D5.3 A SET OF KPIS TO PLAN A SAFE RISK-BASED MAINTENANCE

Irina Stipanovic, INFCON
Sandra Skaric Palic, INFCON

@AshvinH2020
ASHVIN H2020 Project
www.ashvin.eu

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Task leader/Main author	Irina Stipanovic (INFCON), Sandra Skaric Palic (INFCON)
Contributing partners	Joan Ramon Casas (UPC)
Reviewer(s)	Rolando Chacon (UPC), Ilias Koulalis (CERTH)

ABSTRACT

This deliverable describes the developed key performance indicators (KPIs) to plan and control productive, resource efficient, and safe maintenance together with guidelines for their applications. The report also describes the exemplary implementation of the key performance indicators (KPIs) and the associated performance indicators (PIs) on a few selected demonstration projects.

KEYWORDS

Maintenance, key performance indicators, performance indicators, risk

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DISCLAIMER

ACRONYMS & DEFINITIONS

PI	Performance Indicator
KPI	Key Performance Indicator
IoT	Internet of Things
UAV	Unmanned Aerial Vehicle
LCA	Life Cycle Assessment
RAP	Reclaimed Asphalt Pavement
SHM	Structural Health Monitoring
SLS	Serviceability limit state
ULS	Ultimate limit state
SMP	Safety Management Plan
H&S	Health and Safety
PCI	Pavement Condition Index
BCI	Bridge Condition Index
ASTM	American Society for Testing and Materials
LCC	Life Cycle Cost
AADT	Average Annual Daily Traffic
C&DW	Construction and Demolition Waste
LCCM	Life Cycle Cost Model

ASHVIN PROJECT

ASHVIN aims at enabling the European construction industry to significantly improve its productivity, while reducing cost and ensuring absolutely safe work conditions, by providing a proposal for a European wide digital twin standard, an open source digital twin platform integrating Internet of Things IoT and image technologies, and a set of tools and demonstrated procedures to apply the platform and the standard proven to guarantee specified productivity, cost, and safety improvements. The envisioned platform will provide a digital representation of the construction product at hand and allow to collect real-time digital data before, during, and after production of the product to continuously monitor changes in the environment and within the production process. Based on the platform, ASHVIN will develop and demonstrate applications that use the digital twin data. These applications will allow it to fully leverage the potential of the IoT based digital twin platform to reach the expected impacts (better scheduling forecast by 20%; better allocation of resources and optimization of equipment usage; reduced number of accidents; reduction of construction projects). The ASHVIN solutions will overcome worker protection and privacy issues that come with the tracking of construction activities, provide means to fuse video data and sensor data, integrate geo-monitoring data, provide multi-physics simulation methods for digital representing the behavior of a product (not only its shape), provide evidence based engineering methods to design for productivity and safety, provide 4D simulation and visualization methods of construction processes, and develop a lean planning process supported by real-time data. All innovations will be demonstrated on real-world construction projects across Europe. The ASHVIN consortium combines strong R&I players from 9 EU member states with strong expertise in construction and engineering management, digital twin technology, IoT, and data security / privacy.

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1 INTRODUCTION

1.1 Purpose of the document

The work carried out in this report serves to develop a set of Key Performance Indicators to plan and control productive, resource efficient, and safe maintenance together with guidelines for their applications. The exemplary implementation of the KPIs on a few selected demonstration projects with appurtenant performance indicators and the associated data is also provided. This document summarises the work performed in Task 5.3 Risk-based predictive maintenance and presents a basis for the development of the ASHVIN applications and tools, such as MatchFEM, GISI and RISA.

The target group for this document are consortium partners and demonstration project owners, in particular infrastructure managers, decision makers, contractors or consultants responsible for maintenance planning and execution.

1.2 Outline of the document

The document is structured into 5 main sections. The first part of work is related to the review of the literature and internal workshops. Those activities are the basis for the selection of the Key Performance Indicators (KPIs) for planning productive, resource efficient, and safe maintenance. Next step is reviewing of the KPIs by the tool developers to verify which of them can be supported by the ASHVIN applications. The report ends with the implementation plan that describes the most appropriate KPIs for the four constructed assets:

- Demonstration site #1 Railway bridges in Spain
- Demonstration site #2 Residential building in Poland
- Demonstration site #3 Airport runway in Croatia
- Demonstration site #7 Highway bridges in Spain

In addition, Chapter 4 provides the relation between available digital data obtained from the monitoring and appropriate KPI. The structure of the document is shown in Figure 1.

