COST ACTION TU1406

QUALITY SPECIFICATIONS FOR ROADWAY BRIDGES,
STANDARDIZATION AT A EUROPEAN LEVEL

TU1406 WG4 Final report Appendix A7

Bridge Case study

Concrete arch bridge over the river Cro in Guarda district, Portugal

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1. AIMS AND OBJECTIVES

The main goal of this short-term scientific mission was to implement the Quality Control (QC) methodologies established within WG3 into a case study. The subject bridge is one of the defined common prototype of road bridges - arch concrete bridge. It is located in Portugal and inspection history consisting of two reports exists. Obtained results from the QC implementation into this case study, that is the main objective of WG4, will also validate the outcomes of the WG1, WG2 and WG3.

2. WORK CARRIED OUT

The main tasks that were performed during the STSM were the following:

- Implementation of the provided methodology for QC plan (established in WG3) into a case study - arch concrete bridge
- Qualitative and semi-quantitative approach in assessment of reliability of the bridges using MATLAB
- Evaluation of the key performance indicators (KPI): Reliability, Safety, Availability and Costs for different maintenance scenarios and comparison of the results from them.

2.1. CASE STUDY – ARCH CONCRETE BRIDGE

The case study in this report is an arch concrete bridge over the river Cro located in Guarda district, Portugal. The subject bridge is one-span open spandrel deck arch with a total length of 24.00m and a rise of 4.65m. General views of the bridge are shown in Fig.1 below.

Fig.1: Side view of the bridge (left) and view along the road (right)

Structural elements of this bridge are: deck slab (A), arch slab (B), arch abutment/springing (C), spandrel piers(walls) above the arch (D) and piers (walls) at the springing (E). Longitudinal section of the bridge together with its structural system are shown in Fig.2.

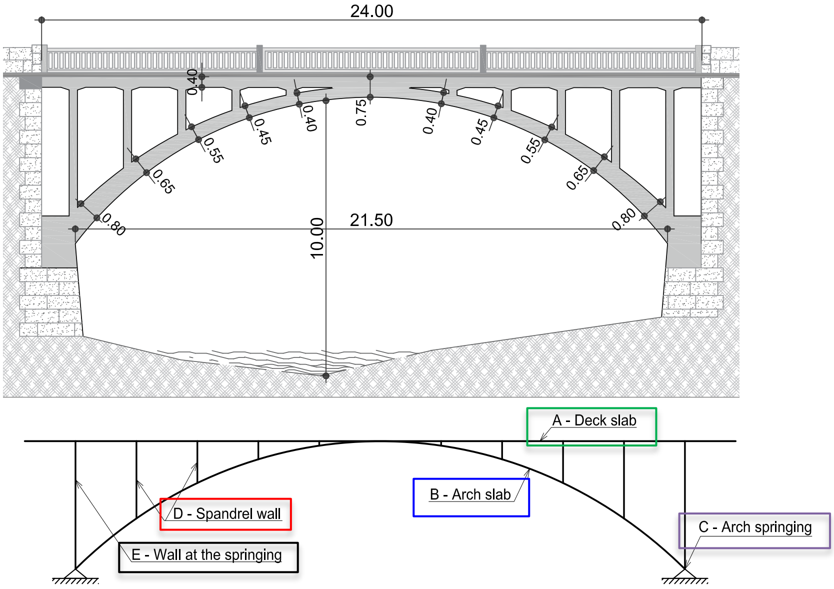

Fig.2: Longitudinal section of the bridge (top) and simplified structural system (bottom)

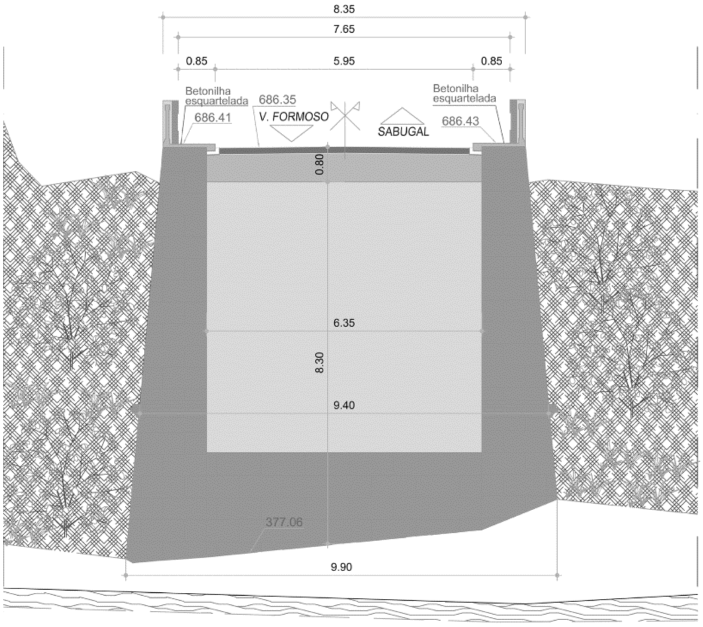

Fig.3: Cross-section of the bridge

The bridge carries the regional road 324(ER) over the river Cro. The cross-section of the road consists of: two traffic lanes 2.53m and 2.51m, two safety strips 0.45m and 0.51m and two sidewalks of 1.0m width. The bridge was constructed in 1940 and repaired in 2010.

