KPI

Actual rating (t=32y)of PIs for Reliability of the Superstructure.

$R\_super,_{act}=1,745$ *

ACTUAL RELIABILITY RATING T=32 YEARS

PI	PI TYPE	PI UNIT	REAL PRACTICE Pjh	STANDARD PRACTICE Pjh*	BEST PRACTICE P*jh	NORMALIZED VALUE	CALIBRATED NORMALIZED VALUE Pnormjh	PI WEIGHTS	PI Ratings	KPI RATING
bearings deformation	related to response	T = number of affected bearings	0	5	0	1	1	0,01010101	0,010101	
bearings displacement	related to response	T = number of affected bearings	0	5	0	1	1	0,01010101	0,010101	
Concrete spalling (area)	defects	T =percentage of affected area (m^2)	10	10	0	0	0	0,005050505	0	
Concrete spalling (depth)	defects	T =max depth of spalled area	20	5	0	-3	-0,2	0,007575758	-0,00152	
concrete cover (insufficient)	related to deterioration/defect	T =percentage of affected area (m^2)	50	10	0	-4	-0,2	0,007575758	-0,00152	
corrosion of flexular reinforcement bars (number)	defects	T =percentage of affected number of bars	20	5	0	-3	-0,2	0,01010101	-0,00202	
corrosion of stirrups (number)	defects	T =percentage of affected number of bars	30	5	0	-5	-0,2	0,012626263	-0,00253	
crack length (due to shrinkage)	defects	T = length (cm)	0,7	1	0,5	0,6	0,6	0,005050505	0,00303	
crack width (due to shrinkage)	defects	T = width (mm)	0,05	0,2	0,1	1,5	1,2	0,005050505	0,006061	
crack width (longitudinal, due to retraction o concrete	defects	T = width (mm)	0,05	0,2	0,1	1,5	1,2	0,007575758	0,009091	
Flexular structural cracks (width)	related to the impact of the defect	T = rating depending on width (mm)	0	0,3	0,2	3	1,2	0,02020202	0,024242	
Calcium leaching (area)	related to deterioration/defect	T =percentage of affected area (m^2)	5	10	0	0,5	0,5	0,007575758	0,003788	
Calcium leaching (intensity)	related to deterioration/defect	T =percentage of affected area (m^2)	3	5	0	0,4	0,4	0,007575758	0,00303	
Spalling depth (loss of concrete section)	related to the impact of the defect	T = ratio of superstructure section loss	10	10	0	0	0	0,017676768	0	
Loss of fl. Bars section (diameter)	related to the impact of the defect	T = ratio of lost diameter	10	10	0	0	0	0,025252525	0	
loss of stirrups section (diameter)	related to the impact of the defect	T = ratio of lost diameter	30	10	0	-2	-0,2	0,025252525	-0,00505	
pitted corrosion	defects	T =percentage of affected bars	0	0	0	1	1	0,012626263	0,012626	
sagging of the inividual beams of one span	related to the impact of the defect	T =mm of midspan	25	20	15	-1	-0,2	0,025252525	-0,00505	1,745
residual horizontal dsiplacement	related to the impact of the defect	T =%vertical slope	0	0	0	1	1	0,025252525	0,025253	
loss of pre-stresing tendons section (diameter)	related to the impact of the defect	T = ratio of lost diameter	3	5	0	0,4	0,4	0,025252525	0,010101	
sulfate content	related to the impact of the defect	T =content in % of cement weight	0,06	0,08	0,06	1	1	0,017676768	0,017677	
carbonation depth	related to the impact of the defect	T =content in % of cement weight	6	10	0	0,4	0,4	0,025252525	0,010101	
chloride content	related to the impact of the defect	T =content in % of cement weight	0,05	0,06	0,04	0,5	0,5	0,02020202	0,010101	
Safety factor for dead/traffic loads	Analytical assessement	T= reduction of safety factor %	5	10	0	0,5	0,5	0,101010101	0,050505	
Traffic load carrying capacity factor	Analytical assessement	T = loads (KN) (qualitative scale here)	8	7	9	0,5	0,5	0,101010101	0,050505	
delamination (in area)	defects	T =ratio of delaminated area/total area	5	10	0	0,5	0,5	0,037878788	0,018939	
delamination (in depth)	defects	T =depth of delamination in mm	3	5	0	0,4	0,4	0,032828283	0,013131	
ductility of steel bars	related to the impact of the defect	T = ratio of fracture/yield strain	1,15	1,15	1,2	0	0	0,037878788	0	
ductility of prestressing strands	related to the impact of the defect	T = ratio of fracture/yield strain	1,1	1,1	1,15	0	0	0,037878788	0	
Shear like structural cracks (width)	related to the impact of the defect	T =t (mm)	0	0,2	0	1	1	0,037878788	0,037879	
damping	dynamic property from SHM	T = change of damping from the uncracked	0,045	0,05	0,02	0,166666667	0,166666667	0,075757576	0,012626	
frequency	dynamic property from SHM	T = measured/design bending frequency	0,9	1	1,2	-0,5	-0,2	0,075757576	-0,01515	
Seismic rating factor	Analytical assessement	T=seismic rating	1,1	1	1,1	1	1	0,050505051	0,050505	
Concrete Strength (actual vers as designed)	Properties from lab testing	T = actual/initial	0,85	0,95	1	-2	-0,2	0,037878788	-0,00758	
Steel Strength (actual vers as designed)	Properties from lab testing	T = actual/initial	0,9	1	1	0	0	0,037878788	0	

1-5 Rating scale. 0 the worst, 5 the best condition rating

PIs representing observed or measured deterioration intensity

PIs representing observed or measured indications of structural loss

PIs representing analytical or analytical monitoring based assessment

PIs representing site & laboratory testing

Final System KPI rating score from (weighted KPI rating)