LITERATURE REVIEW	SELECTION OF KPIS	MAPPING	IMPLEMENTATION ON DEMONSTRATION PROJECTS
Scientific papers Gray literature	Productivity Resource efficient Health and Safety Cost	ASHVIN tools and related KPIS	Selection of KPIs for four demonstration projects

Figure 1 Structure of the document with division into main chapters.

1.3 Selection Approach

While certain maintenance activities are repetitive and generic, other repair interventions require detailed design and extensive construction works. Due to this there is a partial overlapping in Performance Indicators (PIs) for Maintenance with PIs for Design and Construction. With a significant number of indicators being common for planning, design, acquisition, construction, operation and maintenance phase, there are also certain indicators quite specific for the longest life cycle phase, the phase where the structures are in operation. Each selected performance indicator is introduced with a short description, calculation method if needed and data collection protocol. Finally, the indicators are verified on four demonstration projects in the last chapter.

2 METHODOLOGY FOR THE ASSESSMENT OF MAINTENANCE STRATEGIES

2.1 Introduction

Performance monitoring is crucial in order to make strategic decisions about the future management of infrastructure assets. An understanding of the high-level desired outcomes that infrastructure systems are designed to promote serves as the basis for the process of generating relevant performance indicators. These outcomes are often intricate and dynamic, depending on the scope of the analysis and the stakeholders involved. When developing the structure and the scope of the infrastructure performance indicators decision making process can vary from strategic/network (top-down approach) level to tactical, operational/object (bottom-up approach) level (Stipanovic et al., 2017). As shown in Figure 2, top down approaches ensure that chosen indicators help measure infrastructure's contribution to high-level desired outcomes and to decide whether strategic changes are necessary to ensure that infrastructure performance remains 'fit for purpose' (Carhart et al., 2016).

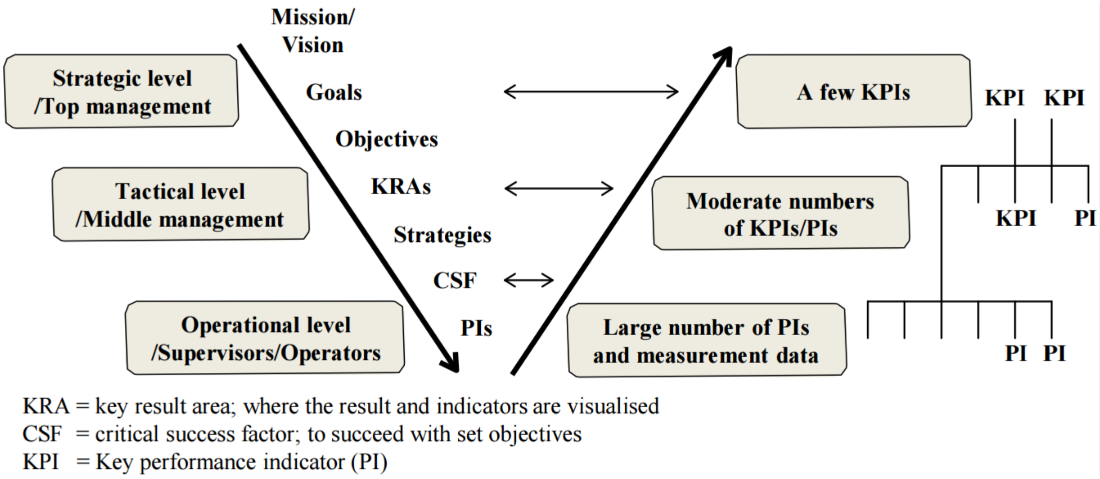

Figure 2 Breakdown of goals and objectives and aggregation of data

Once the performance goals are defined and criterion in the form of a KPI is decided, collection of PIs that constitute the KPI, can be performed. Figure 3 shows the flow of the assessment process ("from data to dashboard") in sub-steps. Additionally, an illustration is given to demonstrate how a benchmark can be created from existing project data ,which allows for a comparison of different maintenance strategies using determined KPIs.

