QUALITY SPECIFICATIONS FOR ROADWAY BRIDGES,
STANDARDIZATION AT A EUROPEAN LEVEL

WG4 Technical Report

Final Report - Appendix B

Guidelines for Preparation of a Case study

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1. Introduction

The objective of COST Action TU1406 is to develop a guideline for the establishment of Quality Control plans (QCP) in roadway bridges, which are one of the most critical components of road infrastructures maintenance. The already finished first three steps of the action included establishing the use of performance indicators (PIs) (WG1. Performance indicators), definition of standardized performance goals (PGs), definition of threshold types to specific key performance indicators (KPIs) (WG2. Performance goals) and the preparation of guideline for the establishment of QC plans in roadway bridges (WG3.Establishment of a QC plan). It is the intension of WG4 to use the developed guidelines with real bridge case studies and evaluate the suggested methodology in order to enable the preparation of recommendations to practicing engineers (WG5. Drafting of guideline/recommendations) (Matos et al 2017).

This document is not intended to replace any of the previously prepared WG reports but to be used as Single bridge case study preparation guidelines and help the user to prepare the case study in organized uniform way. The results will be analysed and used for further development of the guidelines. Each case study report will be stored in the case studies database which can later be used to evaluate the suggested QC procedure as tested in different COST countries.

2. COST TU1406 Case study data base

2.1 General

A case study data base was established in order to store the data for the selected bridge per country. Each county representative was asked to provide data on three prototypes bridges. Twenty four out of thirty eight countries contributed Data Tables from their inventory. If you intend to choose a different bridge for your case study please update us with the new bridge data. If your country did not provide any data yet please do so. Please provide data regarding Girder, frame and arch bridges that will mostly represent the typical highway bridges in the country.

The case studies bridges should be selected carefully in order to represent correctly the most common topologies of highway bridges in use.

2.2 Selecting a case study bridge

A candidate case study bridge should be selected using the following criteria:

1. The bridge must be one of the defined common prototype of road bridge (WG3 report):
   - Girder bridge - Concrete, Composite (steel girders concrete deck slab).
   - Arch bridge - Concrete, Steel, Masonry
   - Frame bridge - Concrete, Steel.
2. The bridge shall meet one of the following criteria:
   - A bridge built and maintained by a highway authority.
   - A bridge built and maintained by concessionaire (as part of PPP, BOT, PFI projects)
   - A bridge built and maintained by Municipality.
3. Preferably the bridge shall be located in a natural hazard area.
4. Inspection history for each bridge shall include at least two rounds of existing inspection which one of is a principal inspection.
5. Preferably a QC plan based on current national standard exist.

6. Easy and safe to access for any complementary data collection
7. If possible, select bridge intended to be inspected soon
8. A bridge that is included in relevant research project - Advantage
9. A bridge that has existing NDT or monitoring data - Advantage

2.3 Bridge ID data tables

A bridge ID data table was created in an excel file. The excel file includes three worksheets, one per structure type. For each worksheet the data should be entered as per the instruction and defined formats.

For assuring the unified data structure and for better understanding the required data items, a guide for documenting bridge data was prepared. In the guide you can find a short explanation per data item. (See " COST TU1406 WG4 - Guide for documenting bridges" in the appendix).

The Data Table contains the bridge data divided into the following groups (" COST TU1406 WG4 Bridge ID Data tables.xls"):

- General identification data
- General classification data
- Service data
- Basic geometrical data
- Structural classification data
- Material classification data
- Loading classification data
- Bridge hydraulics data
- Existing Bridge performance indicators data
- Existing QC Plan data
- Bridge inspection data
- 4 representative pictures

Four types of photos should be added for each bridge at the bottom of each excel worksheet. These are the following photos needed (See figure 12.10 in the appendix):

- General picture of the bridge
- Elevation picture
- Over the deck picture
- Areal road map of the vicinity of the bridge

For any additional clarrifiction please contact Eng. Amos Duke at amos@kimron-eng.com..

2.4 Case study data table

Following submission of the case study report which shall be prepared as per the instruction listed at this document, the report will be connected to the data main table which is used for managing the information. This will be done by the data manager of WG4 (Eng. Amos Duke, amos@kimron-eng.com.).

3. Preparing a case study, process and stages overview

3.1 General description of the process

The preparation of a case study shall be done in stages, incorporating different tasks as schematically described in figure 3.1. The content of each task is briefly described in this chapter while some of the tasks are more deeply discussed in the next few chapters. The professional background and most of the theory are covered by WG3 final report.

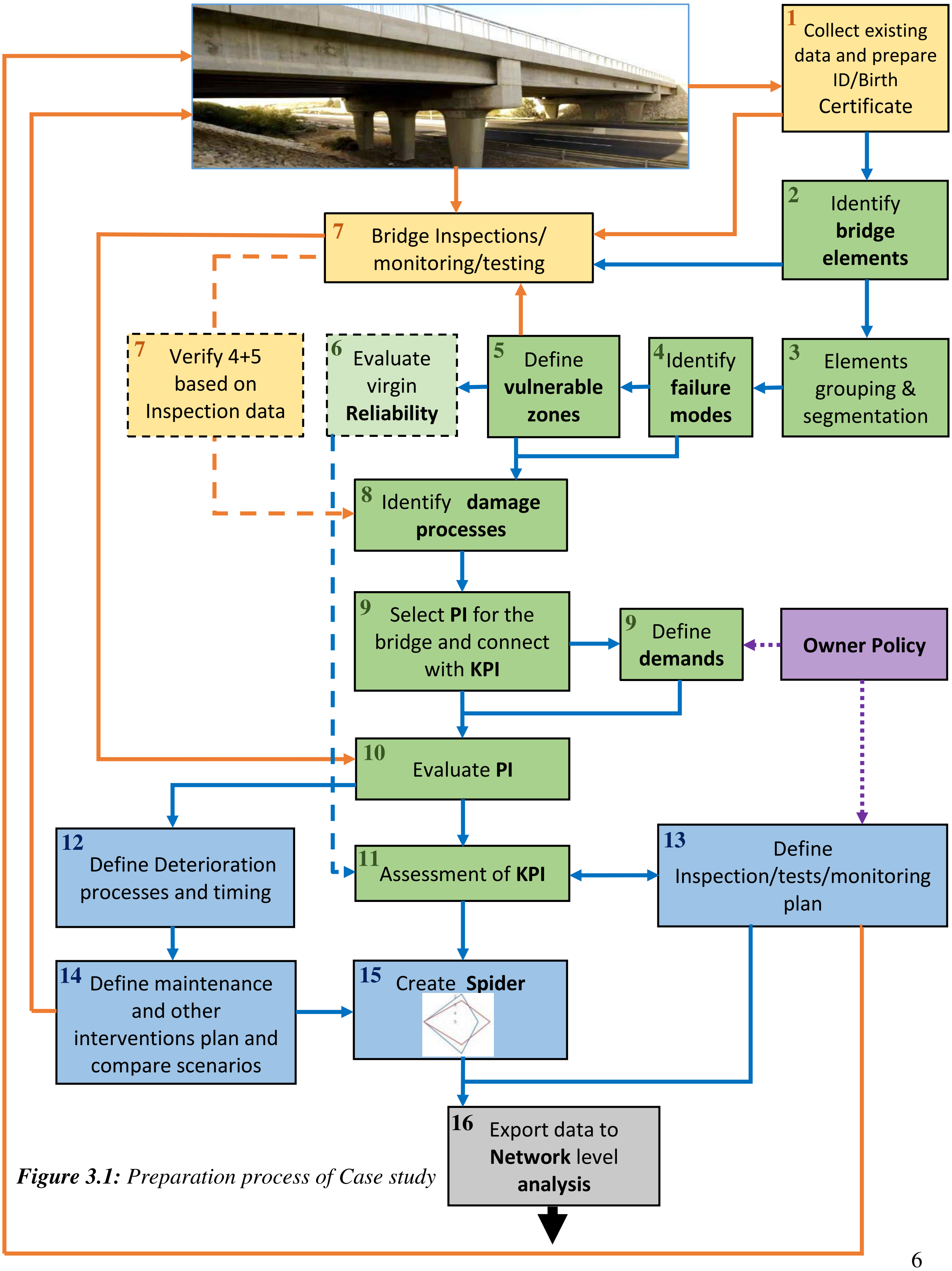

Figure 3.1: *Preparation process of Case study*

3.2 Step by step description of the tasks (by stages)

According to the definitions set on WG3 report (WG3 report chapter 7.1) the listed tasks described in figure 3.1 are divided into two main groups: 'Static' and 'Dynamic'. Tasks no.1 to 10 are considered 'Static' (orange (site) or green (office)) while tasks 12 to 15 are 'Dynamic' (blue). In order to simplify the work of preparing a case study example, table 3.1 gives short description of the work to be done and some useful references to previous work groups reports and to additional explanations detailed in this document.

No.	Task Name	Description of the work to be done	References*
1	Collect existing data and prepare ID/Birth Certificate	Prepare inspection by collecting existing data. Prepare/update a bridge ID/ birth certificate as per the format given in chapter 12 of this document. This information is relying on inventory data (If exist) and additional data acquired on site.	Chapters 2, 4 and 12. WG3 Report: Clause 12.1, Clause 8.5
2	Identify bridge elements	Identify all bridge elements and prepare a bridge element table using the defined taxonomy of TU1406. For each element document the dimensions and dimension units. Existing element list per country current practice can be transformed into the suggested format.	Chapter 4 and 12. WG3 Report: Girder & Frame Clause 8.1, Arch bridge: Clause 9.1 Example: Clause 8.5 Dimensioning: Clause 7.4 Case studies examples: Appendix A1 to A17
3	Elements grouping & segmentation	Arrange bridge elements by grouping together. Grouping can be according to different criteria such as geometry, functionality, materials, exposure etc.	
4	Identify failure modes	Use design documentation and define failure scenarios. For each scenario identify the possible failure modes, for example: rigid body movement (loss of stability), internal mechanism (shear, bending, ...), fatigue, functionality, comfort (to the user), visual appearance (to community), safety (falling parts) etc.	Chapter 5 WG3 Report: Clauses 8.3, 10.4.4, 10.4.5 Case studies examples: Appendix A1 to A17
5	Define vulnerable zones	Check for existence of conceptual weaknesses in the specific bridge type. Define and document the vulnerable zones on the bridge and correlate with the relevant failure mode. Documentation should include plan, elevations and sections as needed with marked positions of the zones and the relevant failure mode using WG3 defined labels.	Chapter 5 WG3 Report: Girder & Frame Clause 7.2 Arch bridge: Clause 7.3 Case studies examples: Appendix A1 to A17
6	Evaluate virgin reliability	If quantitively approach is selected, asses the "Virgin" reliability of the bridge using prototype and specific bridge, historical design data. Simplified or more precise models can be used.	Chapters 4, 8 WG3 Report: Clause 6.3, Clause 12.2,
7	Bridge Inspections/ monitoring/testing	Perform on site visual bridge inspection with/without testing or monitoring. Inspection should be done taking into account the specific recommendations defined for the bridge prototype and the previously defined vulnerable zones and identified failure modes. Possible hidden defects/damages should also be investigated. Damages should be identified, compared with previous inspection results, documented and quantified by severity and extent. Documentation should follow WG3 report recommendations. The need for in depth investigation should be checked. Following the inspection, update the failure modes and vulnerable zones data from stages 4 and 5.	Chapters 6, 8. WG2 Report: Clause 3.1.4 WG3 Report: Clause 3.2, Clause 7.2.5, Clause 7.4, Example: Clauses 8.5, 9.2 Chapter 11 Case studies examples: Appendix A1 to A17
8	Identify damage processes	Identify the damage processes on the bridge using the information collected during the bridge inspection and the predefined proposed damage processes as per WG3 report.	Chapters 7, 8. WG1 Report: Clause 4.2.1.1 WG3 Report: Chapter 4, Clause 5.2 Case studies examples:

No.	Task Name	Description of the work to be done	References*
			Appendix A1 to A17
9	Select PI for the bridge and connect with KPI	Select the appropriate PI and connect to relevant KPI considering the observations and connect with the damage processes (see WG3 report table 5.3).	WG3 Report: Chapter 5, Clause 5.2, table 5.3 Case studies examples: Appendix A1 to A17
10	Evaluate PI	Relevant PI should be selected for the bridge prototype (WG3) and for the specific bridge considering the specific scheme, materials and possible sudden events. The PI should be evaluated using predefined thresholds as per the owner demands (normally defined in the national professional guidelines).	WG3 Report: Clause 7.5, table 5.3, Clause 10.4 Examples: Clause 8.5, 9.2 Case studies examples: Appendix A1 to A17
11	Assessment of KPI	Qualitative assess the resistance reduction based on the observed damages. Evaluate reliability and safety KPIs based on agreed methods ranging from simple "Engineering Judgment" to complex Bayesian Nets. Use suggested WG3 QCP protocol for performance evaluation and derivation of the KPIs from PIs. All KPIs should be normalized. Cost should be scaled based on the maximum yearly cost of all scenarios.	WG2 Report: Chapter 3 WG3 Report: Clause 7.5, table 5.3, Clause 10.4 Examples: Clause 8.5, 9.2 Clause 12.2 (scale) Case study example: Appendix A7 clause 3.1
12	Define Deterioration processes and timing (time to failure)	Following the evaluation of the different PI and KPI assess the remaining service life i.e. the point in time at which Reliability or Safety will reach the defined threshold value (unacceptable return period for a failure) without any intervention. This includes assessment of the speed of the identified active deterioration processes and damage forecast. For each documented damage, indicate the relevant damage process and estimate the time to failure and document on the PI/KPI evaluation table. The assessment can use known existing models for deterioration in time or simple expert opinion.	Chapters 8, 9. WG3 Report: Clause 7.5, Clause 7.10, Clause 8.3, Examples: Clause 8.5 Case studies examples: Appendix A1 to A17
13	Define Inspection/tests/monitoring plan	For the reference scenario and for other preventive scenarios define the inspections type and intervals. For each inspection define the cost (as annual cost). Estimate the future type and timing for NDT/DT testing and monitoring with the related costs.	Chapter 10. WG3 Report: Clause 11.2, table 11.6, clause 12.1
14	Define maintenance and other Interventions plan and compare scenarios	Define several maintenance scenarios with target reliability and safety over time. Define the time frame (for how many years). Estimate the cost of the different interventions per each scenario over time and combine with the costs estimated on stage 13. Define the function of decrease of Reliability and safety. For each scenario create graph per KPI (R, E, A, S) over time (excel file of WG3 can be used). All KPIs should be normalized (range 1 to 5).	Chapter 10. WG3 Report: Clause 7.5, Clause 7.6, Examples: Clause 8.5, 9.2, tables 12.1 to 12.4 Case studies examples: Appendix A1 to A17
15	Create Spider	Create Spider diagrams of net present KPI for the scenarios and compare. This stage can be done for single point in time (spider) comparing the areas of the different scenarios spiders or as a continues process with preparation of 3D volume shape showing the change of the KPIs over time (few spiders). In such case the volume of the 3D shapes created for the different scenarios should be compared.	Chapter 10 and Appendix A1 to A17 WG3 Report: Clause 7.5, Examples: Clause 8.5, 9.2,
16	Export data to Network level analysis	Part of the data should be used for "Network level analysis". The data format and the decision regarding the needed parameters rely on the network analysis method. A possible example using "Multi-objective optimization models" is given in WG2 Report.	WG2 Report: Chapter 5

*Note: references are coloured by WG 1-3 and this report. (**WG1=orange**, **WG2=Blue**, **WG3=Green**, This document= Black)

Table 3.1: *Staged process of the preparation of a case study*

4. Collecting data and inspecting the bridge

4.1 Existing data

The proposed QCP methodology relies heavily on information from the design phase or from in-depth investigation. Existing data should be collected including the following:

- Bridge drawings (originals or from other data source (e.g. from survey)).
- All inventory data items (for minimal data requirements see chapter 12).
- Bridge static calculations (if available) or previous capacity assessments.
- Specific hazards data related to the bridge (Scour data, Seismic data, Geotechnical data, Special heavy load transportation data, etc.).
- Material types properties.
- Equipment properties and types (Bearings type and manufacturer, Expansion joints type, Safety barriers type etc.).
- Previous inspections data

4.2 Checklist for load bearing element assessment

The assessment of load bearing elements differs by typology of a bridge, but in most cases of assessment, it is necessary to gather information about material and structural properties and dimensions as well as about the previous, current and/or future loading on the structure. Environmental conditions are of physical, chemical or biological nature and can influence material properties (Rücker et al., 2006).

It is also necessary to point out that the main difference between design and assessment is, that in the latter uncertainties can be reduced significantly by site specific data from the real structure. Usually simple methods like the study of documents should be applied in the beginning. To reduce uncertainty within higher assessment levels more sophisticated test methods need to be applied. Non-destructive methods are to prefer to destructive methods, whenever this is possible. Beside the provision of data which describes the current state of the structure, also information about time depending processes like deterioration need to be acquired. This can take place with periodic or permanent measurement (i.e. structural health monitoring)

Although the steps in the QC framework are described in Chapter 7.10 of WG3 Report, minimal parameters to be investigated within the proposed COST TU1406 framework for load bearing elements are:

- Bridge inventory information (including location, features, dimensions etc.) – more detailed information provided in Chapter 12 - Appendix of WG3 Report.
- Type of the structure – to distinguish the damage processes (WG3 Report chapter 8.4 and 9.1)
- List of the bridge elements (more detailed information in WG3 Report chapter 8.4.1, 8.4.2, 9.1.1-9.1.6, vulnerable zones (chapter 7.2 and 7.3 in WG3 Report) and failure mode (chapters 10.4.4 and 10.4.5 in WG3 Report)
- Observation results related to defects and indicators related to material properties, bearing capacity, structural integrity and joints (chapter 5.2 in WG3 Report)
- Location and area of observations (Chapter 6.4 in WG3 Report)
- Integration of bridge damages, location and quantities (Chapter 7.4 in WG3 Report)

- Assessment of performance (outcome is performance value) (Chapters 7.5-7.8 in WG3 Report)

In addition to visual inspection it is suggested to use equipment in observations and investigation of damage processes (Rücker et al., 2006):

- Cross sectional and longitudinal geometry changes (defects) from overloading (cracks, ruptures etc) and from deterioration processes (corrosion, spalling, fatigue cracks etc) – more detailed list is provided in Table 4.3 in WG3 Report. It is possible to detect these processes using laser, ultrasonic devices, slide gauge, electronic gauges, etc.
- Structural integrity (e.g. for hidden damage or inhomogeneity) is possible to detect with impact echo testing
- Material strength using tension and compression tests on samples, sclerometer method, pull-out tests, pull-off tests, etc.
- Parameter, influencing the dead load and the superimposed dead load (e.g. material densities, permanent equipment)
- Duration influencing parameters of the structure (e.g. environmental conditions, carbonation and chloride content of concrete) using pH-test, phenolphthalein test, quantitative chloride analysis on samples, etc.
- Serviceability matter (e.g. crack widths, surface conditions of roads)

It is important that the results of the data acquisition should be of the same form, to be able to compare data from different methods and to be able to use data in future assessment procedures (Rücker et al., 2006)

4.3 Checklist of equipment assessment

Elements related to equipment are related to nearly all bridge types. For detailed checklists that may be used during inspections of equipment see chapter 7.2.4 of WG3 Report. The lists are related to bearings, expansion joints, waterproofing, pavement/overlay, barriers and signs.

5. Identifying vulnerable zones and failure modes

The vulnerable zones should be carefully selected according to the visual observation and experiences of the inspector. For a bridge with historical data, the work should be done in the office prior to the onsite work and be updated if additional relevant data is gathered during the inspection (see appendices A4, A7, A9). In case of a bridge without any previous data, it is necessary to identify and map the vulnerable zones during the onsite work. Some useful advices can be found in chapter 7.2 of WG3 report and is described shortly herein:

- Conceptual weaknesses
- Vulnerable zones related to the superstructure
- Vulnerable zones related to substructure
- Damages related to the equipment
- Hidden defects/damages

Clause 7.2 of WG3 report describes the common conceptual weaknesses and vulnerable zones for girder and frame bridges and clause 7.3 for arch bridges. There are also given recommendations for steel bridge decks.

Use design documentation combined with vulnerable zone identification and knowledge of the high bending moments or shear forces in order to define the failure scenarios. For each scenario identify the possible failure modes, for example: rigid body movement (loss of stability), internal mechanism (shear, bending, ...), fatigue, functionality, comfort (to the user), visual appearance (to community), safety (falling parts) etc.

6. Recording Observation and PI for the case study

During the process of bridge inspection, it is important to record and measure in quantitive way the different observations (defects) and correlate them with the relevant PI or just define as symptoms. A detailed explanation can be found in section 5 of WG3 Report. The selection of the proper definition for the recorded defects can be done using the four groups categories listed in tables 5.1 to 5.4 of WG3 Report. Then, the inspector should select the appropriate PI and connect to relevant KPI considering the observations and connect with the damage processes (see WG3 report table 5.3). Relevant PI should be selected for the bridge prototype (WG3) and for the specific bridge considering the specific scheme, materials and possible sudden events. The PI should be evaluated using predefined thresholds as per the owner demands (normally defined in the national professional guidelines).

7. Identifying damage processes

In order to correctly predict the performance of a bridge, conduct preventive maintenance and eventual rehabilitation or decide upon reconstruction, information on damage processes is crucial. During the visual inspection, detailed inspection of the bridge has to be carried out with clear identification of the damage processes as a function of bridge material. Deterioration processes for reinforced concrete structures, adopted from (Breysee, et al., 2012) are given in WG 3 Report, see table 4.1. Additional data is presented here.

7.1 Physical/Mechanical deterioration processes

Damages in bridge structures can be caused due to variety of physical and mechanical causes. Classification can be group as presented in Table 7.1**Error! Reference source not found.**.