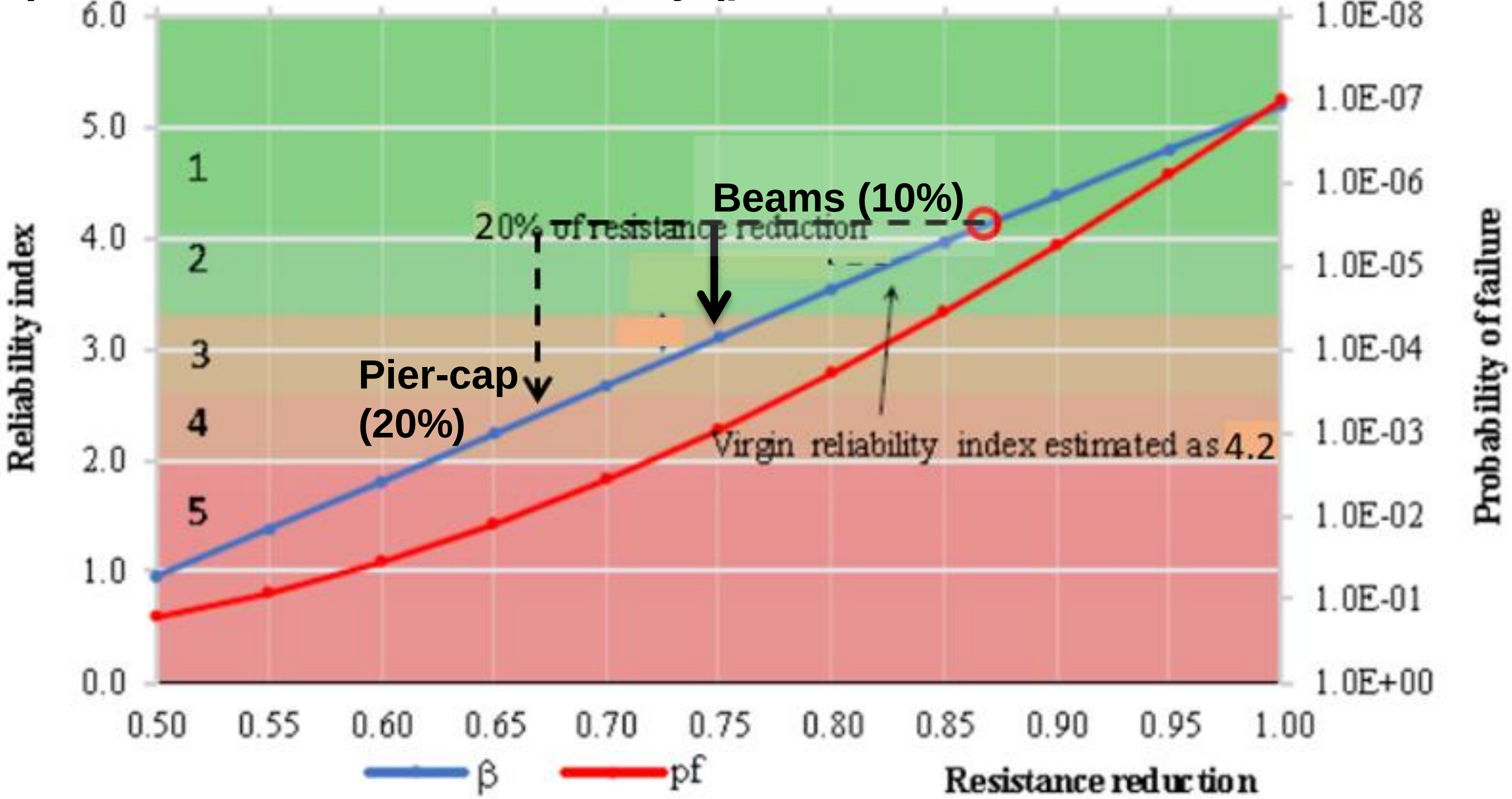
Actual (t=32y) Bridge System rating for Reliability R_System,$_{act}$ = 2,10 *

		ACTUAL T=32 years				
S/N	COMPONENT	Qcomp NOTATION	Qcomp VALUE	WCOMP	KPI RATINGS	SYSTEM RELIABILITY RATING
1	Abutment	Qabut	2,227	0,24589	0,54759703	2,10
2	Pier	Qpier	1,216	0,31421	0,38207936	
3	Superstructure	Qsuper	1,745	0,31421	0,54829645	
4	Pavement	Qpave	4,928	0,12568	0,61935104	
			SUM	1	2,09732388	

•Minimum condition rating of bridge equals substructure rating = 3 in 1-9 scale

or 1,66 in 1-5 scale < 2,10 (more conservative rating based on visual findings)

Simplified calculation of Reliability (β-index chart consider resistance reduce)



		ACTUAL SYSTEM RELIABILITY T=32 years				
S/N	COMPONENT	Qcomp NOTATION	Qcomp VALUE	WCOMP	KPI RATINGS	SYSTEM RELIABILITY RATING
1	Abutment	Qabut	3,6	0,24589	0,885204	3,03
2	Pier	Qpier	2,2	0,31421	0,691262	
3	Superstructure	Qsuper	3,1	0,31421	0,974051	
4	Pavement	Qpave	3,8	0,12568	0,477584	
			SUM	1	3,028101	

Or R,system = 2,2 (min of components)