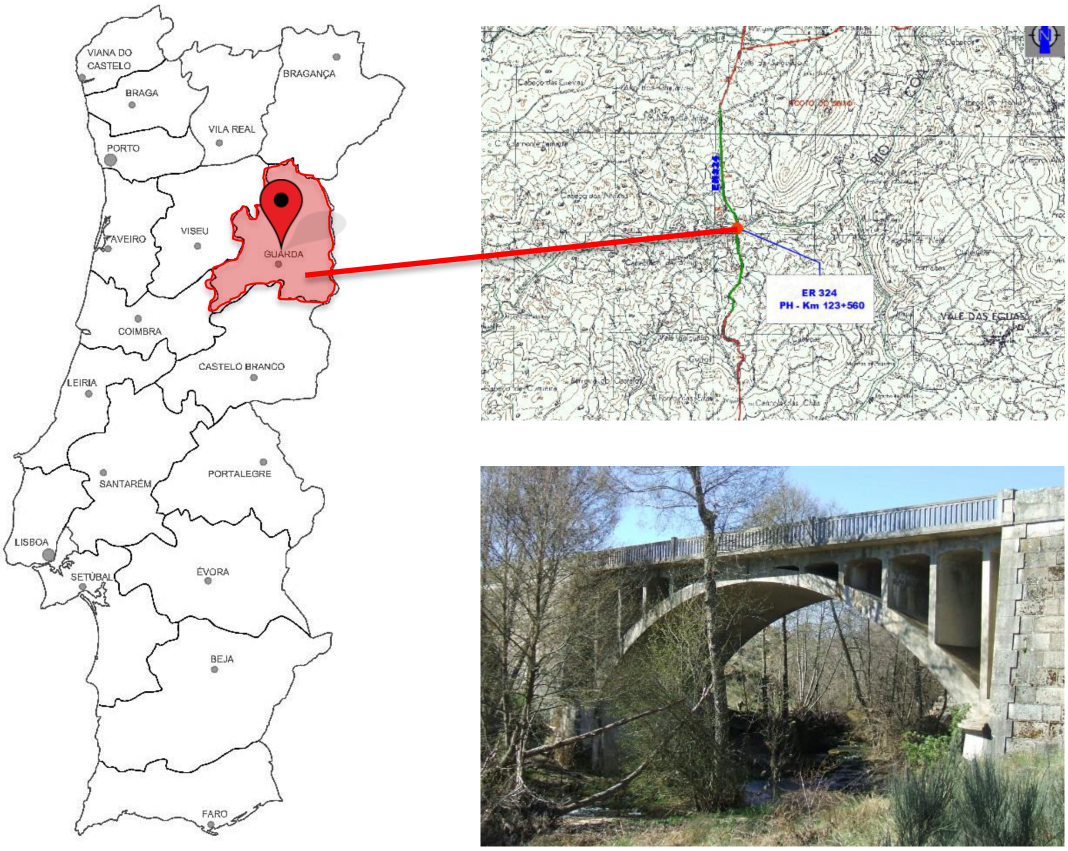

Fig.4: Location of the bridge

The last information about the traffic are from the last counting in 2016.
Average annual daily traffic : 1766
Heavy traffic : 5%

2.1.1. VULNERABLE ZONES

The reliability assessment is not possible without information related to the defects' location. Thus, two available reports from visual inspections were used from which position and type of damages were taken. Observed defects on structural and non-structural elements are presented in Fig.5.

Fig.5: Defects on the main structural and the non-structural elements identified during the inspection

To find the relation between the defect's location and bridge reliability, it was necessary to understand the bridge failure modes. For such a structural system, following failure modes are possible: bending failure of the arch slab, compression failure of the walls and compression failure of the arch supports.
Not all parts of the bridge are equally important with respect to consequences. Considering load bearing elements of the bridge, there are some regions which are highly vulnerable (Fig.6): high moment regions (midspan and supports of the deck slab, midspan of the arch and arch below spandrel walls), high compression regions (supports of the arch and bottom and top sections of the spandrel walls), high deflection regions (midspan of the deck and arch), high compressive stress regions (arch supports).
Vulnerable zones related to bridge equipment (non-structural elements) can be also defined: guard railing, drainage system and approaching slab.

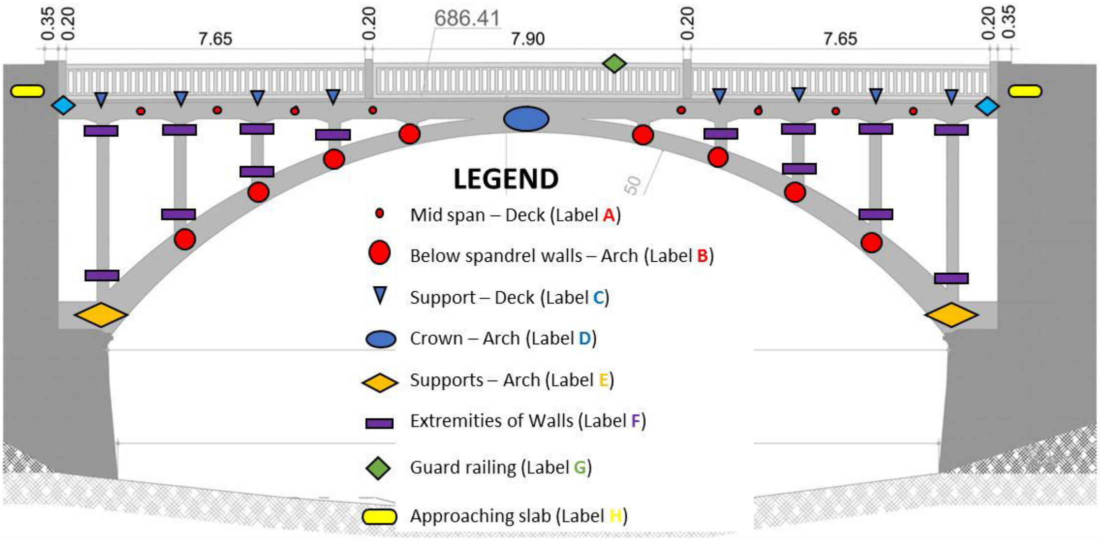

Fig.6: Vulnerable zones of the structural and non-structural elements

Using the data from the visual inspections, the vulnerable areas defined in Fig.6 are linked with the observed defects (Fig.7).
The proposed protocol for the quality control plan is shown in Table 1. For each vulnerable zone with observed pathology, assessment and rating of reliability and safety was performed on the component level. The overall bridge rating was chosen to be the worst rated condition among the load bearing elements, which is slightly conservative approach.

Table 1: The protocol for the QC plan

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	
	C	Deck	Efflorescence	Leaching	Symp.	/	
		Deck	White spots	Carbonization	R	3	
	D	Arch	Longitudinal crack	Structural damage	R	3	
		Arch	Surface cracks	Corrosion	R	3	
Compression failure	E	Arch	No damage	/	/	/	
	F	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	