Overloading or imposed loads
Restraining effects (shrinkage and thermal cracking)
Creep
Freeze-thaw
Abrasion-erosion
Fire

Table 7.1: *Physical/mechanical Deterioration processes - Groups*

7.1.1 **Overloading or imposed loads**

Overloading is a direct type of damage, which is a result of excessive loading which is accumulated over time or differential settlement. It can be due to either static or dynamic loading (impact or seismic effects), short or long-term effects including creep, but as well due to a change in use of a structure without proper structural upgrades, unintentional overloading, and other circumstances. One of possible damages due to overload can occur during construction when concrete has not yet reached design strength. As well, early removal of formwork can result in the overloading of certain concrete members. Overload cracking can be manifested due improperly timed or sequenced strand release in post-tensioned construction. Freight traffic in the European Union is increasing with time. The effects of the overstressing of a bridge can be significant over time. In the short-term case it is caused due to overstress of bridge elements and in the long term case it is the gradual fatigue damage. Evident damages are seen in the formation of cracks in girders and deck, this as a result will reduce the load-bearing capacity of the bridge, further leading to closure of a bridge or a worst-case failure. In this situation several scenarios are possible: strengthening of a bridge, posting, weight limits or replacement of a bridge. In the long-term effects after numerous loading cycles, bridges show signs of fatigue witnessed by the cracking of the superstructure at locations of high stresses (UTCA, 2012). Greater fatigue directly results in a shorter life span of a bridge and the cost effects of fatigue are entangled in the bridge's reduced life. Steel bridges are at a greater risk of experiencing fatigue, see Appendix A9. However, studies have indicated that prestressed concrete bridges and RC decks can exhibit fatigue symptoms if continually overloaded (TRB 1990 and Weissmann and Harrison 1998). Once the loads are removed the material will retain some permanent deformations, creating internal defects that can become a weak point for further deterioration processes, leading to future durability problems. Damage can be assessed on two scales: If the material is considered homogeneous, then average properties (stiffness, strength, aggressive agents, etc.) have to be assessed and to see how they are changed by the occurred damage, on the other hand, if one is looking at the specific defects, then it is necessary to locate them and provide details about specific defects (width, extension, depth, etc.). Different non-destructive methods can be applied in this case including wave propagation, impact-echo, acoustic emission, etc.

7.1.2 **Restraint to volume changes**

Due to fluctuations in moisture content and temperature concrete changes its volume for various reasons. Restraint to volume changes, especially contraction, can cause cracking if the tensile stresses that develop exceed the tensile strength of the concrete. Restraining effects and creep occur due to internal and external processes, which can lead to formation of cracks and further damage. One should be able to distinguish between the formations of different cracks. Due to drying processes, formation of cracks which are usually perpendicular to the surface is unavoidable, with depths reaching several hundred millimetres in thick structures (Shaw, P. and A. Xu, 1998). On the other hand, due to autogenous shrinkage cracks are usually small with low penetration depth. Cracks due to thermal changes should be identified as well and monitored, if possible, by monitoring the temperature elevation in massive components. Visual inspection is the simple way to check the integrity of concrete as the relevant mechanisms that cause the occurrence of cracks makes them appear of the surface of the structure. Besides visual inspection additional methods can be used, for example image analysis or optical methods like flash-thermography. In order to obtain information regarding crack depth NDM can be applied (stress wave propagation), development of non-visual cracks can be detected by acoustic emission, and however, this is mainly used in the laboratory.

When referring to creep a possible defect is seen in the increase of the deflection which has a direct impact on the serviceability of the structures. As deformation increase this can have influence of the stability of the structure and change of loading pattern in the structure, see appendix A9.

7.1.3 **Freeze-thaw cycles**

Characteristic formation of cracks is evident after freeze-thaw cycles, which can be clearly identified during the visual inspection. The crack picture is characterized by network of cracks, scaling and spalling on the surface. Usually direction of the cracks is parallel to the pavement surface, and their number decreases with dept. As these types of cracks are always visible from the surface, visual inspection can reveal and quantify these defects. Once again assistance of the NDM are needed for determination of the crack's depth.

7.1.4 **Abrasion-erosion**

Due to the scope of defects and its visibility, erosion of concrete can be identified by visual inspection. When talking about erosion of concrete, it can be divided in two groups, abrasion-erosion and cavitation-erosion. The former comes as a result of actions of debris rolling and grinding against a concrete structure. For piers in the water one needs to take care of the possible cavitation-erosion which is caused by the repeated impact forces due to collapse of vapor bubbles in rapidly flowing water. It has a rough presence and pitted view see appendix A1. Figure 7.1 shows different types of cracks in connection with different deteriorating processes.

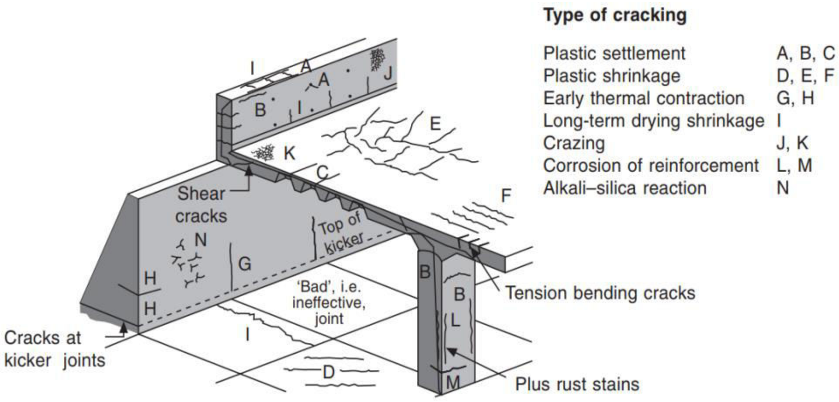

Figure 7.1: *Types of cracks (Day, R. and J. Clarke, 2003)*

7.1.5 **Fire**

Damage due to fire is not so common in bridges. The main effect is a reduction in the strength and stiffness of the concrete. As a consequence, visually spalling can be more gradual, however, in high-strength and ultra-strength concrete, spalling forms can have dangerous consequences (Breunese, A.J. and J.H.H. Fellinger, 2004). Visual inspection can be used as a first procedure to identify the qualitative degree of damage due to fire (color change, cracking and spalling at the concrete surface). The type of aggregate has an impact on the color change. This is a very subjective interpretation due to the complexity of temperature development in concrete, heterogeneity and variability of concrete components reinforcement etc. Once again in order to obtain more reliable data it is necessary to use partially-destructive or destructive tests. During the inspection procedure average concrete cover can be checked by rebound hammer or pull-out test. For point-by-point of samples X-Ray diffraction, Thermogravimetric analysis (TGA) and mechanical wave propagation can be use.

7.2 Chemical deterioration processes

Chemical damage processes at their initial stages usually do not give any visually observable defects that can be detected during the visual inspection. In their advanced stages, damage processes as carbonation or chloride contamination, both usually give observable damage, as spalled or delaminated areas where corroded reinforcement bars are exposed. While carbonated concrete usually gives uniform corrosion of the reinforcement bars, chloride contamination usually gives pitting corrosion, indications that should be detected by skilled inspectors. In general damage processes even in their most advanced stages – where damage is visually observable – need to be assessed by destructive and non-destructive testing – including laboratory chemical analysis – in order to determine the extent, the depth, the rate and the type of the damage process see appendices A1, A3.

7.3 Biological and organic deterioration processes

Biological deterioration processes are easily identified during the visual inspection. Vegetation if combined with other substances may become aggressive. Under certain circumstances vegetation can decompose and form organic acids and sulphides, which may oxidize and form sulphuric acid. Various oils, fats are saponified by lime in hydrated cement which results in the formation of alcohols enabling further reaction with more lime and leading to supplementary deterioration of concrete (Thomas and Skalny, 1994, see appendix A5.

7.4 Classification of defects and deterioration symptoms

Concrete structures will experience different defects due to various determination processes as mentioned above. Visual examination is the first procedure in the determination of the state of the bridge. This is the reason why knowledge of various processes and their causes is of the utmost importance for the inspectors going on the site. According to the DUATINET Technical Guide, Part I, a classification for the types of defects in concrete structures is given in table 7.2.

Classification	Defects and Symptoms
Contamination	Discoloration or staining (leakage, oxides, deposits of oils), incrustation, exudation, vegetation growth, fouling, deposits of dirt or rubbish
Deformation	Deflection, tilting, setting, buckling, change of volume
Deterioration	Concrete delamination with loss of steel bond, concrete compressive strength reduction, internal concrete disintegration due to different processes, steel strength reduction and all concrete properties change due to environmental impact (carbonization, chloride contamination and leaching with formation of efflorescence)
Discontinuity	Defects due to construction faults (bug holes, honeycombing and construction joints). Defects due to deterioration processes (concrete cracking, fracture of steel reinforcement, fracture of prestressing steel)
Displacement	Vertical and horizontal movement with translation of element or structure, bearing distortion or element rotation
Loss of material	Concrete spalling, pop-outs, scaling and other forms of concrete disintegration with significant loss of concrete and/or joint sealants.

Table 7.2: *Defects and symptoms classification in concrete structures*

8. <u>Reporting inspection results and evaluating the performance</u>

One of the most important stages of the proposed methodology of COST TU1406 action, regarding the quality control of bridges, is to assess the impact of observations gained during the visual inspection of the bridge to the performance of the bridge. This impact can be assessed in a qualitative or in a quantitative manner, depending on the nature of the Performance Indicators (PI) that are selected from the list of PIs, established in WG1. Also, the type and the extent of available results from additional testing of the bridge, such as destructive or nondestructive testing, helps to the quantitative measurable assessment of this impact. Finally, the analytical structural assessment used to justify the real mechanism of the observed damage/defect, when applied, can support the accurate assessment of the impact of the observed damage.

In the following scheme (Entity Rrelationship Diagram (ERD) in WG3 report), the proposed procedure is well represented as follows (see Figure 8.1):

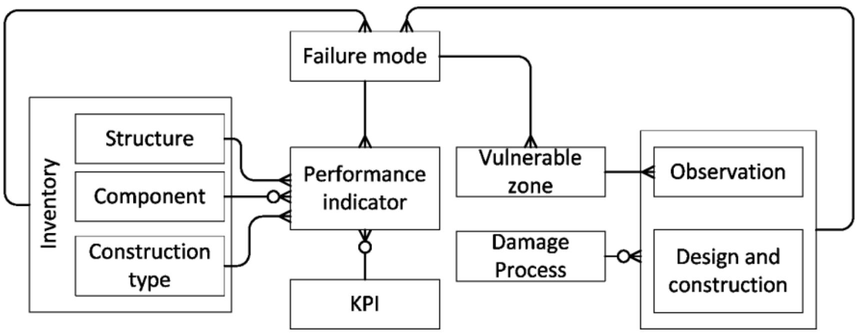

Figure 8.1: *The framework ontology (WG3 Report)*

- From all the observations gained from visual inspection, and stored in the BMS, those related to the vulnerable zones of the main bridge elements are by priority related/assigned to damages/damage processes. Certain observations are treated as symptoms of certain types of damages as in Tables 5.1 – 5.4 of WG3 technical report.
- Vulnerable zones are dictated by the design documents of the bridge, as the areas of the bridge elements described in the components inventory for different construction types, having the lower initial safety factor (in terms of bending moment or shear force etc.) and thus the areas where a certain type of failure mode is more probable to take place here (e.g. (Linneberg, et al., 2017) and (NYSDOT, 1997))

  In the absence of design documents of the bridge, vulnerable zones are selected based on engineering judgment (e.g. supports of beams for shear like failure mode, supports and mid span of beams for bending moment like failure mode in frame scheme, etc.) or based on analytical modelling representing the bridge actual strength/stiffness.
- One or more failure modes can be assigned to the same bridge element of substructure or the superstructure of the bridge as it is analytically presented in par. 7.2 of the WG3 report. More specifically, in par. 7.2.1 vulnerable zones indicated after a long-term experience of application of certain construction types of bridges, e.g. internal hinges of Gerber beam bridges - are presented. In par. 7.2.2 vulnerable zones related to bridge superstructures are given based on the partitioning of an element into regions with different vulnerability, following (NYSDOT, 1997) and (LTBP, 2016). In par 7.2.3 vulnerable zones related to bridge substructures are given for both superstructure and substructure, their vulnerable zones are defined as the high moment or high shear regions of the components, the hinges, construction joints and anchorage zones of the latter as well. In substructure buckling prone zones are considered as well. In practice and in most of the case studies, observed damages are directly related to failure modes, irrelevant of the vulnerability of the location of the defect, as the latter was not assessed by the absence of detailed information.