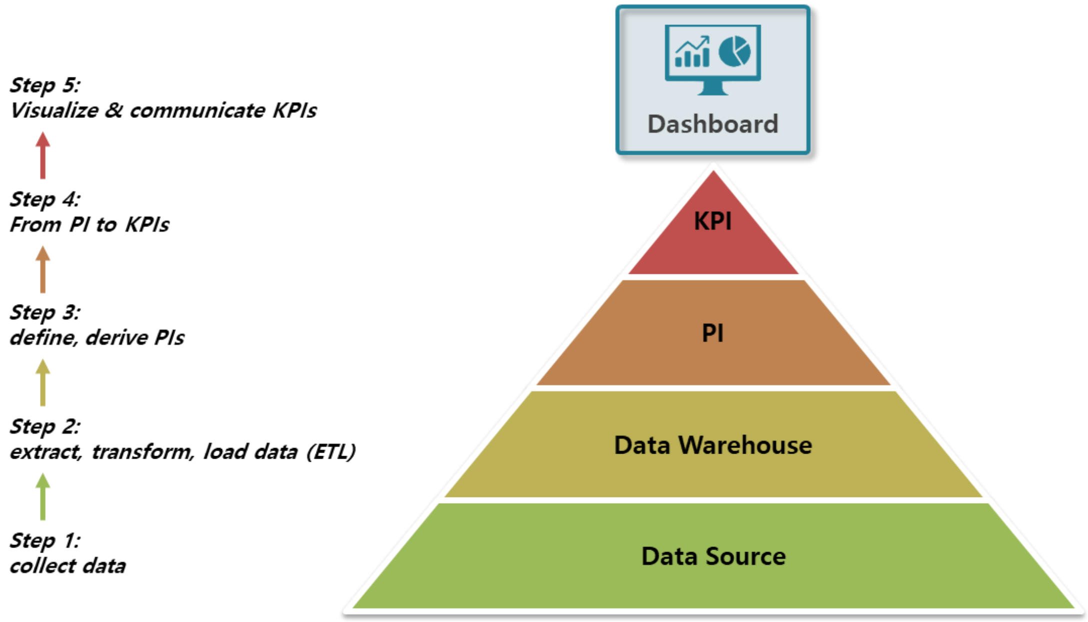

Figure 3 "From Data to Dashboard" - graphical representation of the approach (Krenn, B.., 2021)

2.2 Performance goals

Infrastructure management decision-making procedures and activities use performance goals as their primary input. The whole management process is graded based upon reaching a certain level of these predefined goals. An example is determining whether users are getting the services they want at the level of quality they are willing to pay for and comparing competing or alternative service producers to identify the most effective way to provide infrastructure services. A framework from goals to KPIs and PIs is required to maintain consistency in the databases used and the information provided. The indicators are updated to ensure relevance because information needs, the types of agencies utilizing PIs, and their relationships to one another vary over time and through life span of assets from design, construction, operation and maintenance. Following main focus areas are used to measure performance:

- Economic performance contrasts economic outcomes like number of passengers, number of vehicles or freight (tonne kilometres) to technical outputs like train-kilometres, number of lanes or number of flights. If supply outpaces demand, a high level of productive output may be accompanied by low economic efficiency. The most important issue is occupancy rates since they determine whether economic outputs can be directly compared to technical inputs like labour and capital.
- Productivity examines the simplest output-to-input ratio for an activity and is based on conventional economic assessments. Train-kilometres or seat-kilometres are two possible outputs. The basis for analysis can be the quantity of capital or labour which can be measured to various level of complexity. Analysis further calculates basic or extremely complicated indicators like production boundaries.

- Operational efficiency includes several aspects regarding usage of the infrastructure at both structure or network level influencing users and the society. Availability, punctuality, accuracy or traffic safety are some of the indicators used to define and analyse operational efficiency (ITF, 2019).

The major goal of maintenance planning is to specify the service standards and performance benchmarks that must be met before analysing the various maintenance options to determine the optimal based on the defined KPIs. A maintenance plan is developed to specify the operational strategy, methodology, and recommended work procedures required to ensure the necessary levels of service.

The methodology presented here is based on the TU1406 COST Action project (Strauss, et al., 2016) , (Hajdin et al., 2018), (Pakrashi, et al., 2019) and (Stipanovic, et al., 2017), which served as a guideline for the chosen approach, both in terms of content and concept.