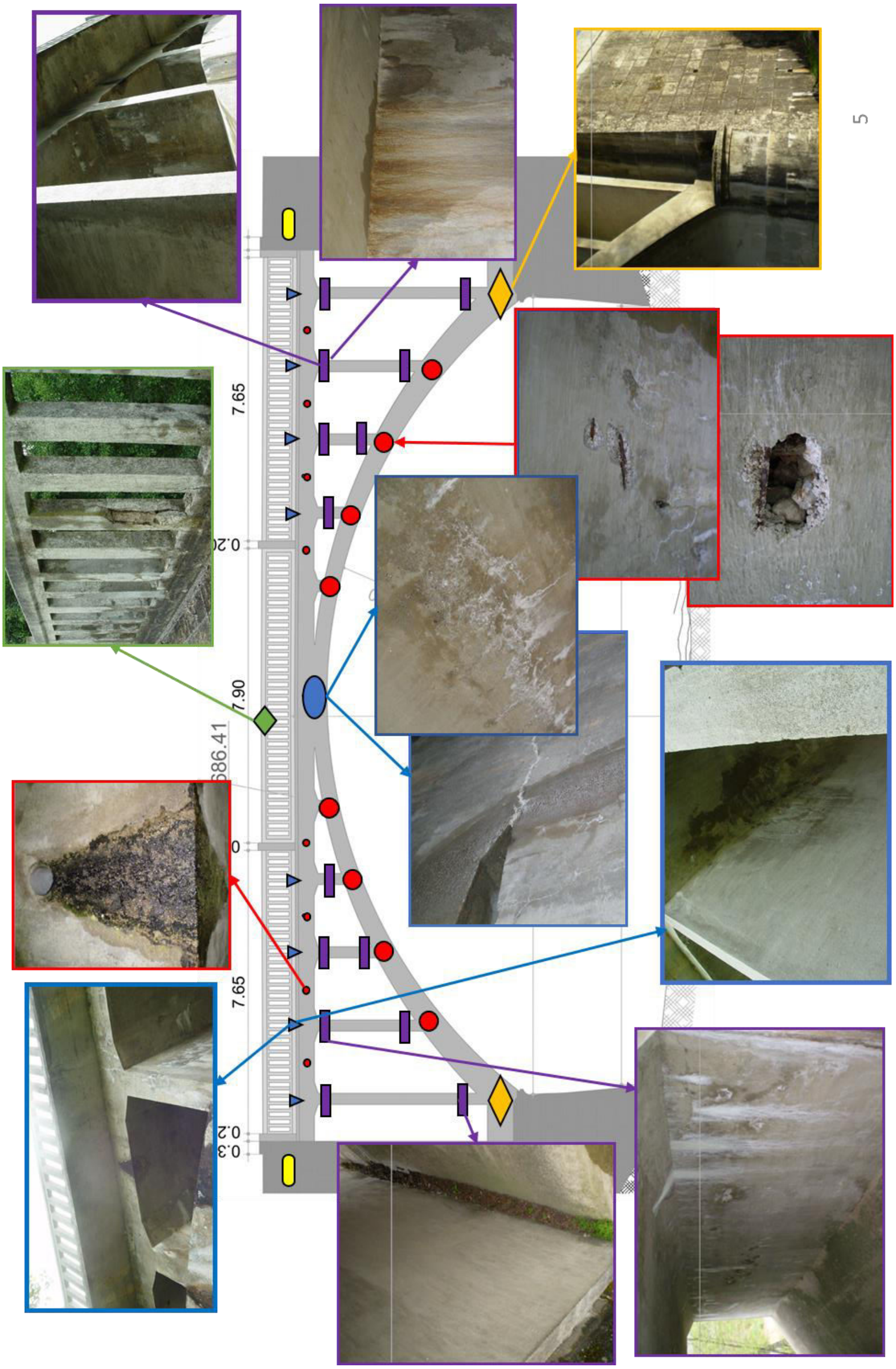

Fig.7: Defects from the observations in the defined vulnerable zones

3. MAIN RESULTS

3.1. SEMI-QUANTITATIVE ASSESMENT OF BRIDGE RELIABILITY

In order to assess the reliability of the bridge, an initial ('virgin') reliability index was roughly calculated using the Monte Carlo simulation and the First-order second-moment (FORM) reliability method.
Ultimate bending moments from the unfavorable load combination taken from the design project are presented in Fig.8 below.

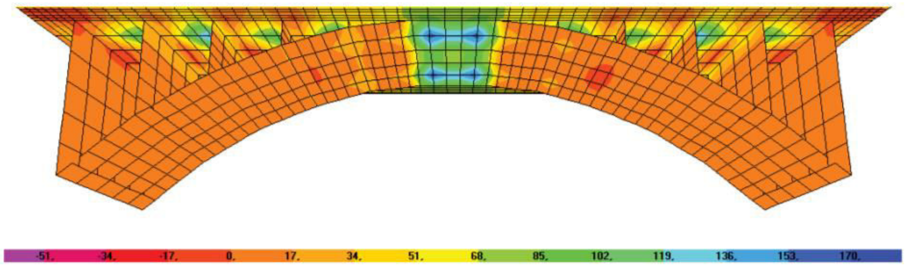

Fig.8: Bending moment from the unfavorable load combination

According to the bending moment diagram, it can be seen that the bending moments at the supports are very low comparing with the bending moment at the midspan, showing that the system is simple supported. Therefore, the overall reliability of the bridge was obtained as the reliability of the midspan section of the arch.
The limit state function for the bending failure mode is the following:

$$Limit\ state\ function\colon\ g(R,S) = R - S = 0$$

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

$$S = M_s = 159.18kNm;\ N_s = 1060.10kN$$

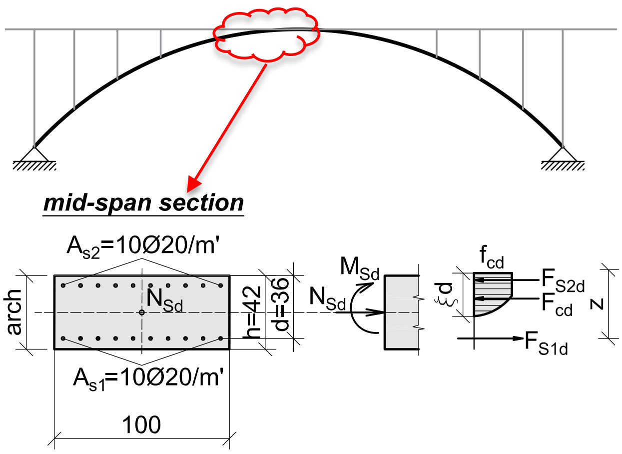

Fig.9: Moment carrying capacity of the arch slab

M_S, A_S, f_y and $f_c$were assumed here as random variables. The depth and the width of the section were considered as deterministic.
Initial reliability index is calculated as the shortest distance from the origin in the n-dimensional space of reduced variables to the curve described by $g(R,S) = R - S = 0$:

$$\beta_0 = \frac{\mu_g}{\sigma_g} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

Using the Monte Carlo simulation technique, the probability of failure was obtained. For that purpose, the parameters of the random variables presented in Table 2 were used. They were taken as suggested in the literature.