  Previous definitions are common for girder and framed bridges, while for arch bridges specific definitions for vulnerable zones are repeated in par. 7.3 of the WG3 report.
- The quantitative instead of a generic qualitative assessment of identified bridge damage is proposed in par. 7.4 in the WG3 report, where general relations that consider the extent and the intensity of the observed damage are proposed, with reference to (Sustainable Bridges, 2007). The extent of the damage is measured as percentage of the total number of segments or of the total area of the initial undamaged component while intensity is measured as the percentage loss of the material of the initial depth of the material (loss of concrete cover etc.). The detail and the level of the inspection is critical for the precision of the quantitative approach.

  It is to be noted that while in WG3 report no specific and clear procedure for the qualitative or the previous quantitative evaluation of the observations' impact on PIs is given, this is followed in some of the case studies. e.g. in Strymonas bridge case study (see Appendix A3) both qualitative and quantitative evaluation of the observations/measurements have impact on a large number of PIs. The PIs are discretized among the four identified KPIs, thus providing the respective quality context. The PIs are quantified and benchmarked in this case study, through the following values: (a) the actual ("real practice") values obtained during the inspection, monitoring, and maintenance processes, (b) the conventional ("standard practice") values, namely the lower-bound thresholds derived from regulatory frameworks and/or practical experience, and (c) the "best practice" values, namely the optimal thresholds, derived from regulatory frameworks and state-of-the-art. This procedure follows a methodological framework for bridge QC (Mateus, Bragança, 2011).

- The assessment of the observations' impact directly to KPIs is proposed, according to par.6.4 of the WG3 report. In the following scheme (see Figure 8.2) the direct assignment of triggered failure modes of a simple supported beam (FM1, FM2, FM3) to KPI of Reliability, based on owner/operator established thresholds (e.g. exceeding of a crack width or of a reinforcement bar section loss etc.) is well demonstrated.

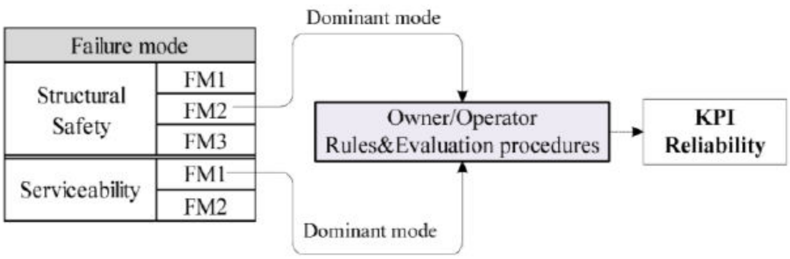

Figure 8.2: *From failure modes to KPI of Reliability (taken from WG3 Report)*

If a more precise approach is needed, then for each failure mode, the corresponding degree of compliance, in a probabilistic format is proposed in the same paragraph to calculate reliability of the existing bridge, considering also the virgin reliability of the as built bridge.

In the given relations a simplified calculation of the β-reliability index and of the respecting probability of failure are given for a simple supported beam (determinate systems), as a function of the location of the damage ($\xi=x/L$)

If β due to the identified damage is lower than recommended as per (CEN EN 1990, 2002) then a lower rating can be assigned to the KPI evaluation score. This procedure is not simple for a non-determinate bridge structure – e.g. framed bridges – where more than one failure modes should be considered for triggering a collapse mechanism. While calculation of reliability index needs extensive material testing and load monitoring to determine the uncertainties involved in the examination of the failure modes.

In par. 7.5.1 of the WG3 report, the proposed procedure is based on engineering judgement, both for the evaluation of the impact on KPIs as well as for the prediction of point of time when the triggered failure mode is expected to take place in the future (see Figure 8.3).

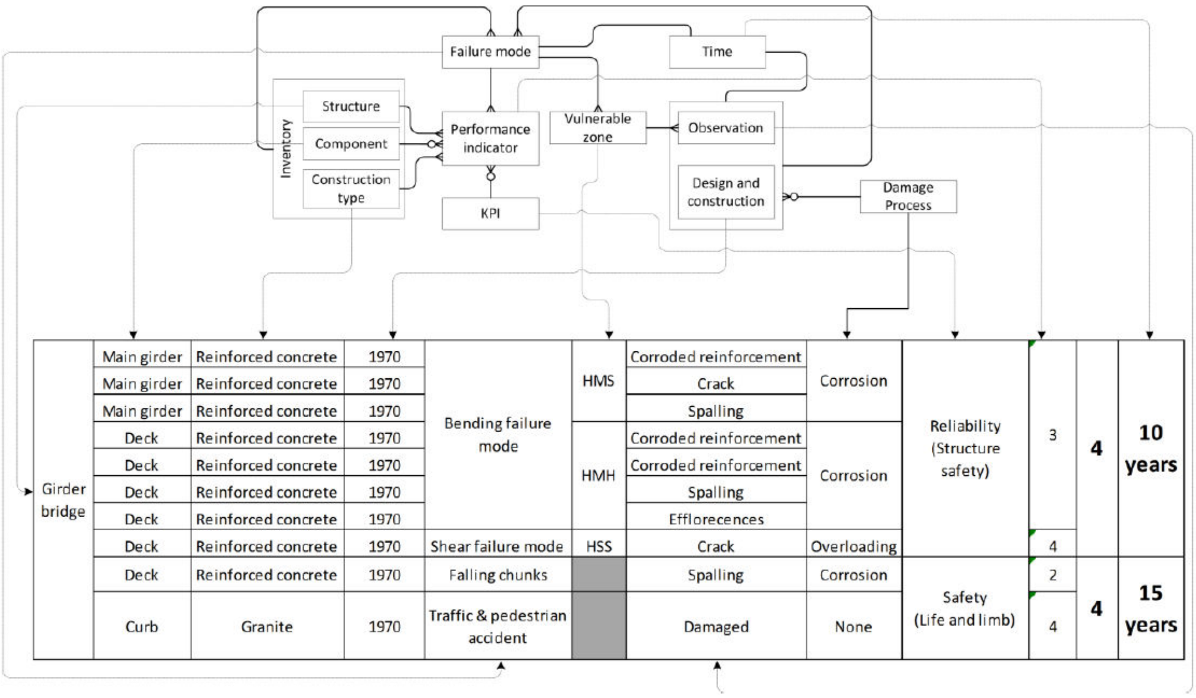

Figure 8.3: *The protocol with time scale, i.e. dynamic (taken from WG3 Report)*

There is no recommended method for considering the contribution of each failure mode to the total KPI rating, in this example of Reliability and Safety; in the WG3 report example, seems that the worst rating is considered as the bridge system KPI rating score. Also, the worst prediction over the remaining life time of the bridge, or the most early expected failure mode is governing the final decision for the maintenance program to be adopted. This procedure is more or less adopted in the majority of the case studies, where 4 KPI are adopted – Reliability, Safety, Availability and Cost - while in few case studies (e.g. Strymonas bridge case study) the assessment of the impact of the observed damages to a group of PIs, is carried out separately for each component and then the final KPI evaluation scores (for 4 KPI – Reliability, Safety, Availability and Cost) are calculated using weighting factors based on expert's opinion (using Analytical Hierarchy Process).

It is to be noted that in clause 7.5.2 of the WG3 report more sophisticated Bayesian based evaluation methods for KPI are presented in a generic way, not followed by the completed case studies so far.

9. Evaluating the remaining service life

9.1 Evaluating the time to failure

Following the evaluation of the different PI and KPI values and arranging the data in a structured table (see WG3 report, figure 7.14 'suggested protocol for performance evaluation') it is necessary to assess the remaining service life for the case study bridge, i.e. the point in time at which Reliability or Safety will reach the defined threshold value (unacceptable return period for a failure) without any intervention. This includes assessment of the speed of the identified active deterioration processes and damage forecast.

For each of the documented damages, indicate the relevant damage process and estimate the time to failure while documenting it on the PI/KPI evaluation table. The estimated value will be used for creating the reference and preventive QCP scenarios with their interventions and related costs. The assessment can use different known existing deterioration models as referenced herein clause 9.2 or by using a simpler expert opinion approach (see appendices A1 to A9).

Once decided by bridge owner to implement the suggested QCP methodology suggested by COST TU1406 it is expected that the prediction models and methods will be decided upon and approved by the asset managing authority as it has a great influence on the actual results of the QCP.

9.2 Overview of existing prediction models

Due to the different combined effects of mechanical impact, harsh environment, and extreme events the performance of bridges deteriorates over time (Hakim and Abdul Razak 2014, Frangopol and Soliman 2016). With the major aim to reduce life cycle costs and generally to improve sustainability it is essential to consider the way of extending the service life of bridges (Strauss et al. 2012, Bocchini et al. 2013, Abé 2015). A report done (Mirzaei et al. 2014), analyzed 25 different BMSs, indicated that nineteen of provided systems can predict deterioration and subsequent duration of service life, where twelve of these systems use probabilistic methods. Every model somehow extrapolates the future performance of the structure in question, whether it is in a deterministic or probabilistic approach.

The most used prediction models are the statistical models based on Markov property (Jiang Yi and Sinha C. Kumares), (A Ansell G Racutanu & H Sundquist, 2002). These models use condition ratings from visual inspections as input (Firouzi and Rahai 2013). Among different types of models which use Markov property, the simple homogeneous Markov chain model is predominantly implemented in BMSs up until now. Usual statistical prediction models used are the Markov homogeneous and inhomogeneous chain, Markov process with exponential and Weibull distribution and gamma process. (Zambon et. Al, 2017).

Regarding the deterministic models generally the division of the models can be in the view of mathematical and physical deterministic deterioration models. Mathematical models are formed on the basis of processing the statistical data on the state of a large number of bridges (West et al. 1989), physical models are based on the knowledge of physical and chemical phenomena, which cause the structure deterioration, and on measuring the parameters that affect the progress of the process (Bjegovic et al. 2004).