B1. Actual rating of PIs for Safety of the Bridge $Safety,Syst_{act}=3,031$

ACTUAL SAFETY RATING OF THE BRIDGE SYSTEM

KPI (BENCHMARK)	KPI NOTIFICATION	PI	PI TYPE	PI UNIT	REAL PRACTICE Pjh	STANDARD PRACTICE Pjh*	BEST PRACTICE P*jh	NORMALIZED VALUE	CALIBRATED NORMALIZED VALUE Pnormjh	PI WEIGHTS	PI ratings	KPI RATING
Safety	S	Safety for the driver in terms of Safety barriers condition/adequacy	rating	T= Condition of safety barriers	8	5	9	0.75	0.75	0.108695652	0.081522	3.0307971
SYSTEM		Safety for the driver due to the uneveness of the asphalt pavement	rating	T= required hours	0	1	0.75	4	1	0.086956522	0.086957	
		Safety for the driver due to the asphalt pavement defects (pot holes)	rating	T= depth* area of pot holes	0.001	0.005	0	0.8	0.8	0.108695652	0.086957	
		Safety for the driver due to the approach pavement settlement	rating	T= slope of the transmission pavement	0	0.2	0	1	1	0.086956522	0.086957	
		Safety for the driver due to frequent traffic lane closures	rating	T= qualitative rating	10	9	8	-1	-0.2	0.086956522	-0.01739	
		Safety for the driver due to asphalt pavement wearing and tearing (rutting, ravelling)	rating	T= rutting depth in mm	4	9	4	1	1	0.086956522	0.086957	
		Safety for the driver due to asphalt pavement sliding under wet/rain conditions	rating	T= condition rating of the antiskid pavement	8	6	9	0.6666667	0.666666667	0.108695652	0.072464	
		Safety for the fisher boats from debris falls of the spalled concrete surface of the piers and superstructure	rating	T= depth of spalled areas in mm	15	1	0	-14	-0.2	0.065217391	-0.01304	
		Safety of the driver due to the damage of expansion joints	rating	T= condition rating of expansion joints	8	4	9	0.8	0.8	0.108695652	0.086957	
		Safety of the driver due to extreme sagging of the superstructure post-tensioned beams	rating	T= midspan deflection in cm	3	10	5	1.4	1	0.065217391	0.065217	
		Safety of the driver/ people due to the fall of spalled concrete surface debris under the bridge	rating	T= depth of spalled areas in mm	15	1	0	-14	-0.2	0.086956522	-0.01739	

B2. Actual rating of PIs for Availability of the Bridge. $A\_system,_{act}=4,6202$

ACTUAL AVAILABILITY RATING OF THE SYSTEM

KPI (BENCHMARK)	KPI NOTIFICATION	PI	PI TYPE	PI UNIT	REAL PRACTICE Pjh	STANDARD PRACTICE Pjh*	BEST PRACTICE P*jh	NORMALIZED VALUE	CALIBRATED NORMALIZED VALUE Pnormjh	PI WEIGHTS	PI ratings	KPI RATING
Availability	A	Traffic lane closure for inspection with underside mechanized platform	rating	T= required hours	8	4	4	0	0	0.075949367	0	4.6202532
SYSTEM		Traffic lane closure for deinstallation/installation of expansion joints	rating	T= required hours	0	1	0.75	4	1	0.101265823	0.101265823	
		Traffic lane closure for expansion joint repair	rating	T= required hours	0	4	2.5	2.666666667	1	0.050632911	0.050632911	
		Traffic lane closure for expansion joint replacement	rating	T= required days	0	0.8	0.4	2	1	0.101265823	0.101265823	
		Traffic bridge closure for uplifting of the bridge to replace bearings	rating	T= required days	0.1	0.4	0.375	12	1	0.126582278	0.126582278	
		Traffic bridge closure for maintaining/rehabilitating the post-tensioning beams	rating	T= required days	0	1	0.75	4	1	0.126582278	0.126582278	
		Traffic bridge closure for maintaining/rehabilitating the piers/foundations	rating	T= required days	0.125	0.125	0.125	1	1	0.126582278	0.126582278	
		Traffic lane bridge closure for maintaining/replacing the safety barriers	rating	T= required hours	0	2	1.5	4	1	0.050632911	0.050632911	
		Traffic lane closure for maintaining the sidewalks	rating	T= required days	0.375	0.375	0.375	1	1	0.050632911	0.050632911	
		Traffic bridge closure for maintaining the approach pavement	rating	T= required hours	0.5	0.5	0.5	1	1	0.050632911	0.050632911	
		Traffic lane closure for replacing/maintaining the pavement/waterprrofing membrane	rating	T= required days	0	0.228	0.175	4.301886792	1	0.126582278	0.126582278	
		Traffic bridge closure for replacing/maintaining the lighting towers	rating	T= required hours	0.1	0.1	0.1	1	1	0.012658228	0.012658228	

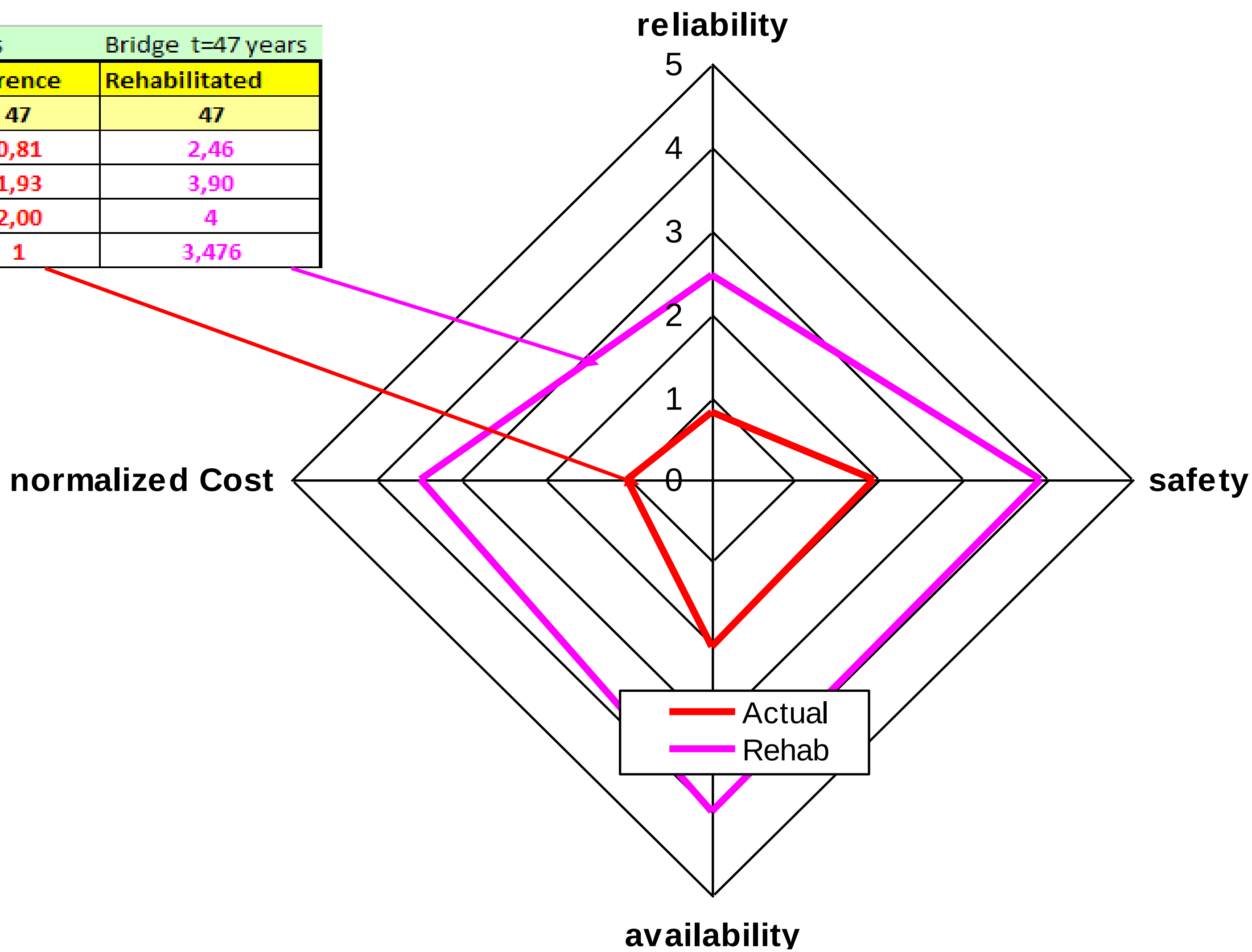
C. Costs expected, for 2 alternative scenarios
1st scenario (rehabilitation at t = 47 years)
2nd scenario (rehabilitation at t = 33 years)