Table 2: Parameters of the random variables

Random variable	Nominal value	μ	λ	σ	V
M_S	156.28 kNm/m'	151.22	0.95	18.15	0.12
A_S	31.42 cm^2	32.05	1.02	0.64	0.02
f_y	335 MPa	368.5	1.05	38.69	0.105
f_c	48 MPa	49.92	1.04	6.99	0.14

The initial reliability index is also calculated with the First-order second-moment (FOSM) reliability method using the information on the mean and standard deviation of the random variables:

$$\beta_0 = \frac{g(\mu_{As}, \mu_{fy}, \mu_{fc}, \mu_Q)}{\sqrt{(a_1 \times \sigma_{As})^2 + (a_2 \times \sigma_{fy})^2 + (a_3 \times \sigma_{fc})^2 + (a_4 \times \sigma_Q)^2}}$$

With both methods, initial reliability index of 4.26 was obtained. On the basis of the report from the last visual inspection, approximately 8% resistance reduction was assessed, since the last inspection was taken 5 years after repairing of the bridge and the bridge is still in overall good condition. Therefore, the initial reliability index for the further analysis is reduced from 4.26 to the value of 4.17, using the approach schematically presented in Fig. 10.

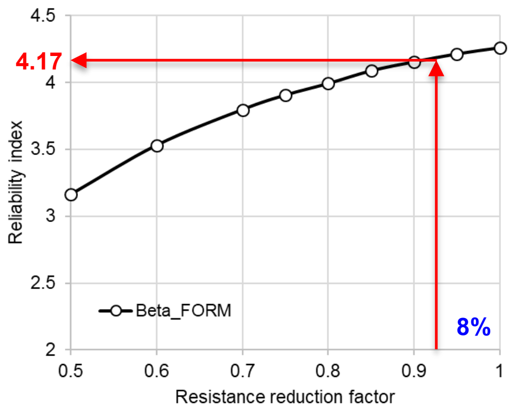

Fig.10: Influence of the resistance reduction factor

3.2. MAINTENANCE ACTIONS

Evolution in time of reliability, safety, availability and costs was done under three maintenance types:

- no maintenance or “do nothing and rebuild”;
- corrective (essential) maintenance and
- preventative maintenance.

“Do-nothing and rebuild” is chosen to be a reference scenario.

Deterioration models for the reliability index applied in this case study are explained briefly.

3.2.1. DETERIORATION MODEL UNDER NO MAINTENANCE

Herein, a bi-linear deterioration model for reliability index was used:

$$\beta(t) = \begin{cases} \beta_o, & 0 \le t \le t_i \\ \beta_o - (t - t_i)\alpha, & t \ge t_i \end{cases}$$

Where: $\beta(t)$ is the time-dependent reliability index, t_i is the time of initiation of a deterioration, α is the deterioration rate of a reliability (here assumed 0.07/year) and t is the age of the bridge (in years).
Since this model is applied on the existing structure, it is assuming that the deterioration processes are already initiated in the past, therefore the time of the initiation of the deterioration t_i is assumed to be zero. From the same reasons, β_0 in this model refers to the reliability index at the time of the last inspection, i.e. to the reduced initial index due to the qualitatively assessed resistance reduction (in this case 4.17).

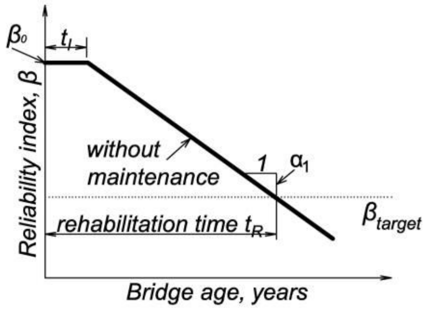

Fig.11: Bridge reliability profile without maintenance

In this scenario, no maintenance was considered until reliability reached an index of 2 which is the upper bound of the state 5. In that point of time, replacement of the whole structure was considered leading to a highest improvement of the reliability ($\gamma = \beta_0 - \beta_{state5} = 4.26 - 2.00 = 2.26$) immediately after the replacement. The reliability index in this point is equal to the initial "virgin" reliability β_0 since the whole deteriorated structure is replaced with a new one. Restoring of the reliability index to an initial value also leads to a delay in the degradation process ($t_i = 7$ years). The same action of replacing the whole bridge was taken each time the reliability index reached the state 5 without any maintenance in between (degradation rate 0.07/year).

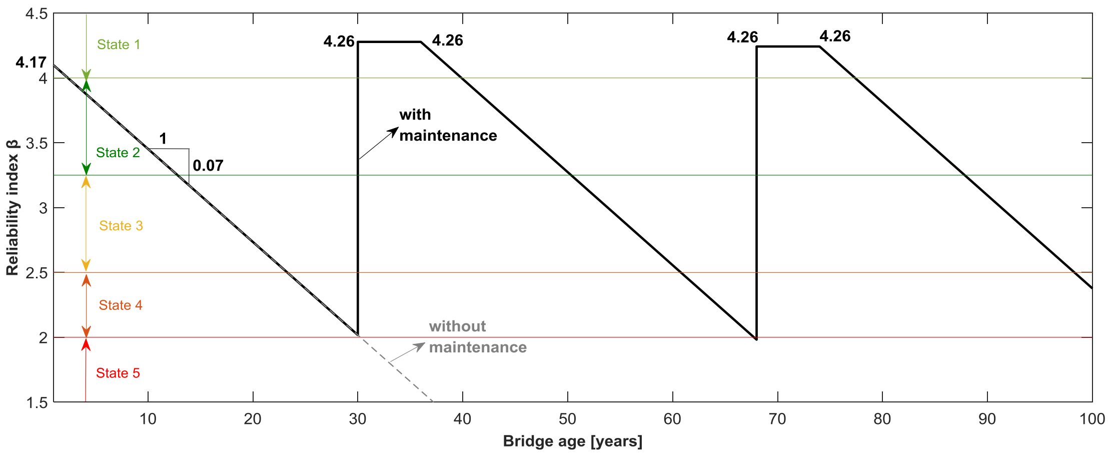

Fig.12: Semi-quantitative performance indicator Reliability for the scenario "do nothing and rebuild"

Reliability is transformed into the qualitative manner using the correlation between the quantitative and qualitative performance indicator scale proposed by WG3 of the Cost Action TU1406 (Table 3).