Physical models, contrary to statistical models, take into account the damage-causing processes (Puz and Radic 2011) and are independent on the subjectivity of visual inspection. The basis of these models is description of deterioration based on the environmental loads and relevant material parameters. The physical models are complex and the deterioration process may include several different mechanisms, which work simultaneously or in various phases of the process. They do not consider deterioration as a complete process, rather they just consider particular phenomena causing deterioration. So far, several researchers discussed the possibility of implementing physical models into service life prediction and bridge management; such are for example Maekawa et al. (2003), Hallberg and Racutanu (2007), Papadakis et al. (2007), Shin et al. (2011), and Ghodoosi et al. (2014). It is interesting to note that physical models in the form given in fib Bulletins 34 (2006), 59 (2011), and 76 (2015) have not yet been implemented in any of the operational BMSs as much as the authors are aware. The end of service life is mostly attributable to serviceability issues, such as corrosion-induced deterioration, in addition to factors related to budgetary, regulatory, and bridge management processes and constraints. Chloride- and carbonation-induced corrosion models can clearly be identified as main causes of deterioration in transportation infrastructure (fib Bulletin 59, 2011, Papadakis 2013) and broadly accepted models exist for these processes.

The old masonry arch bridges represent a huge infrastructural heritage asset. Out of all European railway bridges 60% are masonry, 23% concrete, 22% metallic (Tomor, 2013). Most probably a very similar ratio is applicable for highway bridges. The fatigue assessment of a bridge and the related residual service life may be predicted using behavioral models of masonry capable of simulating the response under cyclic loads. Based on fatigue experimental tests and regression analyses, some stress life curves (also indicated usually as S-N curves) have been proposed in literature to evaluate the masonry fatigue response.

Regarding codes, in the British guidelines BD 21/01 (2001) a fatigue limit of 50% of the Ultimate Limit State (ULS) is suggested. However, long term fatigue tests on multi-ring masonry arch barrels have indicated that the fatigue limit may be lower than 40% of ULS (Melbourne et al. 2004), and the permissible limit state PLS may be a more suitable option for identifying residual life for masonry bridges. However, looking at the other standards Italian Code NTC (2008) and EuroCode 6 (2006) no information regarding this limit is indicated. For details regarding stress-strain life curves see (Roca et al., 2004), (Roberts et al., 2006,) (Casas, 2009). For steel structures S-N curves and procedures to fatigue assessment are available by considered codes NTC (2008), EC1 (2003) and EC3 (2003), in the case of masonry elements no stress-life curves are proposed. For fatigue assessment and service-life prediction of existing steel bridges, Soliman et al. (2013) focused on service-life prediction for steel bridges by combining structural health monitoring (SHM) with a probabilistic bilinear stress–number of cycles (S-N) approach. Literature review revealed that it is possible to assess fatigue life of steel bridges if measured responses are available for their entire lifetimes, however this is usually not the case. Another alternative is use of bootstrap method to predict future measured responses. It provides a simple approach for generating plausible sets of stress data that reproduce the empirical probability distribution of measured stress data, which can in turn be used for service-life prediction. Bootstrapping is implemented by randomly sampling from an independent measured data set with replacement to create additional data sets that can be used for further statistical analysis. Efron (1979), Carey (2004), Sahrapeyma et al. (2013), and many others describe the bootstrap approach. Further explanations for the use of bootstrap analysis for fatigue lifetime prediction are given in Bigerelle and Iost (1999) and Bigerelle et al. (2006). Their research showed that the bootstrap is a powerful tool for modeling probability density function of fatigue life time prediction. This method can be used for damage detection of bridges Follen et al. (2014).

In the recent times there is a major use of the Bayesian optimization techniques and Artificial Neural Networks (ANNs) for prediction of the remaining service lives and estimation of serviceability conditions of bridges of different materials. One of the advantages of the ANN method over conventional methods is that once the model is trained it can be used as accurate and quick tool for estimation of the service lives of bridges. The back-propagation neural networks have the capability of predicting the reliability index and estimating the failure probability and the service lives of masonry arch bridges with good accuracy. Knowing the failure probabilities of the selected bridge, the remaining service life of the structure can be estimated based on the estimated value from ANN.

9.3 Extension of service life

In order to extend the service life of bridges, one needs to have an effective bridge management as indicated in figure 9.1.

An effective bridge management process will interconnect the different processes, for example, from the routine inspection and maintenance, vegetation cleaning should be triggered and that will prevent stonework deterioration, debris clearance from watercourses will prevent scour damage, etc. For concrete structures elements that effect the durability of concrete should be addressed as soon as possible, for example leaking expansion joint or failed waterproofing, heavy vehicles turning on expansion joint, stop/start traffic leads to joint durability issues and necessitate component replacement. In this respect, additional testing of the concrete structures should be done, for example: Dust sample - depth of penetration of chlorides; Chloride concentration at various depths; Phenolphthalein test - depth of carbonation; Half-cell Potential using Copper/Copper Sulphate electrode for corrosion, Concrete Resistivity; assessment of load carrying capacity. Individual significance and importance of all the above-mentioned elements is heterogeneous which makes this process complex and, in most cases, not straight forward.

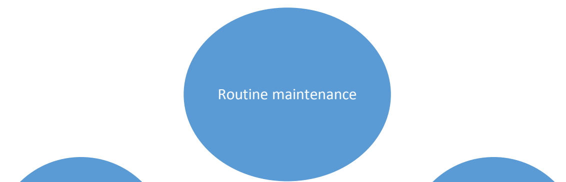

Figure 9.1: Effective management

10. Preparing possible maintenance scenarios

10.1 General description of the scenarios related tasks

In order to be able to decide upon the best QCP for the case study bridge, it is important to execute and document the following tasks:

- Define several maintenance scenarios with target reliability and safety over time. A reference scenario must be defined based on minimum intervention approach (do nothing..). Define additional preventive approach scenarios. For each scenario define the related interventions by time and type.
- Based on the specific data and age of the case study bridge, decide in advance regarding the preferred time frame (e.g. 50, 80, 100, 120 years).
- Detail the content of the defined interventions. It is advisable to create detailed maintenance tasks table per intervention type and correlate the tasks with the estimated change (improvement) of the Reliability and Safety KPIs.
- For preventive scenarios it is advisable to group together (by time) different tasks and create a periodical repeated intervention with the estimated cost.
- Estimate the cost of the different interventions per each scenario over time.
- Estimate the type, schedule and cost for the inspections and testing/monitoring per each scenario over time.
- Combine interventions and inspections/testing tasks with the related costs estimated in previous stages and create the scenarios QCP.
- Define the function of decrease of Reliability and safety.
- KPIs should be normalized (range 1 to 5).
- For each scenario create graphs per KPI (R, E, A, S) over time (excel file of WG3 can be used).
- Create a spider diagram, compare the scenarios and determine the optimum scenario for the case study bridge.

It is important to use a real intervention cost data from bridge owner's database or another reliable source. Limited reference data is given here.

10.2 Maintenance scenarios

Maintenance scenarios are defining the complex care of the bridge during its service life. The general recommendation in many European countries can be found in the results of the SBRI+ project. The results of the project are used here for demonstration how to establish the maintenance scenarios (Lemma et. al.).

During the operation phase of a bridge, regular inspections are necessary to allow the continuous monitoring of the bridge condition, evaluation and eventual need for maintenance and rehabilitation actions. The definition and aim of each the types of inspections are:

- Routine inspection – visual observation to detect small damage that can be promptly repaired; The team is formed by one or two members of the maintenance staff with specific training;
- Principal inspection – detailed visual inspection with special means of access. The aim is the assessment of the bridge condition rating evolution, with the definition of potential repair/rehabilitation actions;
- Special inspection – detailed inspection when there is a need for a specific repair plan for the complete or partial rehabilitation of the bridge. Tests and laboratory analysis are also used to help evaluate damage conditions and allow recommendations for damage repairs.

The frequency assumed for each type of inspection is shown in table 10.1.

Type of Inspection	Inspection frequency	Average occurrence during 100 years
Routine	0,5-2 years	50-100
Principal	4-6 years	17-25
Special	25-50 years	2-4

Table 10.1: *Standard preventive scenario - Inspection frequency and average occurrence.*

Maintenance activities can be divided into categories regarding the intensity of maintenance. In this recommendation two types of maintenance scenarios were considered:

- Preventive – a scenario with a 100-year service life, according to the normal service life of bridges, for which there will be enough money to undergo all the necessary inspections and maintenance/repair actions;
- Referenced – standard lack of money – along the bridge lifecycle, there is not enough money to undergo the necessary maintenance/repair actions and the bridge will be critically deteriorated and with traffic restrictions on year 100. Inspection frequency will have to be increased in the last years for the knowledge of the actual bridge condition, and also maintenance actions are introduced to extend the service life of some elements critically deteriorated;

Basic definitions for the scenarios are described in the following clauses.

10.2.1 **Preventive scenario**

In the preventive scenario, the types and inspection frequencies shown in table 10.1 are considered necessary to maintain the knowledge of the bridge condition and average service life of bridge elements. The frequency of maintenance/repair actions is considered essential in maintaining a good reliability and safety levels of the bridge (target values should be established by the owner). Regarding maintenance/repair, in the preventive scenario, it is assumed that maintenance actions take place before the end of the average service life of the elements of the bridge. Structural elements are replaced when the average service life is reached.

For the operation phase, it is assumed that the average service life for each structural or non-structural element of the bridge is the same for the preventive and lack of money scenario, according to table 10.2. Based on the average service life, a maintenance/repair works frequency should be assumed. Some common values are shown in tables 10.1 and 10.2. When preparing a specific case study, it is important to use the values used in the relevant country base on the local existing data from real bridge rehabilitations done in the recent years. Prices and types of interventions and rehabilitation tasks may vary a lot between countries and should be carefully assumed.

Element	Average service life (years)
Superstructure concrete	100-120
Safety barrier	25-40
Superstructure steel	100-120
Steel corrosion protection, depending on the type (duplex, painting, galvanizing) and the aggressivity of the environment	15-35
Expansion Joints	10-40
Road surface, depending on the volume of heavy trucks	10-20
Waterproofing Layer	20-40
Elastomeric bearing	30-50
Railing	40

Table 10.2: *Average service life assumed for bridge elements.*

Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	20-25
Parapets	Rehabilitation/Replacement	25/50
Safety barrier	Partial replacement	25
Steel corrosion protection	Repainting of corrosion protection	15
Expansion Joints	Partial (small mainly rubber or plastic elements)/full replacement	5/15 Rubber cushion seal anchored expansion joints (right lane/all lanes) 10/40 for modular strip seal exp. joints (right lane/all lanes)
Road surface	Minor repairs	10
Water Proofing Layer	Partial replacement/Full replacement	20/40
Elastomeric bearings	Replacement	30-50
Railing	Painting	15

Table 10.3: Preventive scenario - average maintenance/repair work frequency.

10.2.2 Referenced - lack of money scenario

In this scenario, it is assumed that in the early stages of the bridge, inspection actions will be less frequent, due to lack of money, and as the estimated end of the bridge service life approaches, inspection actions are more frequent for better monitoring and controlling the bridge reliability and safety levels.

Repair actions are delayed and scheduled towards the end of the service life and new maintenance actions are introduced to extend the service life of some bridge elements, in order to delay or remove other maintenance actions.