Maintenance costs	Rehabilitation at t=47	Rehabilitation at t=33
Pavement routine maintenance	**80000**	40000
Pavement rehabilitation	210000	210000
Expansion joints	710000	710000
Bearings	250000	500000
Safety barriers	220000	220000
Rehabilitation of piers	**750000**	600000
Rehabilitation of superstructure	**1200000**	700000
Inspection /NDT/SHM/Assessment costs	**720000**	470000
Total costs	**4140000**	**3450000**

Bridge life period examined (t=32 years (today) – t=80 years)

D.1 Spider diagrams at t=47years with/without rehabilitation

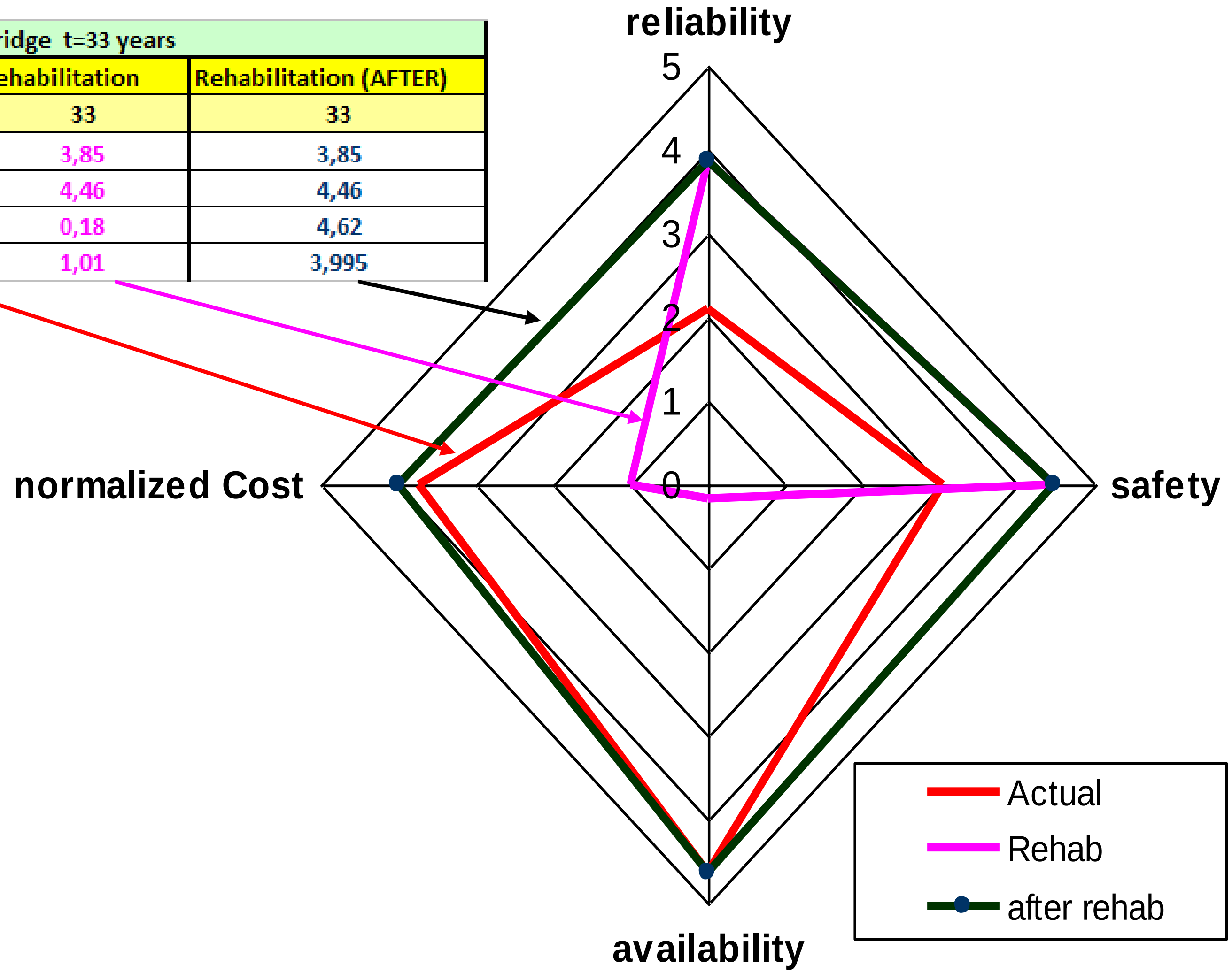
Bridge after 15 years t=47 years		Bridge t=47 years
t=47years/47years	**Reference**	**Rehabilitated**
time	**47**	**47**
reliability	0,81	2,46
safety	1,93	3,90
availability	2,00	4
normalized Cost	1	3,476