Table 3: Scale for KPI Reliability in WG3 Report

Reliability scale	Quantitative scale (β)
1	>4.00
2	3.25-4.00
3	2.50-3.25
4	2.00-2.50
5	<2.00

For this scenario, availability, costs and safety were evaluated only qualitatively. Availability is decreasing rapidly during the transition of the reliability from a level 4 to a level 5. It has highest value during the replacement of the bridge. Since no maintenance in this scenario was considered, costs were included only due to the bridge replacement. Decrease of the user safety was considered to be faster than the decrease in the structural reliability.

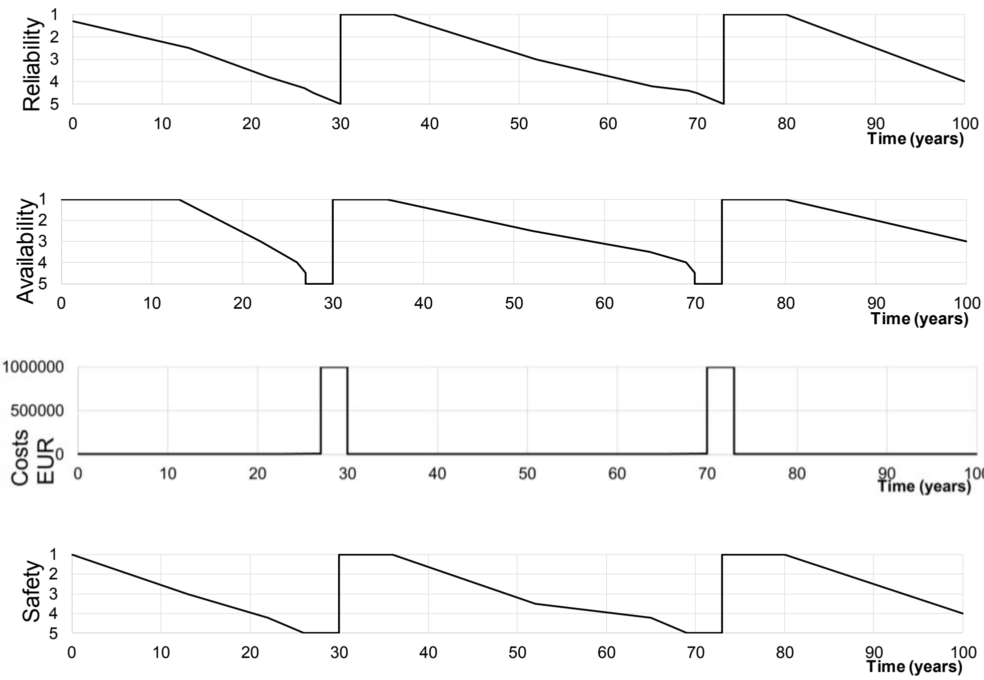

Fig.13: Qualitative performance indicators for the scenario “do nothing and rebuild”

3.2.2.DETERIORATION MODEL UNDER CORRECTIVE MAINTENANCE

Typical corrective activities that can be performed on reinforced concrete bridges are:

- Substructure and superstructure repairs
- Resealing expansion joints
- Replacing wearing surfaces
- Expansion joint and bearing replacement
- Drainage improvement (extending or enlarging deck drains)
- Curb repairs and replacement
- Scour protection
- Removing debris from waterway channels

The effects of the corrective maintenance actions were modeled through an improvement in reliability immediately after the application of a maintenance γ and a reduction of the deterioration rate for a period of time after its application t_{pD} (see equation below).

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

Where: t_I is the time of damage initiation, taken here as zero value; α is the reliability deterioration rate without maintenance (0.07/year); t_{PI} is the time of first application of corrective maintenance; t_P is the time of reapplication of corrective maintenance; t_{PD} is the duration of maintenance effect on the bridge reliability; θ is the reliability deterioration rate during maintenance effect.

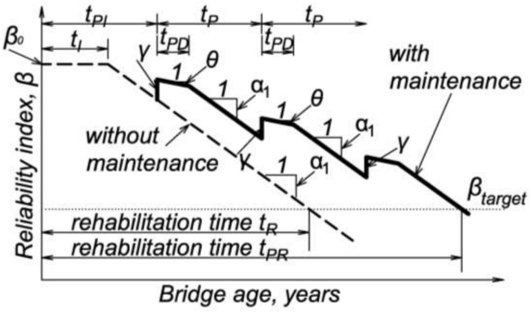

Fig.14: Bridge reliability profile with corrective maintenance

According to the documentation of the bridge defects, the following corrective actions corresponding to the observed defects were assumed to be taken. Unitary prices for the assumed corrective actions were only roughly estimated on the basis of the BMS Software (Infrastructure of Portugal).

1		**Defect description:** Three to four isolated moderate spalls and delamination of the pavement, moderate riding quality. **Corrective maintenance:** Repairing the asphalt wearing surface (1), applying thin overlay and anti-slip pavement (2). **Cost:** (1) 50Euro per m2 (2) 40Euro per m2
2		**Defect description:** A lot of cracking due to corrosion of reinforcement **Corrective maintenance:** Replacement of the concrete railing **Cost:** 50Euro per m’
3		**Defect description:** Failure of the sealer material. Water and debris can freely enter the opening and damage the bridge elements below. **Corrective maintenance:** Repair / Replacement of the expansion joints including surrounding concrete (‘viajoint’) **Cost:** 200Euro per m’

4		**Defect description:** Localized areas of white and wet spots, surface cracks **Corrective maintenance:** (1) Replacement of the concrete deck slab; (2) Improvement of drainage system (replacement of drainage sinks, pipes and gutters); (3) waterproofing placement **Cost:** (1) 200Euro per m2 (2) 100Euro per un. (3) 50Euro per m2 + 10Euro per m’
5	 	**Defect description:** Over 50% of the walls have cracks, brown spots and leakage **Corrective maintenance:** Repair the walls **Cost:** 250Euro per m3

In this scenario, first corrective (essential) maintenance action was taken while the bridge is still in overall good condition (state 3). Identical corrective actions were assumed to be taken periodically over 13 years with lower improvement in reliability ($\gamma = 0.53$).