Regarding the assumptions in the previous sections, the average service life for the bridge elements is the same for all scenarios but the assumed frequency for maintenance/repair actions is normally much longer as shown in table 10.4

Bridge Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	40-50
Parapets	Replacement	50
Safety barrier	Partial replacement	25
Steel corrosion protection	Repainting of corrosion protection	30-50
Expansion Joints	Partial/full replacement	10/20 Rubber cushion seal anchored expansion joints (right lane/all lanes) 20/40 for modular strip seal exp. joints (right lane/all lanes)
Road surface	Minor repairs	15
Water Proofing Layer	Replacement	50
Bridge Element	**Maintenance action**	**Standard maintenance frequency (years)**
Elastomeric bearings	Replacement	50
Railing	Painting	30

***Table 10.4:** Referenced - lack of money scenario - average maintenance/repair work frequency.*

10.2.3 Application of the scenarios on existing bridge

The previous two scenarios are given for new bridges. However, usually the evaluated bridges are old. Then, the service life can be applied and shortened according to the bridge age. Also, the time schedules of the scenarios should be chosen carefully.

It is advisable in each case study to prepare a schedule with all the interventions and inspections along the remaining service life of the bridge and try to unify interventions by time as the additional indirect costs and traffic disturbance should be minimized.

10.2.4 Costs for the maintenance works

The costs for the maintenance works are strongly individual. Generally, it is necessary to calculate:

- Costs for the repair works,
- Cost for the traffic restrictions, traffic signs, temporary roads etc.,

- Cost for the individual reconstruction works

For the estimation of the repair works and the duration, table 10.5 can be used.

Maintenance		Rate of work	Unit cost
To	**Type**		
Bearings	Repair	1,5 day/un	200-2100 €/un (depending on the bearing type)
Bearings	Replacement	2 day/un	(2100 + cost of new bearing) €/un
Concrete deck	Refurbishment	0,08 days/m²	30 €/m²
Expansion joints	Repair	0,75 m/h	10 €/m
Expansion joints	Maintenance	40 m/day	25-50 €/m
Expansion joints	Replacement	3,5 m/day	500-4000 €/m Depending of the type. 300-1000€/m asphaltic plug joint 4000€/m modular joint
Railings (pedestrian)	Refurbishment	4 m²/h	90 €/m
Railings (pedestrian)	Replacement	1,75 m/h	75-150 €/m
Road surface	Repair	0,02 days/m²	12-20 €/m²
Road surface	Replacement	0,02 days/m²	12-20 €/m²
Safety barriers	Replacement	1,3 m²/h	150-250 €/m
Steel girders	Refurbishment	0,02 days/m²	75 €/m²
Steel girders	Repair	0,02 days/m²	100 €/m²
Water proofing layer	Replacement	0,02 days/m²	60-200 €/m²

Table 10.5: *Operation types, rates of work and maintenance unit cost*

The cost for the traffic restrictions and cost for the individual reconstruction works must be calculated individually according to the experiences of the evaluation engineer. Usually, the standard prices are defined in many European countries. Also, it should be noted, that the repair of one element can results in the replacement of other elements. For example, replacement of the waterproofing means also to replace pavement and the parapets.

10.2.5 **Selecting the optimal scenario for a case study**

Following the preparation of the combined interventions and inspections/testing list and the related costs estimated for the scenarios QCP, it is important to define the function of decrease of Reliability and safety over time and prepare the time dependent graphs for the KPIs (R, E, A, S - excel file of WG3 can be used) see Figure 10.1. The KPIs should be normalized. Normalization of KPIs is proposed to be done in 1-5 scale (1 the best to 5 the worst condition see WG3 Report clause 12.2). Specifically, for KPI Cost, first the maximum yearly costs that are expected can be regarded as five and the costs in other years can be scaled appropriately.

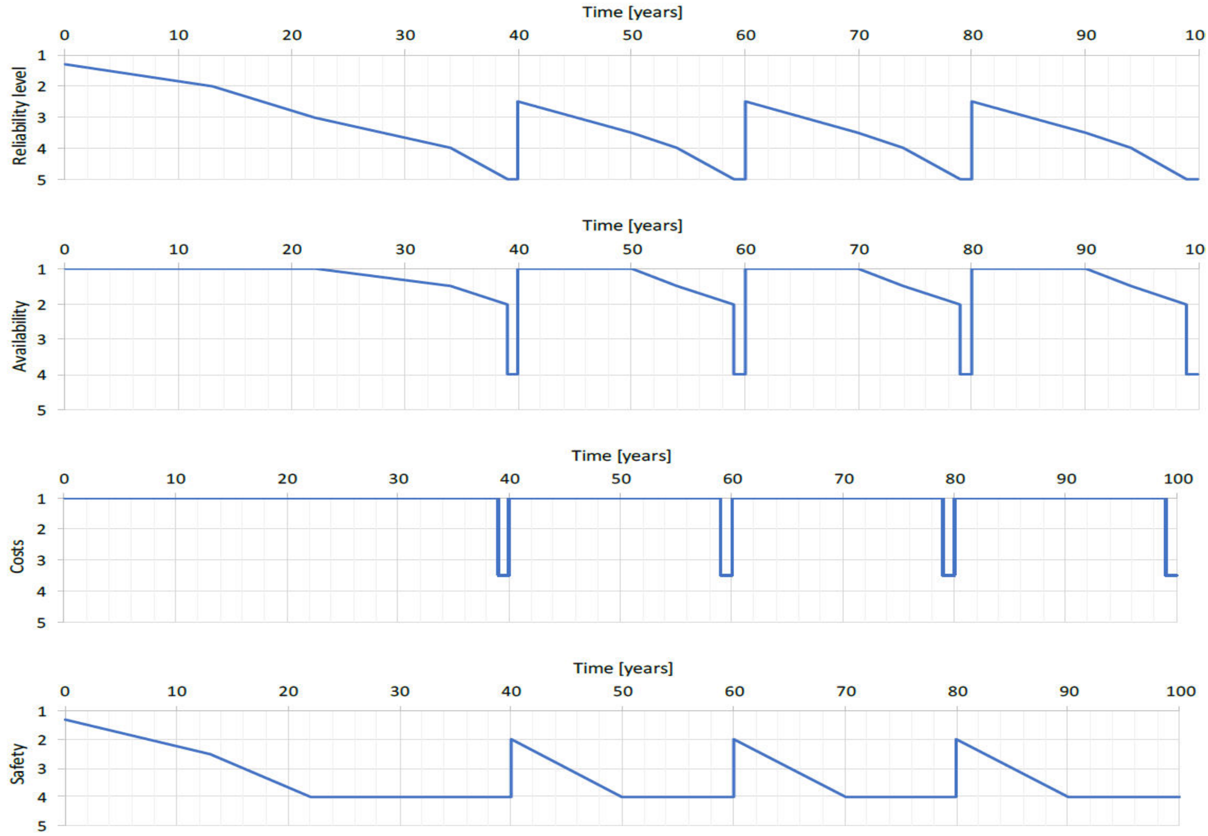

Figure 10.1: *Normalized KPIs diagrams over time, (from Appendix A7)*

The KPIs can be conveniently visualized using a "spider net diagram" (see Figure 10.2 below from WG3 report). In almost all the case studies the spider net diagram was done for 4 KPIs, described previously.

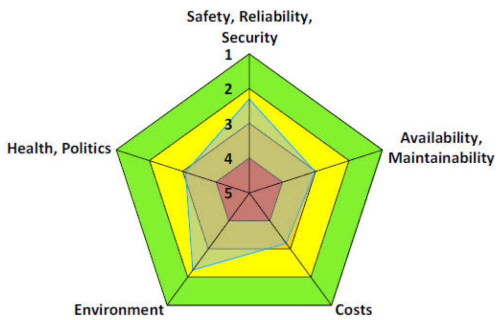

Figure 10.2: *"Spider net" diagram, from (Stipanovic, et al., 2017)*

As the selection of the optimal maintenance strategy is required, the representation needed includes the actual (current) and the predicted (future) KPI scores for the remaining life of the assessed bridge. In the following Figure 10.3, each of the KPIs are given on a separate axis, and when their development over time is of interest, the time axis can be appended orthogonally on the plane of the diagram. In this manner, the "performance tube" can be generated. In Figures 10.2 and 10.3 there are five axes corresponding to the adopted KPIs within WG3 report. As an example, the linear change of the KPIs' values in time is adopted here. In general, the necks in the diagram represent the time intervals of low performance, whereas the areas with "full" pentagon cross-section are the time periods of high performance. Alternatively, volume between the "full" pentagon and the "performance tube" can be regarded as performance deficit that is to be minimized.

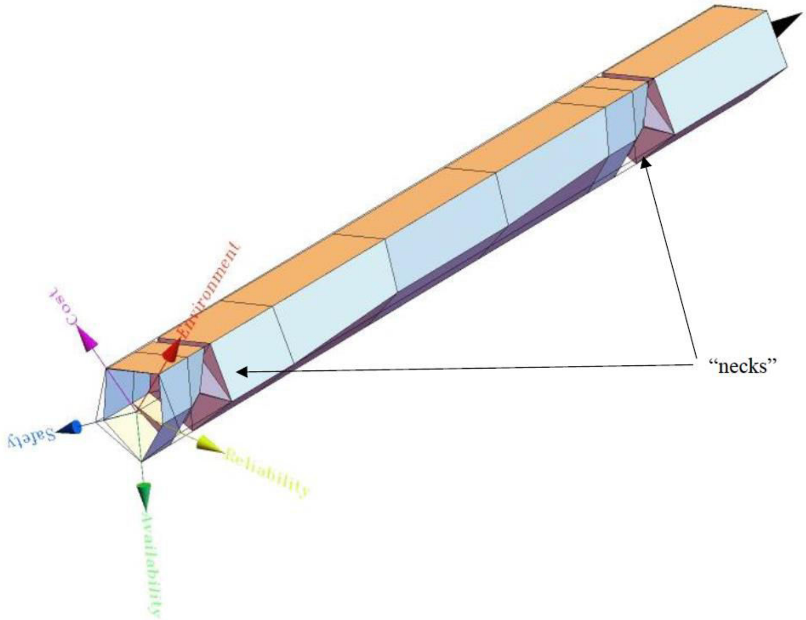

Figure 10.3: *3D Spider net - Performance Diagram*

Criteria for the selection of the optimal maintenance strategy are applied in order to select between alternative strategies. This can be done by comparing average spider diagrams (representing the average KPI scores along the examined remaining life) for each alternative, by comparing the net present values of the costs associated to each alternative. In Strymonas case study the volume of the full tetragon, representing the performance of 4 KPIs along the remaining life of the bridge is calculated for both the reference and the preventative strategies. Then the alternative with the higher volume, is associated to the strategy that keeps the performance of the bridge in higher level for the remaining life.