Spider diagrams of 2 scenarios on various times

D. 2 Spider diagrams of actual condition and of the condition during and after rehab (t=33)

Bridge today t=32 years		Bridge t=33 years	
t=32years/33years	Reference	Rehabilitation	Rehabilitation (AFTER)
time	32	33	33
reliability	2,1	3,85	3,85
safety	3,03	4,46	4,46
availability	4,62	0,18	4,62
normalized Cost	3,74	1,01	3,995



Life cycle prediction for scenario 1 (Rehab in t=47)

Life cycle prediction for scenario 2 (Rehab in t=33)

Comparison of the alternative scenarios

A comprehensive comparison of the two approaches is achieved herein only if cumulative effects of the followed maintenance strategy are expressed in one of the following ways:

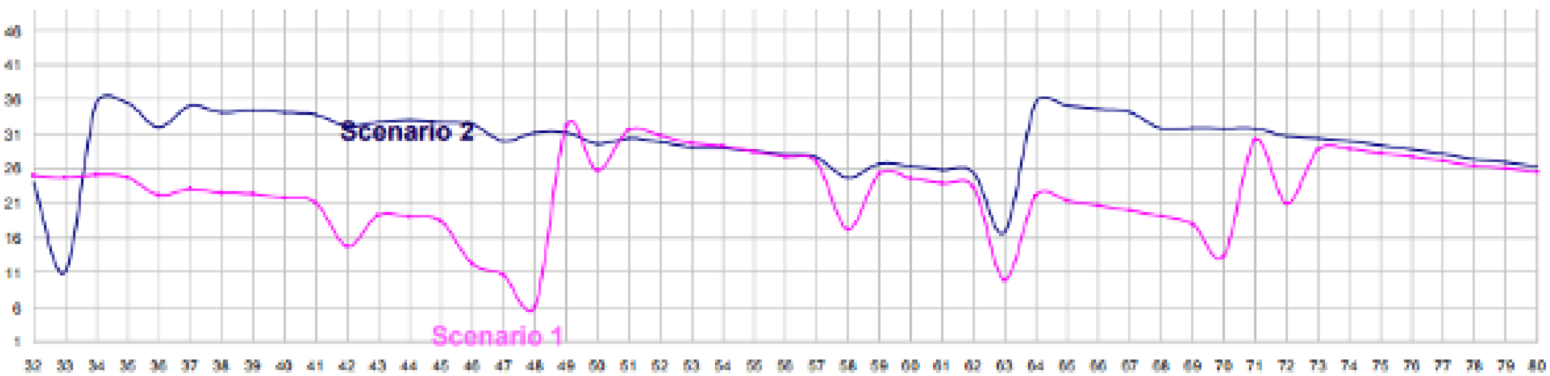
1. **Comparison of the 2 life cycle net present values**

   1st scenario NPValue^1 = 2682465 €

   2nd scenario NPValue^2 = 2132119 €

   NPV^2 < NPV^1

2. **Comparison of the SpiderGrams life cycle volumes for the 2 scenarios**



Scenario 1 Life cycle Spidergram volume: 1123,3
Scenario 2 Life cycle Spidergram volume: 1466,6

SV^2 > SV^1

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THANK YOU FOR YOUR ATTENTION!

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INDUSTRY ADVISORY BOARD – OWNERS MEETING

Sustainable Bridge Management

Standards, Guidelines and Recommendations

Helmut Wenzel – WENZEL Consulting Engineers, Austria

WENZEL Consult

22nd November 2018
Bergisch Gladbach, Germany

WG5 Work Ongoing:

1. WG5 collects the results of the other WGs and prepares it for standardization
2. There is a liaison to CEN TG250, ISO TC 350 and TC 59
3. Contributions to EUROCODES and ISO 21292-2 on Sustainable Construction in Civil Works are prepared
4. Guidelines on the COST TU 1406 results are prepared
5. A book publication is under development

What are Standards?

1. Represent a harmonised procedure agreed by all stakeholders
2. This makes them rather general than very specific (frameworks)
3. National or project specific rules have to be created (NDPs)
4. Standards strictly apply in standard cases only
5. Extraordinary cases are not covered. This opens adjustment of standardized process to specific cases

Relevant Standards for Bridge Management

1. ISO 55000 Asset Management
2. ISO 31000 Risk Management Framework
3. EN 199x Eurocodes (DIN 1076, national)
4. EN 16991 Risk Based Inspection
5. ISO 21929 Sustainability of Construction Works
6. Safety, Environment and Security Guidelines
7. National Management Strategy (your case)

Why do we need Standards?

- From national to global markets
- Makes works comparable
- Provides juristically safe environment for operators
- Allows competition to get economic tenders
- Allows suppliers to develop economic products

Do Standards restrict Owners?

- No. They can be excluded if they don’t fit
- Every Nation can issue Nationally Determined Parameters (NDP) to fit the frameworks for any specific case
- Examples: Seismic Hazards, Snow Loads
- But also rules for visual inspections or the use of monitoring results in the assessment process (i.e. Austria, RVS)
- Standards are for standard cases only! For special cases engineering and expert knowledge shall be applied (quote from EN 1990, page 7)

EN 1990:2002 says:

Status and field of application of Eurocodes, page 7

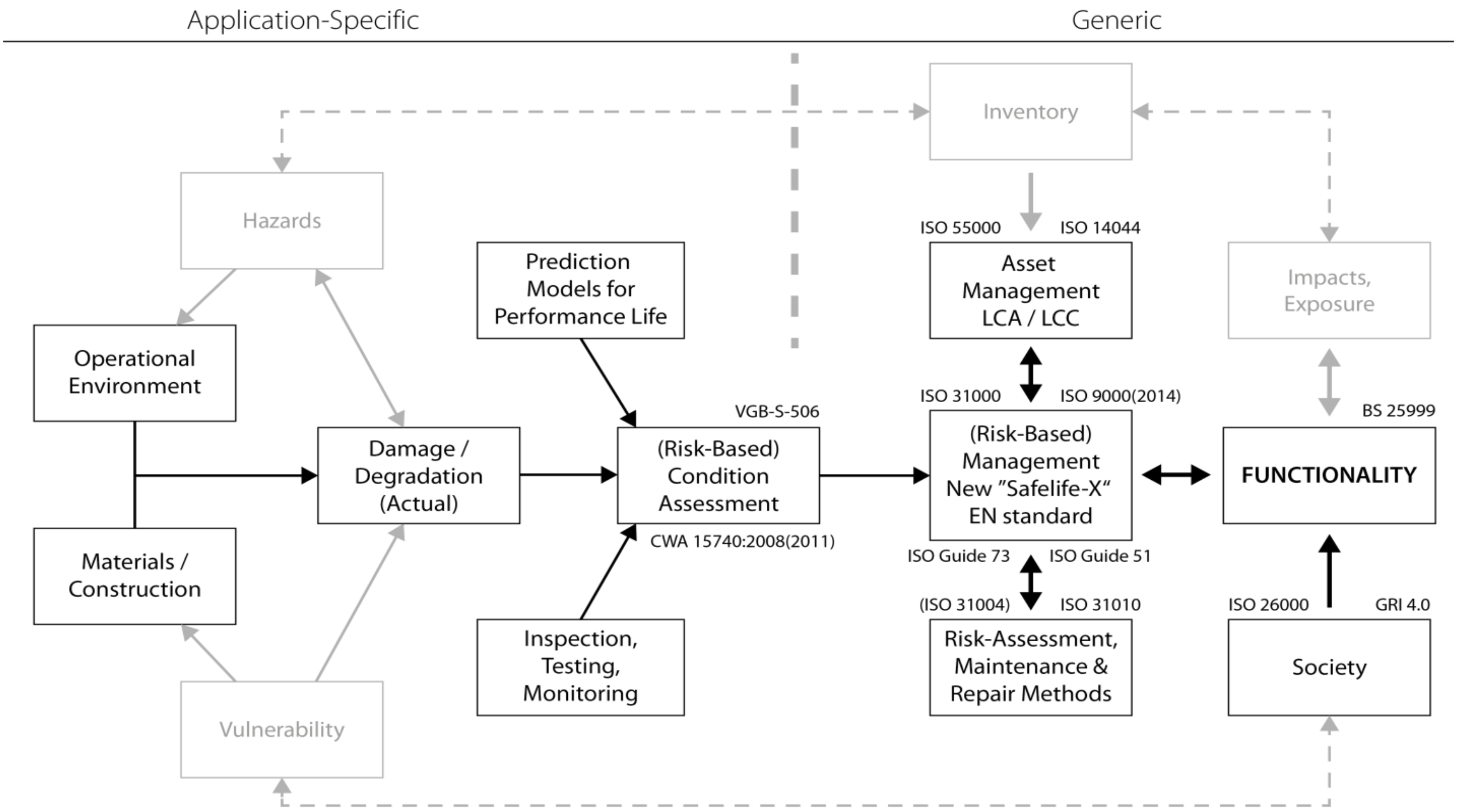
The Eurocode standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases.