KPIs present a direct connection to a performance goal. KPIs are determined from a number of performance indicators (PIs), while PIs are collected at an operational level through visual inspections, on-site or laboratory tests, structural health monitoring etc. The collection of PIs should be in line with the KPIs and with pre-defined procedures for the performance analysis of the structure. Every value of the PI chosen for a particular project is significant because it can be utilized to optimize the analytical evaluation and suggested technological solutions. The definition of PIs can greatly enhance construction and maintenance tasks. There can be distinct PIs that lower investment costs, enhance health and safety on construction sites, boost productivity and improve resource efficiency.

In the ASHVIN project four main KPIs are defined already in the proposal stage, productivity, resource efficiency, health and safety and cost. This deliverable analyses different PIs which will be used to determine the four main ASHVIN KPIs for validation and adjustment of scenarios in the maintenance phase of structure's life span. Figure 4 shows some proposed PIs as sub-criteria for KPIs.

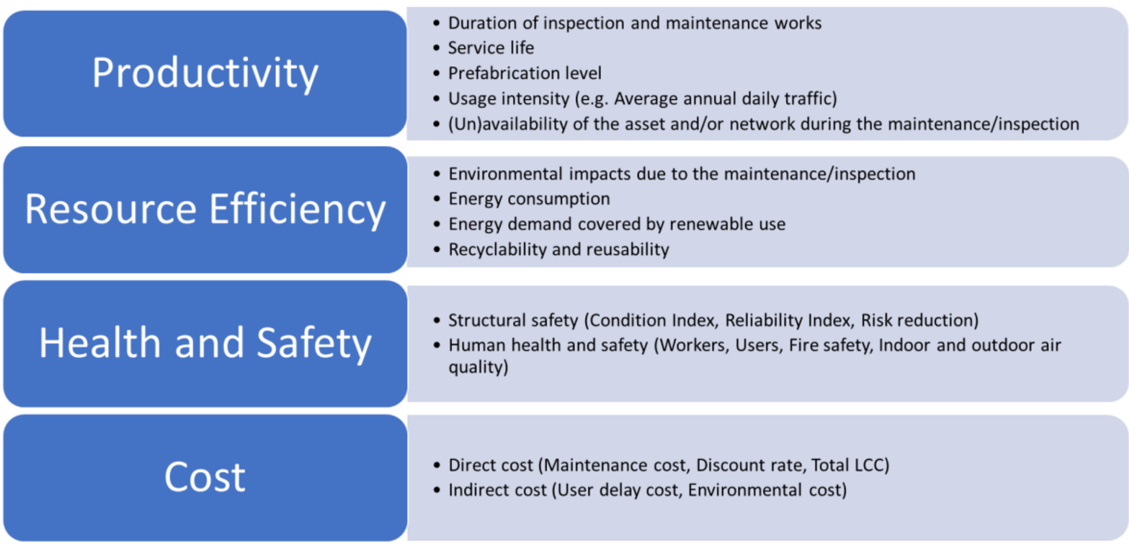

Figure 4 Key Performance Indicators (KPIs) for maintenance

3 KEY PERFORMANCE INDICATORS AND DATA

Decisions on when to conduct a condition assessment, under what conditions to apply maintenance action, and which maintenance technique to use are all part of the maintenance plans. The parameters of the inspection policy, the maintenance threshold of deterioration level, and the expense and results of maintenance procedures all play a role in these choices. The maintenance strategy optimization is built sequentially, with the goal of minimizing lifetime maintenance costs, while ensuring structural and user safety and minimizing the impacts on the end-users and environment. Four Key Performance Indicators proposed in ASHVIN project, productivity, resource efficiency, health and safety and cost, will be used to develop risk based maintenance strategy.

To design a measurement system that is as comprehensive as feasible, a mix of the quantitative and qualitative approaches needs to be used (Stenström et al., 2012). The qualitative assessment is occasionally the only method utilized to assess the state of an asset when there is no sufficient data or when the integrity is in dispute. Alternately, where data is available, quantitative approach is always preferred since it is traceable and repeatable. In the following chapters for each KPI a list of associated performance indicators is proposed. These indicators are derived, calculated, or directly collected from project-related data, generic data, measurable data, or from expert judgement.