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12. Appendix

Bridge ID data tables (excel file and instructions attached separately)

COST TU1406 WG4 - Bridge ID data for candidiate Case study bridges TU1406 COST ACTION

Note: For explanation on how to fill the different data items see at the "COST TU1406 WG4 - Guide for Documenting Sample Bridge Data"

item No.	Description	Item Type	Instructions	Value	Comments
General Identification Data					
1.1	Country	Text	Please Fill in the country name		
1.2	Region	Text	Please fill in the region name		
1.3	Bridge Identification Code	Text	As in the BMS system		
1.4	Bridge Name	Text	As in the BMS system		
1.5	General Description	Text	Free text describing the Bridge		
1.6	Road Number	Text/Number	The road number that the bridge assign to as in the BMS system		
1.7.1	Belong to street name	Text	To be used only if the bridge is located on municipality street/road		
1.7.2	Near building No.	Number	Nearest building number if the bridge is located on municipality street/road		
1.8	Linear reference point	KKK.MMMM	For bridges located on network roads with linear referencing		
1.9.1	Latitude	N 31°48'45.36"	Bridge location - N		
1.9.1	Longitude	E 31°48'45.36"	Bridge location - E		

Figure 12.1: General identification data Group in the Data Table

item No.	Description	Item Type	Instructions	Value	Comments
General Classification Data					
2.1	Bridge Primary use	Text	Please Select from the predefined list describing the main use of the bridge	Choose from the predefined list here	
2.2	Road Classification	Text	Please Select from the predefined list	4 lane or more Municipal road	
2.3	Emergency Classification	Yes/No	'yes'= if the road is defined for use by security forces during emergencies	Choose from the predefined list here	
2.4.1	Built by	Text	Name of the authority who build the bridge		
2.4.2	Built by - Type of authority	Text	Please choose one of the options in the pre defined list	Choose from the predefined list here	
2.5.1	Ownership	Text	Name of the authority who own the bridge		
2.5.2	Ownership - Type of authority	Text	Please choose one of the options in the pre defined list	Choose from the predefined list here	
2.6.1	Maintenance Responsibility	Text	Name of the authority responsible for the bridge maintenance		
2.6.2	Maintenance Responsibility - type of authority	Text	Please choose one of the options in the pre defined list	Choose from the predefined list here	
2.7	Toll Road Indication*	Yes/No	'yes' =if the bridge is a part of road requiring payment for use	Choose from the predefined list here	
2.8	Abnormal Loads Route*	Yes/No	'yes' = if the bridge is a part of heavy load transportation route	Choose from the predefined list here	
2.9	Special Historical Significance*	Yes/No	'yes' = if the bridge has special historical Significance	Choose from the predefined list here	
2.10	Temporary Structure*	Yes/No	'yes' = If the bridge is defined as temporary structure in the BMS	Choose from the predefined list here	

Figure 12.2: General classification data Group in the Data Table

item No.	Description	Item Type	Instructions	Value	Comments
Service Data					
3.1	Year Built	YYYY	Please indicate the original year		
3.2	Year of Rehabilitation	YYYY	Please fill only if the bridge was rehabilitate		
3.3	Main Use on (over) the Bridge	Text		Choose from the predefined list here	
3.4	Secondary Use on (over) the Bridge	Text		Choose from the predefined list here	
3.5	Number of Carriageways or Railroad Tracks on (over) the Bridge	NN (Integer)			
3.6	Number of Lanes on (over) the Bridge	NN (Integer)			
3.7	Direction of Traffic on the Bridge	Text		Choose from the predefined list here	
3.8	Main Use Under the Bridge	Text		Choose from the predefined list here	
3.9	Secondary Use Under the Bridge	Text		Choose from the predefined list here	
3.10	Number of Carriageways or Railroad Tracks Under the Bridge	NN (Integer)			
3.11	Number of Lanes Under the Bridge	NN (Integer)			
3.12	Direction of Traffic Under the Structure	Text		Choose from the predefined list here	
3.13	AADT Annual Average Daily Traffic	NNNNNN (Integer)			
3.14	Year of last AADT measurement	YYYY			
3.15	AADTT Annual Average Daily Truck Traffic out of all traffic	NNN (percent)	Percentage of the truck from the total vehicle number		
3.16	Detour on Existing Roads	Text	Possible/Non Possible	Choose from the predefined list here	
3.17	Detour Length	KKK (km)	The length of the detour is the number of additional kilometers added to the road as a result of performing the detour, rounded up to the closest whole kilometer		
3.18	Local Detour	Text	Possible/Non Possible	Choose from the predefined list here	
3.19	Method of Performing Local Detour	Text	The method for performing local detour (from a list)	Choose from the predefined list here	
3.20	Designed by	Text	Name of the original designer of the bridge		
3.21	Rehabilitation or Widening Designed by	Text	Name of the rehabilitation/Widening designer		

Figure 12.3: Service data Group in the Data Table

item No.	Description	Item Type	Instructions	Value	Comments
Geometrical Data					
4.1	Number of Spans	NN (Integer)	Please fill in the total number of spans		
4.2	Length of Maximal Span [m]	XXX.X [m]			
4.3	Total Length of Structure [m]	XXXX.X [m]			
4.4	Length of Right Side [m]	XXXX.X [m]			
4.5	Length of Left Side [m]	XXXX.X [m]			
4.6	Span Lengths	XXX.X [m] * No. of spans	Please write in the define format see guide		
4.7	Existing Change of Width	Text	Please indicate if change of width exist	Choose from the predefined list here	
4.8	Minimal External Width perpendicular to Road Center Line [m]	XXX.X [m]			
4.9	Maximal External Width Perpendicular to Road Center Line [m]	XXX.X [m]			
4.10	Curb or Sidewalk Width – Right [m]	XX.XX [m]			
4.11	Curb or Sidewalk Width – Left [m]	XX.XX [m]			
4.12	Minimum Carriageway Width (between curbs) [m]	XX.XX [m]			
4.13	Total Carriageway Width (curb to curb) [m]	XX.XX [m]			
4.14	Median type	Text		Choose from the predefined list here	
4.15	Skew angle [deg]	XX degrees	Please indicate on comments if there is a variable skew angle between Piers/Abutments		
4.16	Minimum Vertical Under-clearance in Traffic Area [m]	XX.XX [m]			
4.17	Minimal Vertical Over-clearance Above the Structure [m]	XX.XX [m]	To be used only if an over bridge obstacle exist (like sign gantry on/over the deck)		
4.18	Existing vertical clearance Restriction Sign Value	XX.XX [m]			
4.19	Minimal Lateral Clearance [m]	XX.X [m]			
4.2	Maximal Pier/Abutment Height [m]	XX.XX [m]			
4.21	Deck Surface area [m2]	Area [m2]	Please fill in the total calculated deck area of the bridge see guide		
4.22	Original Bridge Drawings	Yes/No	Yes= Original set of bridge drawings exist, No= Drawings do not exist	Choose from the predefined list here	
4.23	Bridge Rehabilitation Drawings	Yes/No	Yes= Original set of bridge rehabilitation drawings exist, No= Drawings do not exist	Choose from the predefined list here	

***Figure 12.4**: Basic geometrical data Group in the Data Table*

item No.	Description	Item Type	Instructions	Value	Comments
Structural Classification Data					
5.1	Number of Bridge Deck Types	N (Integer)			
5.2.1	Deck Classification 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.2.2	Deck Classification 2	Text	To be used if more then one deck type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.2.3	Deck Classification 3	Text	To be used if more then one deck type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.3.1	Abutment/wall 1 Classification	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.3.2	Abutment/wall 2 Classification	Text	To be used if more then Abutment type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Gravity Abutment	
5.4	Number of Pier Types	N (Integer)			
5.5.1	Pier Classification 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.5.2	Pier Classification 2	Text	To be used if more then one Pier type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.5.3	Pier Classification 3	Text	To be used if more then one Pier type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.6	Prestressing type	Text	To be used for Prestressed concrete bridges only. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.7.1	Bearings Type 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.7.2	Bearings Type 2	Text	To be used if more then one Bearing type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.7.3	Bearings Type 3	Text	To be used if more then one Bearing type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.7.4	Bearings Type 4	Text	To be used if more then one Bearing type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.8.1	Joints type 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.8.2	Joints type 2	Text	To be used if more then one Joint type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.8.3	Joints type 3	Text	To be used if more then one Joint type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
5.8.4	Joints type 4	Text	To be used if more then one Joint type exist in the bridge. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	

***Figure 12.5**: Structural classification data Group in the Data Table*

item No.	Description	Item Type	Instructions	Value	Comments
Material Classification Data					
6.1.1	Bridge Deck Top Slab Material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.1.2	Bridge Deck Top Slab Material 2	Text	To be used if more then one material type exist for the bridge top slab. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.1.3	Bridge Deck Top Slab Material 3	Text	To be used if more then one material type exist for the bridge top slab. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.2.1	Superstructure material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.2.2	Superstructure material 2	Text	To be used if more then one material type exist for the bridge Superstructure. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.2.3	Superstructure material 3	Text	To be used if more then one material type exist for the bridge Superstructure. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.3.1	Abutment/Wall material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.3.2	Abutment/Wall material 2	Text	To be used if more then one material type exist for the bridge Abutments. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.3.3	Abutment/Wall material 3	Text	To be used if more then one material type exist for the bridge Abutments. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.4.1	Pier material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.4.2	Pier material 2	Text	To be used if more then one material type exist for the bridge Piers. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.4.3	Pier material 3	Text	To be used if more then one material type exist in the bridge Piers. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.5.1	Slope protection material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.5.2	Slope protection material 2	Text	To be used if more then one material type exist for the bridge slope protection. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.6.1	Safety barrier material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.6.2	Safety barrier material 2	Text	To be used if more then one material type exist for the bridge safety barriers. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.7.1	Pedestrian safety railing material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.7.2	Pedestrian safety railing material 2	Text	To be used if more then one material type exist for the bridge safety railing. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.8.1	Deck surface cover material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.8.2	Deck surface cover material 2	Text	To be used if more then one material type exist for the bridge Deck surface cover. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.8.3	Deck surface cover material 3	Text	To be used if more then one material type exist for the bridge Deck surface cover. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.9.1	Deck waterproofing material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.9.2	Deck waterproofing material 2	Text	To be used if more then one material type exist for the bridge Deck waterproofing. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.10.1	Parapet material 1	Text	If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	
6.10.2	Parapet material 2	Text	To be used if more then one material type exist for the bridge Parapet. If 'other' is chosen please describe in free text at the comment field	Choose from the predefined list here	

Figure 12.6: *Material classification data Group in the Data Table*

item No.	Description	Item Type	Instructions	Value	Comments
Loading Classification Data					
7.1	Load rating method	Text	Please explain the load rating method in few words and indicate the relevant professional document		
7.2	Load rating actual value	Text	If load rating method exist, please indicate the load class or value and the units		
7.3	Year of last load rating	Year	If load rating exist please indicate the year where the last load rating was performed		
7.4	Load restriction sign on site	NNN (integer) [ton]	Please indicate id the bridge has on site load restriction sign and the value in [ton]		
7.5	Seismic load rating method	Text	Please explain the seismic rating method in few words and indicate the relevant professional document		
7.6	Seismic load rating	Text	If seismic rating method exist, please indicate the class or value and the units		
7.7	Year of last Seismic load rating	Year	If seismic rating exist, please indicate the year where the last rating was performed		
7.8	Other loading classification	Text	Please describe other loading classification (if exist)		
7.9	Other loading classification	Text	Please describe other loading classification (if exist)		
Bridge Hydraulic Data					
8.1	Maximal Designed Relative Water Level	NN.N (Number)	Please indicate the relative designed water level below the deck soffit (or over the structure). Positive number = under the deck. Negative number = over the deck		
8.2	Hydraulic design return period	YYY (years)			
8.3	Hydraulic Performance indicator	Text	If Hydraulic performance indicator exist, please indicate the class/value and describe the method in few words and indicate the relevant professional document.		