Standard Cases vs Special Cases

Yes

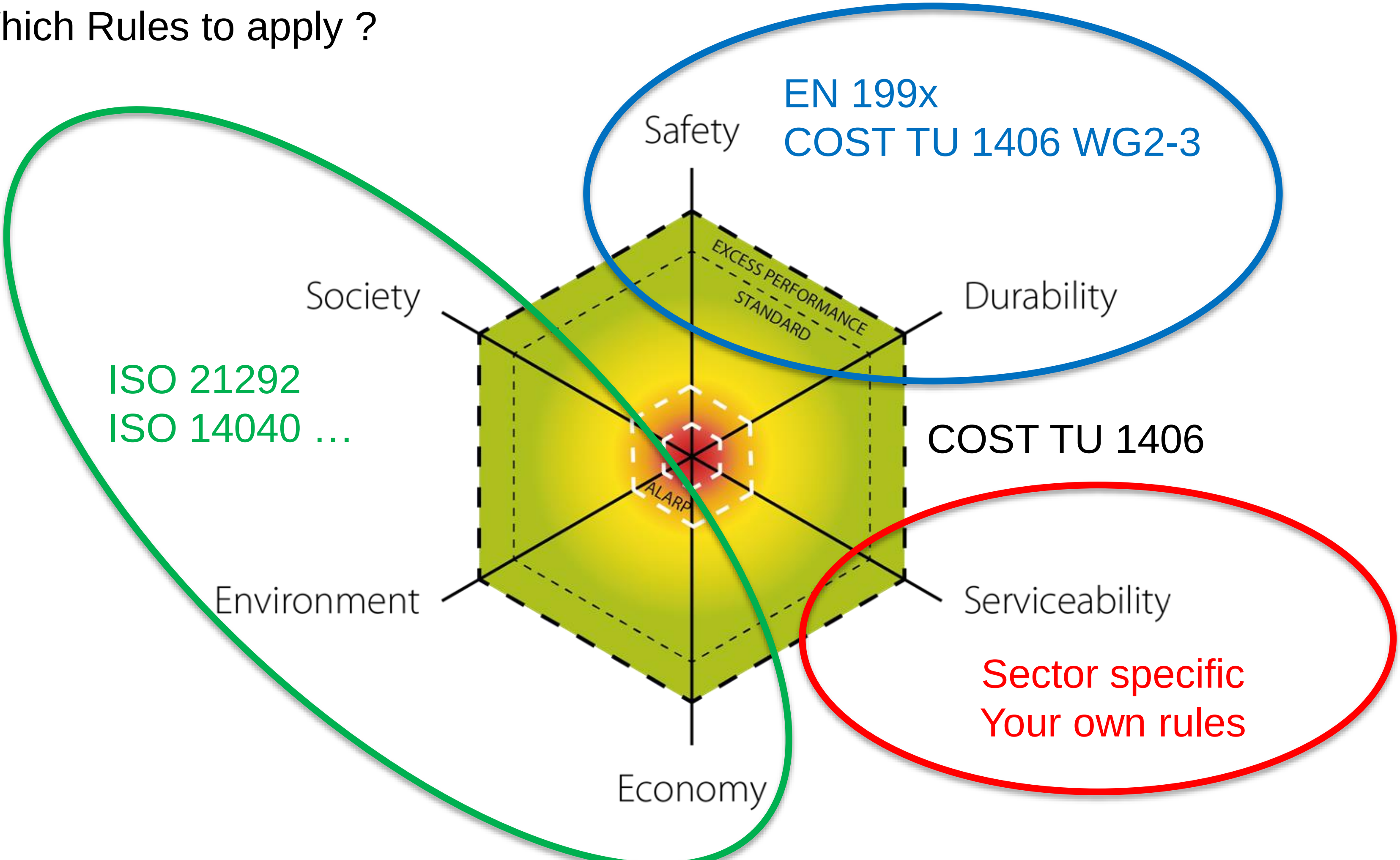
No

Example Risk based Asset Management



Example Risk based Asset Management

Which Rules to apply ?

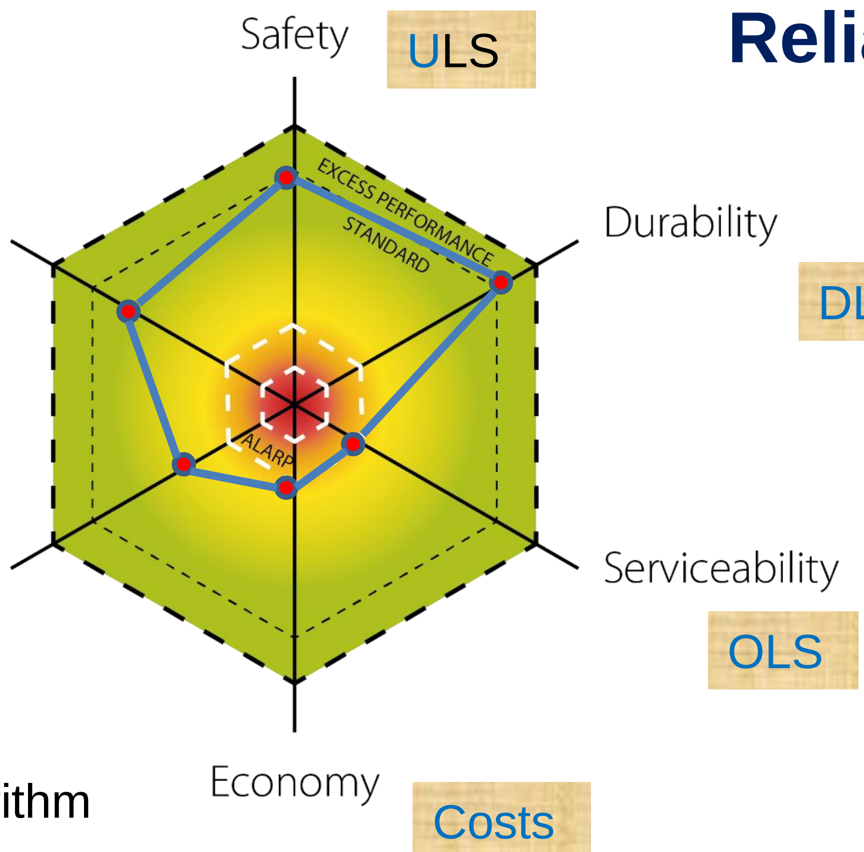


Risk = Effects of Uncertainty on Objectives

Quantification of Risk

ISO 21929

Reliability



Sustainability Factors

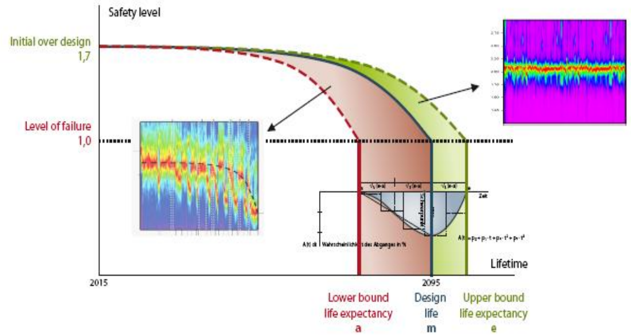
Your Rules

Risk Assessment Algorithm

Application to define Aging (Degradation)

Examples
from practice

EN 16991:2018



/TC

Date: 2012-06

prCWA 63:2012

/TC

Secretariat: ON

Ageing behaviour of Structural Components with regard to Integrated Lifetime Assessment and subsequent Asset Management of Constructed Facilities —