3.1 Productivity

A major issue that the construction industry is facing, regarding its productivity, is the lack of space for standardization and mass manufacturing. A large portion of the work being done revolves around the delivery of unique items that must be made at the area where the products must be used. It is even more pronounced during the maintenance works, as these activities are taking place on already built structures and all maintenance processes need to be adjusted to the existing conditions. The PIs proposed here are focusing on measuring productivity during operational and maintenance stage of structures, and to compare influence of different maintenance strategies or activities during its application on the users, environment, network, and other areas of impact.

3.1.1 Duration of inspection and maintenance works

Duration of inspection and maintenance activities have an impact on the performance of the asset. It is important to identify the time spent on the inspection works which requires closing parts of the asset or influences the usage of the asset (e.g. closed lane and limited speed during the inspection will cause traffic jams) and the time required for execution of maintenance works which influence availability of the asset and/or the network. Systematic and comprehensive maintenance planning with very clear objectives, set priorities and the order of the necessary tasks and resources can significantly decrease the duration of works and the impact on the availability of the asset.

<u>Data collection</u>

Data about duration of activities can be collected from previously performed similar maintenance works and from construction organization experts. Certain maintenance activities are divided into sub activities and defined in detailed dynamic plans with time overlapping where possible for efficient execution of works. Duration of inspection and maintenance work is an indicator for which unit of time such as hours or days is used. The data may be collected from monitoring systems, i.e. tracking construction machines, from cameras or Unmanned Aerial Vehicles UAVs, or from the infrastructure management systems where the time of restrictions or special regulations are recorded, see Figure 5. These data are used as input parameter into the RISA model, for the calculation of user delay costs, see paragraph 3.4.

Figure 5 Process flow for collection of PIs for duration of inspection and maintenance works

3.1.2 Service life

European cities are managing the problem of ageing infrastructure, so maintenance of different types of structures during their whole life has grown increasingly important over past decades. The expected service life for major structures has increased from 50 to 100 or even 120 years as a result of new materials and technological solutions. Research on the durability of the structures, elements and materials has grown in scope, covering a range of topics that include design, systems and technologies, construction methods, maintenance, repairs, and upgrades. Making the necessary decisions depends on having complete awareness of the situation as it is today and any potential degradation mechanisms which will lead to decreased performance in the future. Depending on the type of infrastructure and constituent materials there are main recurring issues that can be addressed with appropriate repair and retrofit solutions. There is no unique solution that fits all approaches for assisting owners and operators during the whole lifecycle of their assets, but rather a combination of solutions and the appropriate timing of interventions.

This information is needed to develop a life cycle model for a certain structure and plan type of maintenance activity in the future and at the point in time when it is performed. Different maintenance options have different service life, see Figure 6. If a maintenance option needs replacement sooner than another option, its productivity is lower. Service life of a certain maintenance solution is generally measured in years.

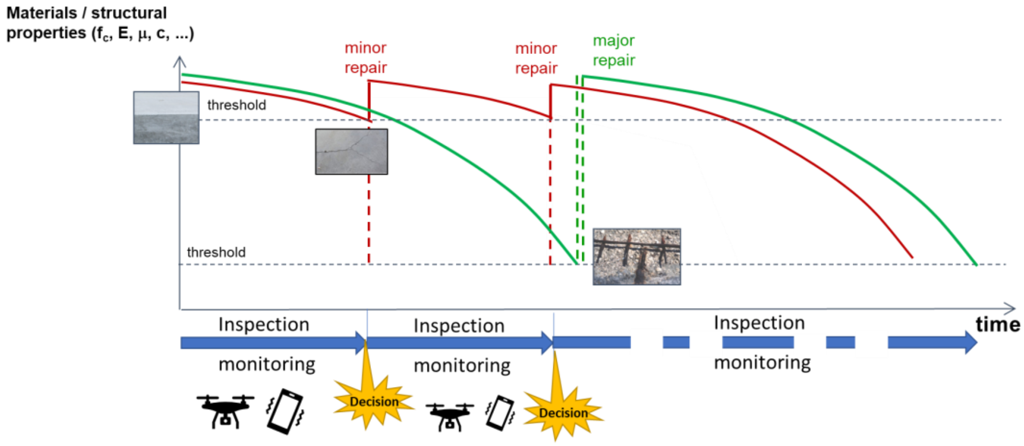

Figure 6 Comparison of service life of different maintenance solutions

Data collection

Service life prediction is performed based on the collected necessary laboratory and field data for the development of different whole life cycle scenarios. Condition assessment and SHM data serves to build component performance curves, manage and integrate data and information related to service life prediction and finally asset management. Different degradation mechanisms may occur and it is important that the actual ones are recognized and understood to decide which data should be collected (e.g. humidity, corrosion rate, crack propagation parameters, etc.). Based on the collected data, it is possible to calculate the time-varying performance properties, and the estimate the expected service life until a relevant limit state is reached.