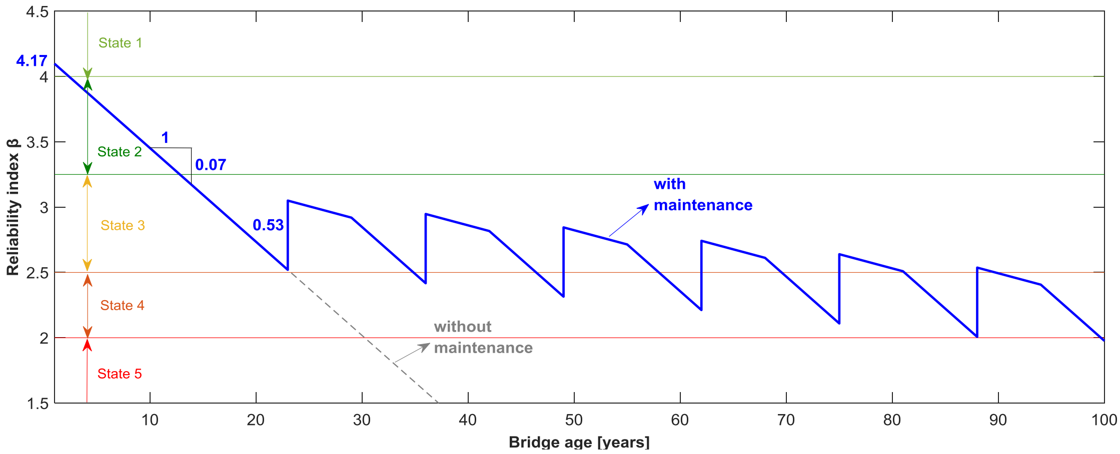

Fig.15: Semi-quantitative performance indicator Reliability for the corrective maintenance scenario

For this scenario, availability, costs and safety were evaluated only qualitatively. A decrease in availability was considered over time. During the corrective action, the availability is reduced, while immediately after the action, a small improvement was assumed. Moderate costs were considered for the corrective actions. User safety was considered to decrease over time, with a small improvement immediately after the performed action.

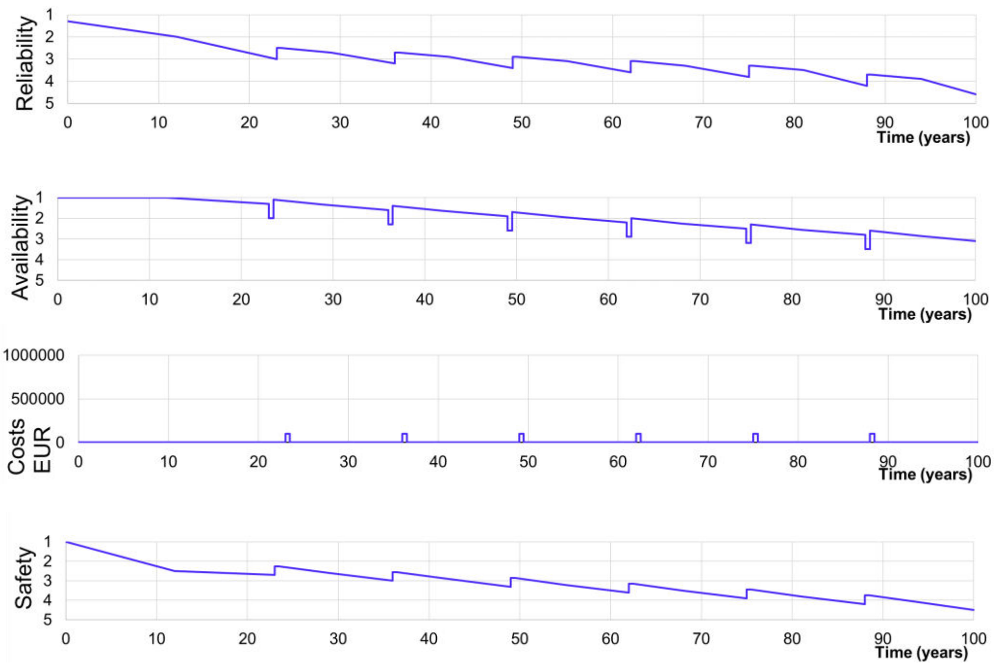

Fig.16: Qualitative performance indicators for the corrective scenario

3.2.3.DETERIORATION MODEL UNDER PREVENTATIVE MAINTENANCE

The concept of preventative bridge maintenance suggests that many relatively small repairs and activities are performed to keep the bridge in a good condition and thereby avoid large expanses in major rehabilitation or replacement. Typical preventative (cyclic) activities performed on scheduled time intervals are:

- Bridge washing
- Deck sealing and applying over-layers
- Concrete sealing (sub- and superstructure)
- Cleaning and lubricating bearings and expansion joints
- Cleaning bridge drainage system

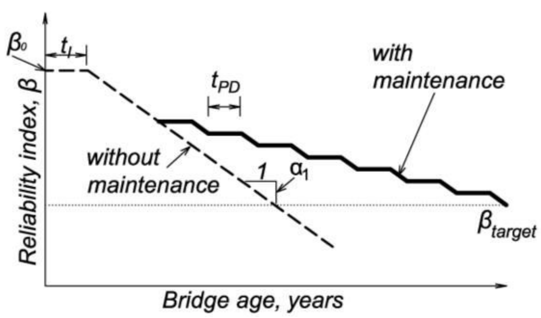

Fig.17: Bridge reliability profile with preventative maintenance

The effects of preventative maintenance actions were modeled through a delay of a degradation process for a period of time t_{PD} immediately after application of the action, without any improvement in reliability index.
This type of maintenance is a cyclic maintenance, where typical activities are taken in planned intervals. For the same bridge pathology, the following preventative actions were assumed to be taken:

1		**Defect description:** Three to four isolated moderate spalls and delamination of the pavement, moderate riding quality. **Preventative maintenance:** Clean the bridge, sealing the cracks in the asphalt, apply overlayers **Cost:** 20Euros per m2
2		**Defect description:** Reduced diameter of the sinks **Preventative maintenance:** Cleaning the sinks and scuppers **Cost:** not available
3		**Defect description:** Localized areas of white and wet spots, surface cracks **Preventative maintenance:** Cleaning and concrete deck sealing (1); filling or sealing of cracks with width >0.30mm (2) **Cost:** (1) 100Euros per m' (2) 50Euros per m'
4		**Defect description:** Over 50% of the walls have cracks, brown spots and leakage **Preventative maintenance:** Cleaning and surface repair of concrete (<30mm) in localized areas, removing degraded concrete, cleaning and protecting the reinforcement **Cost:** 30Euros per m2

5		**Defect description:** Vegetation and deterioration **Preventative maintenance:** Cleaning and Repairing the sidewalks (execution of new RC sidewalk) **Cost:** 50Euro per m2

Here, preventative actions were assumed to be taken over 6 years delaying the degradation of the reliability with a time duration of 3 years.