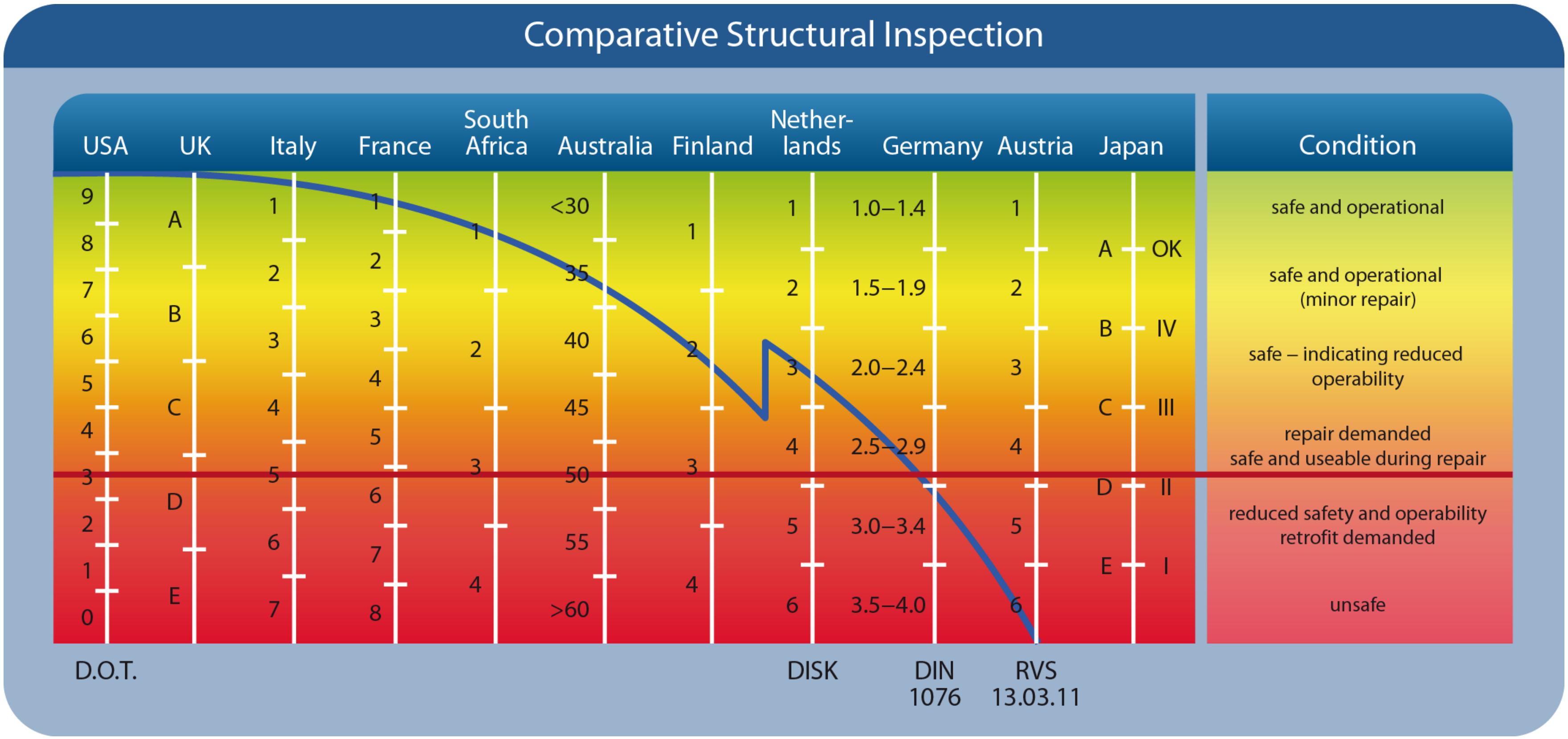
Alterungsverhalten von Bauteilen in Bezug auf ganzheitliche Lebenszyklusbewertungen und weiterführendes Erhaltungsmanagement von Infrastrukturbauten —

ICS:

Descriptors: Draft version May 16th, 2012

Apply the internationally harmonised Rating

Examples from practice

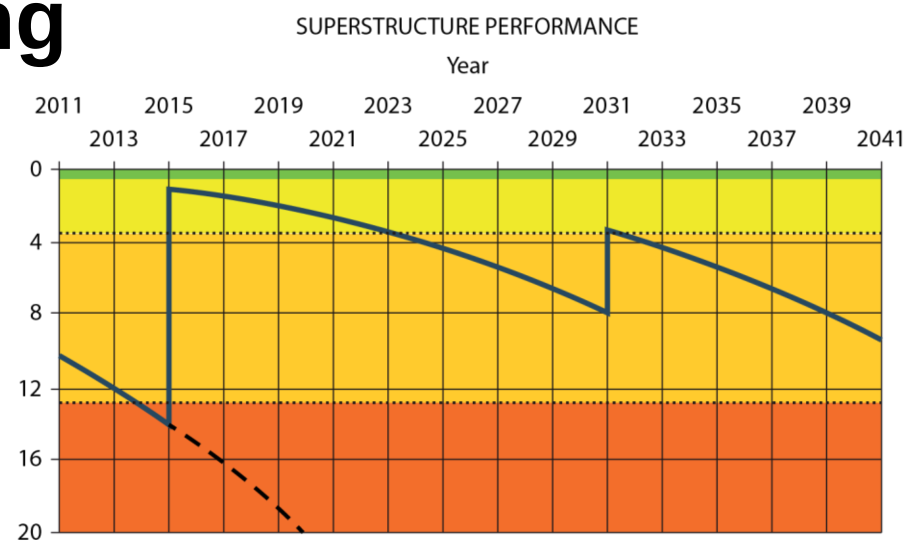


Get the Trigger Mechanisms => Maintenance Measures

Examples from practice

SUPERSTRUCTURE		
PARAMTER	median	
t_n =	0	
h_n (2054) =	20	
b_0 =	0	
t =	45	
c =	3	
a_n=	2.19E-04	
weighting factor	1.3	
	Do Nothing c = 3	Rating
t		
0	0.0000	1
1	0.0002	1
2	**0.0018**	1
3	0.0059	1
4	0.0140	1
5	0.0274	1
6	0.0474	1
7	0.0753	1
8	0.1124	1
9	0.1600	2
10	0.2195	2
11	0.2921	2
12	0.3793	2
13	0.4822	2
14	0.6022	2
15	0.7407	2
16	0.8990	2
17	1.0783	2
18	1.2800	2
19	1.5054	2
20	1.7558	2
21	2.0326	2
22	2.3370	2
23	2.6704	2
24	3.0341	2
25	3.4294	2
26	3.8576	3
27	4.3200	3
28	4.8180	3
29	5.3529	3
30	5.9259	3
31	6.5385	3
32	7.1919	3
33	7.8874	3
34	8.6264	3
35	9.4102	3
36	10.2400	3
37	11.1173	3
38	12.0432	3
39	13.0193	3
	14.0466	4
	15.1267	4
42	16.2607	4
	17.4501	4
	18.6961	4
	20	4

Rating



Routine Maintenance

Answer: When and How much to invest

.... ***Heavy Maintenance***

.... ***Strengthening***

1 – Excellent Condition
2 – Good Condition
3 – Satisfactory Condition
4 – Poor Condition
5 – Critical Condition

Where do we go ?

- GIS surface and platform
- BIM
- Risk based procedures   EN 16991
- Risk Assessment driven   ISO 14040
- Sustainability driven   ISO 21929
- Room for subjective (wisdom) driven Information
- From Science to Politics, Operators, Managers

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COST ACTION

THANK YOU FOR YOUR ATTENTION!

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