Figure 12.7: *Loading classification and Bridge Hydraulics data Group in the Data Table*

item No.	Description	Item Type	Instructions	Value	Comments
Bridge Performance Indicators					
9.1.1	Bridge Condition Performance Indicator - Description	Text	Please Describe the BCPI in use in few words and indicate the relevant professional document		
9.1.2	Bridge Condition Performance Indicator - Value	Number/Text	Please indicate the value of the BCPI in use for this bridge		
9.2.1	Bridge Availability Performance Indicator - Description	Text	Please Describe the BAPI in use in few words and indicate the relevant professional document		
9.2.2	Bridge Availability Performance Indicator - Value	Number/Text	Please indicate the value of the BAPI in use for this bridge		
9.3.1	Bridge Reliability Performance Indicator - Description	Text	Please Describe the BRPI in use in few words and indicate the relevant professional document		
9.3.2	Bridge Reliability Performance Indicator - Value	Number/Text	Please indicate the value of the BRPI in use for this bridge		
9.4.1	Bridge Safety Performance Indicator - Description	Text	Please Describe the BSPI in use in few words and indicate the relevant professional document		
9.4.2	Bridge Safety Performance Indicator - Value	Number/Text	Please indicate the value of the BSPI in use for this bridge		
9.5.1	Other Bridge Performance assessment Indicator - Description	Text	Please Describe the Assessment Indicator in use in few words and indicate the relevant professional document		
9.5.2	Other Bridge Performance assessment Indicator - Value	Number/Text	Please indicate the value of the Assessment Indicator in use for this bridge		
9.6.1	Other Bridge Performance assessment Indicator - Description	Text	Please Describe the Assessment Indicator in use in few words and indicate the relevant professional document		
9.6.2	Other Bridge Performance assessment Indicator - Value	Number/Text	Please indicate the value of the Assessment Indicator in use for this bridge		
9.7.1	Other Bridge Performance assessment Indicator - Description	Text	Please Describe the Assessment Indicator in use in few words and indicate the relevant professional document		
9.7.2	Other Bridge Performance assessment Indicator - Value	Number/Text	Please indicate the value of the Assessment Indicator in use for this bridge		

Figure 12.8: *Existing Bridge performance indicators data Group in the Data Table*

item No.	Description	Item Type	Instructions	Value	Comments
Quality control plan					
10.1	Quality control plan exist for the Bridge	Yes/No	Yes= Quality control plane already exist for the Bridge, No= QC Plan do not exist	Choose from the predefined list here	
10.2	QC Plan documentation	Text	Please describe the method in few words and indicate the relevant professional document		
Bridge Inspection Data					
11.1	Number of already performed inspections	NN (Integer)	Please indicate the total number of the inspection performed to date		
11.2	Year of first inspection	Year			
11.3	Year of last inspection	Year			
11.4	Frequency of Routine Inspection	MM (months)			
11.5	Year of the last Damage control inspection	Year	To be filled only if damage control inspection performed		
11.6	Year of the last underwater inspection	Year	To be filled only if underwater inspection performed		
11.7	Year of the last In-Depth inspection	Year	To be filled only if In-Depth inspection performed		
11.8	Year of the last Special inspection	Year	To be filled only if Special inspection performed		
11.9	Inspection equipment mounted on the Bridge	Text	Please describe in text the permanent inspection equipment attched to the bridge		

Figure 12.9: *Existing QC Plan and Bridge Inspection data Group in the Data Table*

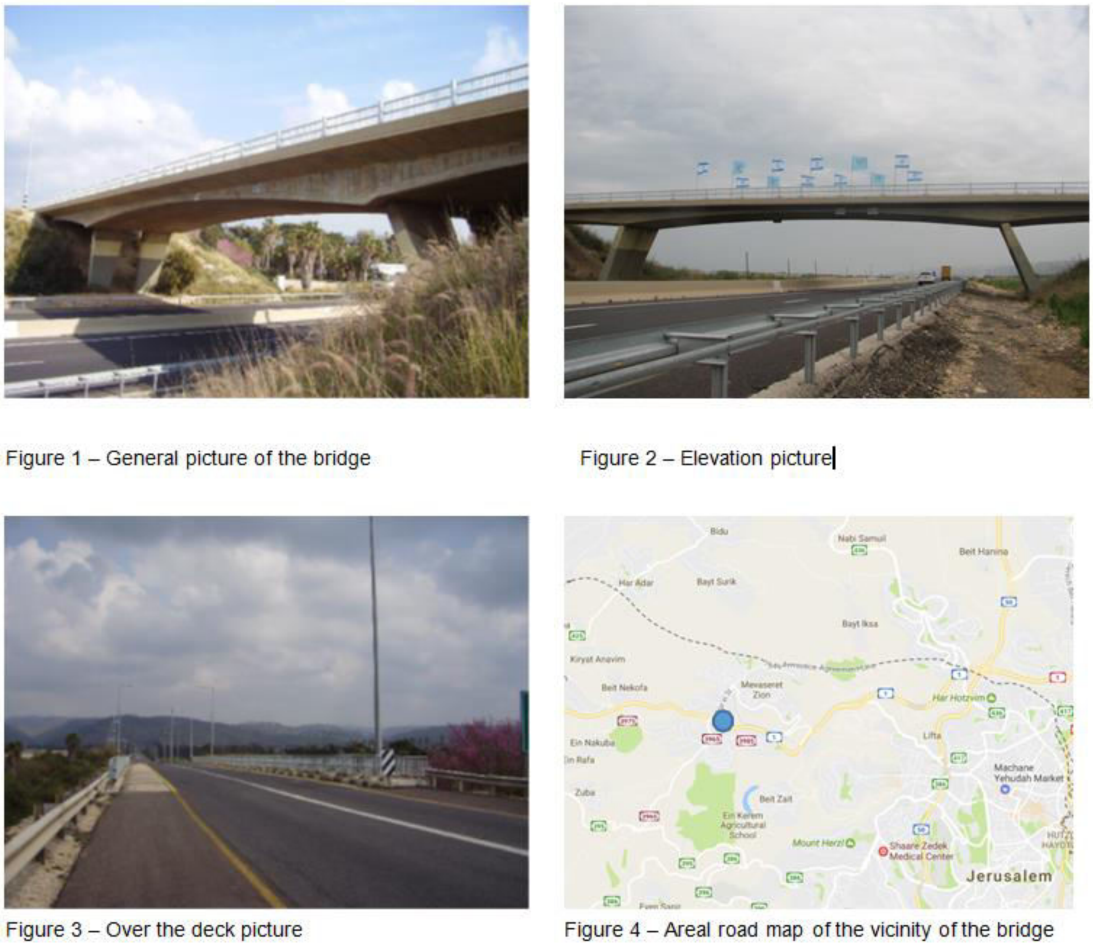

Figure 12.10-1-4: *Examples of the four photos for each bridge that should be added to the Data Table*

	Country	Submision	Girder	Arch	Frame
1	Austria	yes	V	V	V
2	Belgium	yes	V	V	V
3	Bosnia and Herzegovina	yes	VV	VV	VV
4	Croatia	yes	V	V	V
5	Czech Republic	yes	VV	V	V
6	Estonia	yes	V	V	V
7	Finland	yes	V	V	V
8	France	yes	V	-	VV
9	Germany	yes	V	V	V
10	Greece	yes	V	V	V
11	Israel	yes	V	V	V
12	Latvia	yes	V	-	-
13	Lebanon	yes	V	-	-
14	Macedonia	yes	V	V	V
15	Montenegro	yes	V	V	V
16	Netherlands	yes	V	V	V
17	Poland	yes	VV	-	-
18	Portugal	yes	V	VV	V
19	Republic of Serbia	yes	V		
20	Romania	yes	V	V	-
21	Spain	yes	V	V	-
22	Sweden	yes	V	V	-
23	Switzerland	yes	V	V	V
24	Turkey	yes	V	V	V

1	Bulgaria	no
2	Cyprus	no
3	Denmark	no
4	Hungary	no
5	Iceland	no
6	Ireland	no
7	Italy	no
8	Lithuania	no
9	Luxemburg	no
10	Malta	no
11	Norway	no
12	Slovakia	no
13	Slovenia	no
14	United Kingdom	no

Figure 12.11: *The list of the countries who submitted the Data Tables*

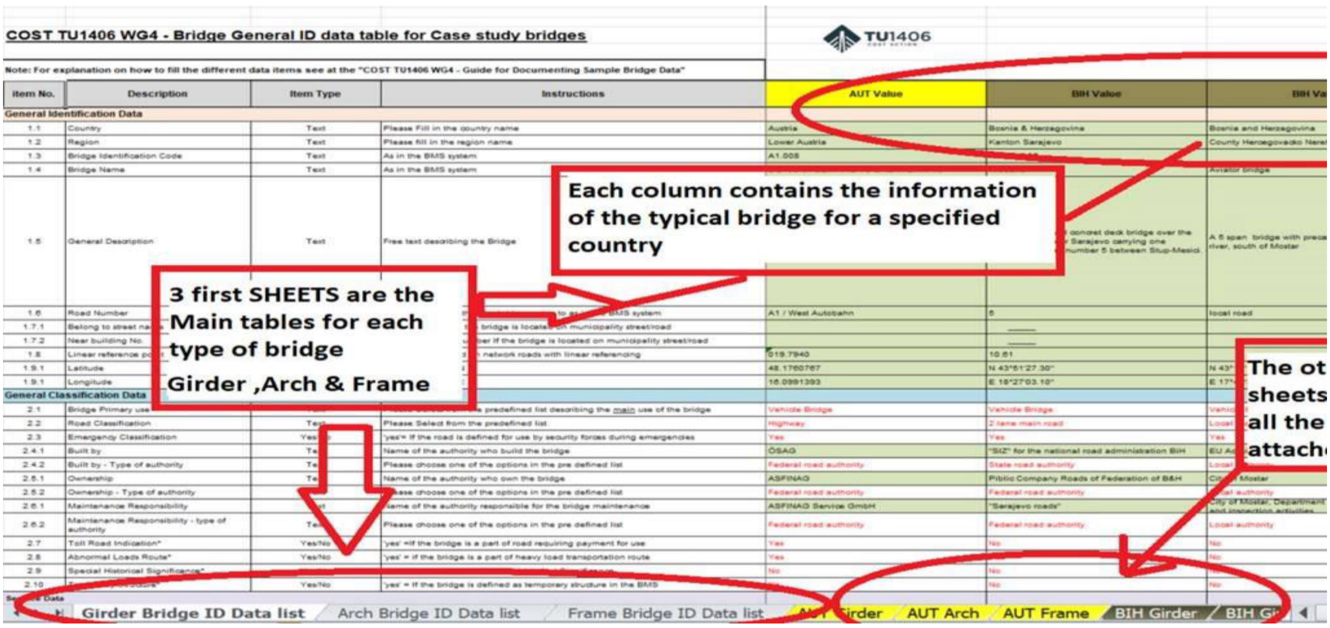

Figure 12.12*: The Main Data Table*