Table 1 Overview of relevant data related to service life (Stipanovic et al., 2017)

Damage category	Type of damage	Main performance indicators	Example
0	No damage		
I	Smaller defects resulted from the construction process	– Surface imperfections – Small cracks (shrinkage cracking)	
II	Smaller defects resulted from the exploitation	– Surface cracks – Delamination of surface cement paste film – Evaporation of $Ca(OH)2$	 
III	Defects that in long term decrease durability of the structure. Repair is needed.	– Network of cracks in concrete cover – Contamination of concrete cover (chloride, pH) – Concrete loss due to frost and de-icing salts damage	 
IV	Defects that can, in the foreseeable future, decrease the reliability of the structure. Repair is needed now.	– Delamination, spalling of concrete cover (partially) – Honeycombs in concrete – Corrosion of steel visible – Loss of steel cross section due to corrosion	 
V	Defects that present a serious danger for safety of the structure. Intervention is needed emergently, and if necessary limitation or shutdown of traffic.	– Delamination and spalling of concrete cover(full) – Advanced corrosion of steel, – Significant loss of steel cross section	

In Table 1 the overview of typical damages occurring before and after maintenance works on concrete structures is presented with the relevant data that may be collected to evaluate the damage level and remaining service life. Extensive database of PIs for bridges and infrastructure has been established within COST TU 1406 project (https://eurostruct.org/file-repository/).

Most of the relevant data described in Table 1 can be determined by using UAVs, scanners or thermal cameras, which can be then integrated into the GISI tool, which is a tool for implementing geolocated and classified damages or any irregularities into digital twin model of the structure.

3.1.3 Prefabrication level

The literature overview shows that measuring the level of prefabrication adoption is largely inconclusive in terms of definitions, approaches, and results. The measurements can be perceived from two generic categories: quantitative and qualitative (Lu et al., 2018). Quantitative assessments might provide a clear, index-style picture of how much of a building is prefabricated. It may also serve as an independent variable to generate the quantitative relationships between other construction-related variables, such as the amount of energy that may be saved when prefabrication is used to a given degree (Hong et al., 2016). However, in some circumstances, employing the value or volume associated with prefabrication alone as the only measurement could be problematic. This is due to the possibility of using completely different prefabricated elements (e.g. inventory and in-build elements) in assessment for a certain project based only on their prefabrication rate. Generally for assessing the prefabrication level, the qualitative approach: "degree of product readiness when delivered to the site", is preferable.

Gibb (2001), for example, proposed a five-level taxonomy of prefabrication adoption:

- Level 0 - a project does not use any form of prefabrication at all, e.g. fully cast-in-situ;
- Level 1 - Component and sub-assembly (e.g. lintels);
- Level 2 - Non-volumetric assembly (e.g. 2-dimensional precast concrete wall panels, precast components with no usage space enclosed);
- Level 3 – Volumetric assembly (e.g. volumetric bathrooms, kitchens with usable space enclosed);
- Level 4 - Modular building (e.g. 3-dimensional modules which form the fabric of the building structure).

Factors influencing the categorisation of pre-assembly are shown in Figure 7 (Gibb, 2001). Gibb (2001) preferred term pre-assembly, which literally means ' to assemble-before', to the term prefabrication. Pre-assembly covers the manufacture and assembly (usually off-site) of buildings or parts of buildings or structures earlier than they would traditionally be constructed on site, and their subsequent installation into their final position.

Steinhardt et al. (2014) introduced a similar six-level taxonomy where Levels 0 to 5 represent none, prefabricated trusses and beams, prefabricated structural panels, specialized pods, modules, and fully completed houses delivered to site respectively.