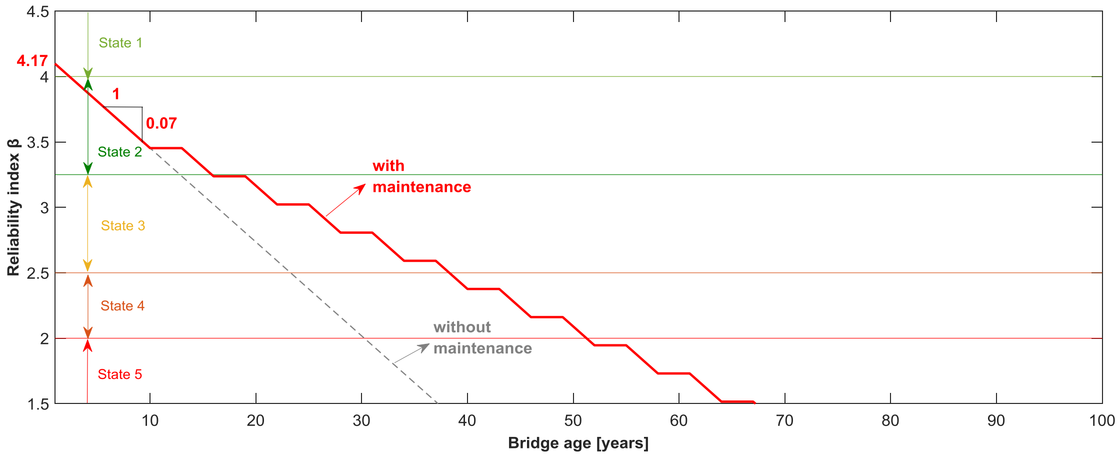

Fig.18: Semi-qualitative performance indicator Reliability for the preventative maintenance scenario

Availability was assumed to decrease over time with a small improvement immediately after the preventative action. Minimum costs for these actions were considered. User safety is decreasing faster than the reliability level.

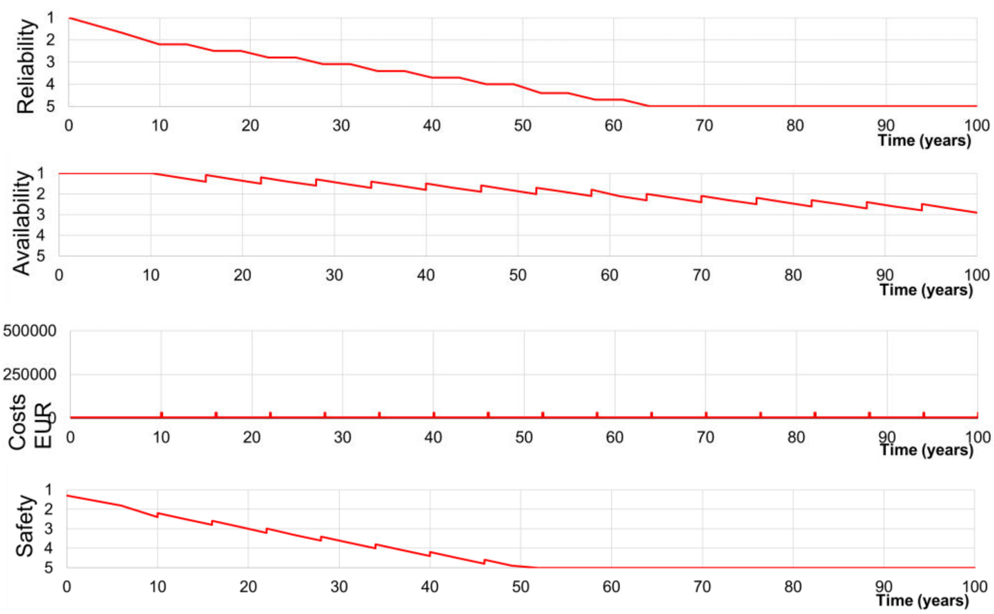

Fig.19: Qualitative performance indicators for the preventative scenario

3.2.4.COMPARISON

Fig.20 presents the comparison between the reliability index for different maintenance scenarios. Four-leg spider diagram is generated with the net present values for KPIs for each scenario: "Do nothing and rebuild", Corrective and Preventative scenario (Fig.21).

According to the area of the spider with the net present values of KPIs (Fig.21), it can be seen that the Corrective scenario is the most appropriate one with the largest spider area. Effectiveness of each scenario in terms of the reference one (in this case "do nothing and rebuild" scenario) is presented in the Table 4 below.

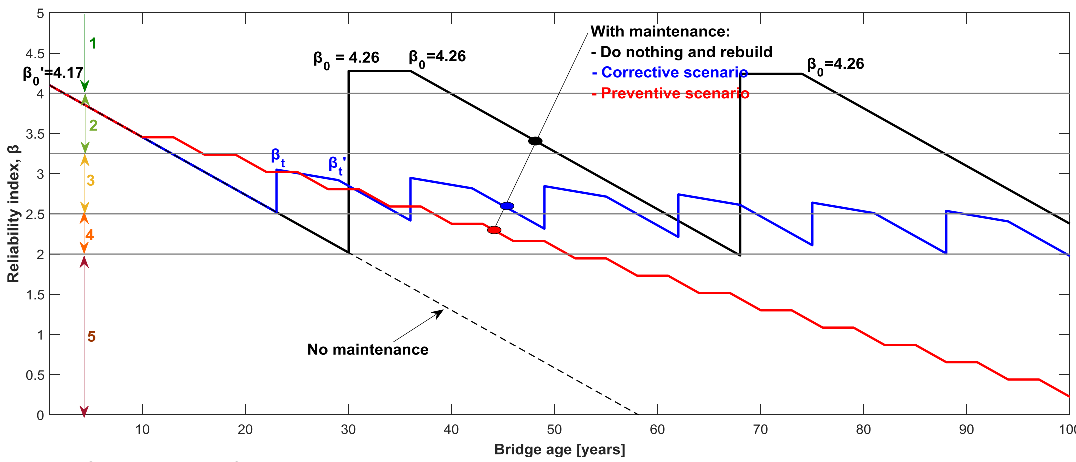

Fig.20: Comparison of the reliability index in each maintenance scenario

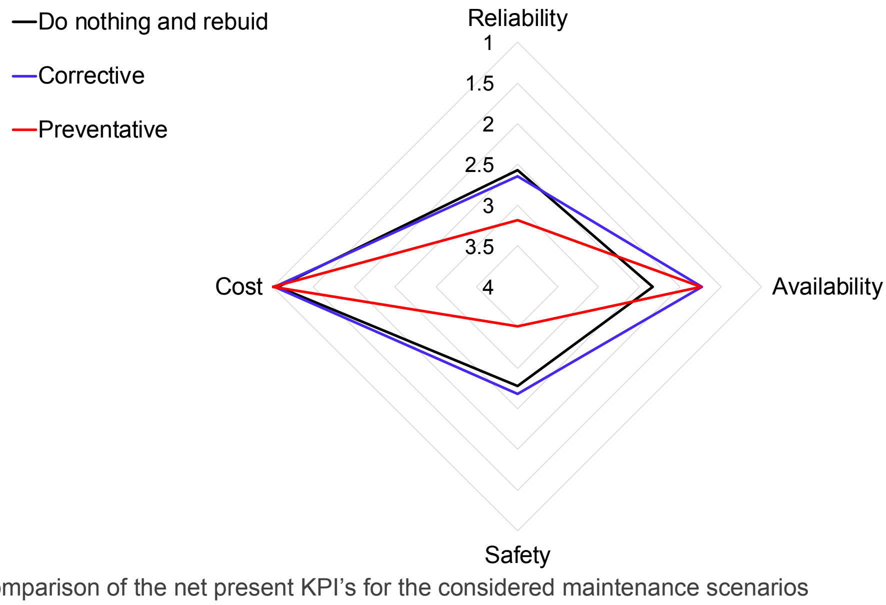

Fig.21: Comparison of the net present KPI's for the considered maintenance scenarios

Table 4: Effectiveness of each scenario in terms of the reference one

Maintenance scenario	Spider Area [units^2]	In terms of "Do nothing and rebuild"
Do nothing and rebuild	15.34	/
Corrective	16.89	10.10%
Preventative	11.96	/

Comparison is also made in terms of the spidergraph's area (Fig.22) and volume (Fig.23) at each point of time. The volumes of the spidergrams are calculated for the bridge life time of 70 and 100 years (Table 5). Right before the second replacement of the bridge in the "do nothing" scenario (at 70 years), the largest spider volume has the corrective approach, while the approach consisting of only preventative actions has the smallest volume. For 100 years life time, the largest volume has the scenario "do nothing and rebuild". The main difference between each of the considered scenarios is the cost of the actions, which becomes similar after the normalization. This normalization is probably responsible for the bigger volume of the "do nothing and rebuild" scenario for the life time of 100 years.

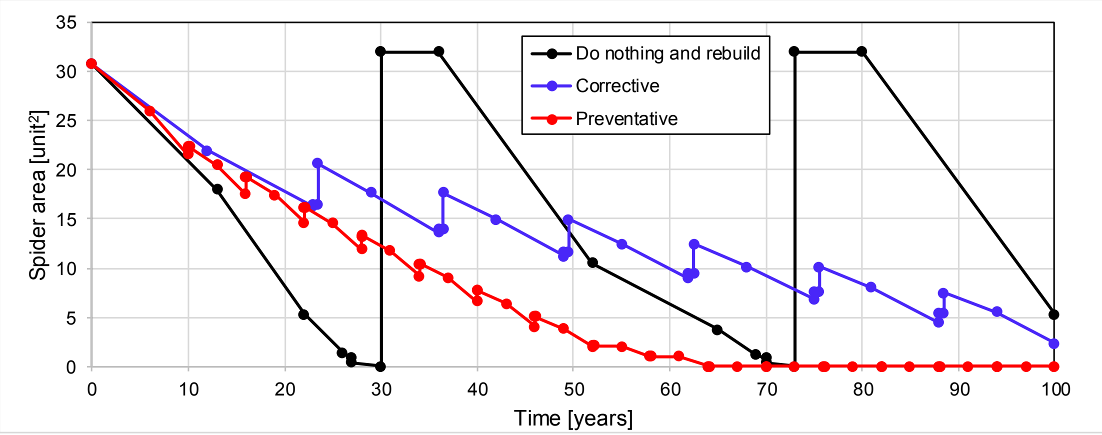

Fig.22: Calculated spider area for "Do nothing and rebuild", Corrective and Preventative scenario

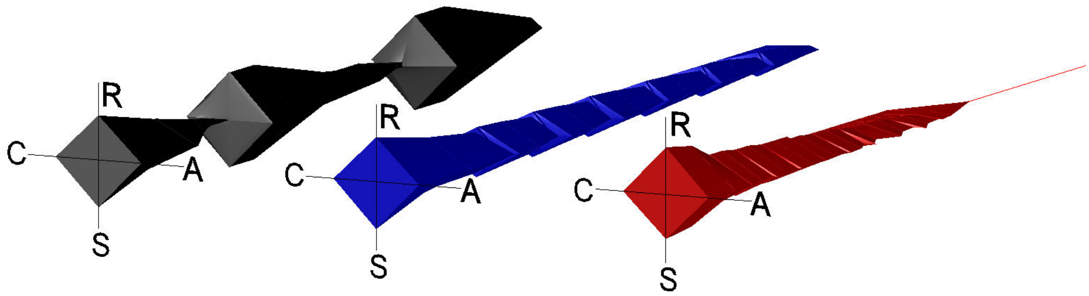

Fig.23: 3D spider diagrams for "Do nothing and rebuild", Corrective and Preventative scenario

Table 5: Comparison between sipdergram volume for each scenario

Maintenance scenario	Volume_70years [unit^3]	Volume_100years [unit^3]
Do nothing and rebuild	1037	**1646**
Corrective	**1184**	1389
Preventative	780	780

4. FUTURE COLLABORATION

The potential for future collaboration between the home institute, University Ss. Cyril and Methodius Skopje, and the host institute, University of Minho, as a result of this STSM is very promising. During this STSM, assessment of the existing Portuguese concrete bridge was done only qualitatively and semi-quantitatively. Prof. Jose Matos and his team of Phd students are intensively using FEM Software DIANA, which is very powerful tool for quantitative assessment of existing concrete bridges.

Developing Markov model together with Prof. Matos's team for forecasting long-term processes in concrete bridges, as concrete creep and shrinkage (main topic of my Phd thesis), is another possibility.

5. FORESEEN PUBLICATIONS/ARTICLES

The findings of this STSM will contribute to the: testing and validating the QC methodologies established in WG3, validating the outcomes from WG1, WG2 and WG3 and providing a data base for WG4.
The results from this case-study are going to be a part of a conference paper which will be submitted for the upcoming IABMAS 2019 conference in Guimaraes.

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