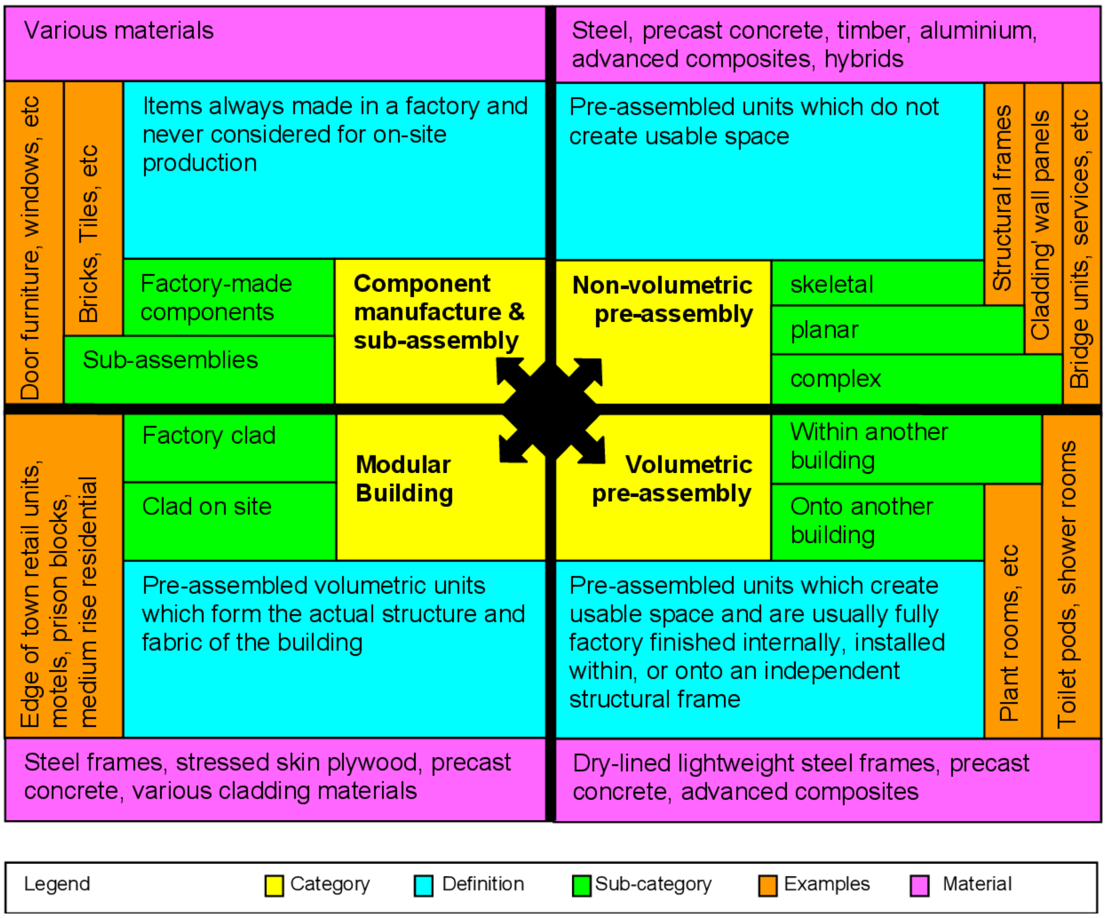

Figure 7 Categorisation of pre-assembly (Gibb, 2001)

Data collection

The levels of prefabrication or pre-assembly can be determined from the proposed maintenance scenario (repair or strengthening interventions) and used for the evaluation of the prefabrication level, as PI for the productivity assessment. Depending on the available data, type of asset or type of maintenance activity qualitative approach (e.g. level 0-4)) or quantitative approach with a more defined metrics (e.g. percentage of prefabricated elements in m', m^2, m^3 or unit) can be used.

3.1.4 Usage intensity

For transport infrastructure the average annual daily traffic (AADT) is often used to describe traffic volume characteristics of a roadway in a planning context. AADTs is an information available from continuous count stations or from road operators and stakeholders. The FHWA (FHWA, 2013) formula for estimating AADT from a long-term or whole-year traffic count is:

$$AADT = \frac{1}{7}\sum_{i=1}^{7}\left[\frac{1}{12}\sum_{j=1}^{12}\left(\frac{1}{n}\sum_{k=1}^{n} VOL_{ijk}\right)\right]$$

where

AADT - average annual daily traffic

VOL - daily traffic for day k, of day of the week i, and month j

i - day of the week

j - month of the year

k - the occurrence order number of the day of the week

n - the number of days of that day of the week during that month.

Data collection

Most often average daily traffic intensity is taken into analysis per user group, freight, commute, leisure etc. This PI can be collected from traffic monitoring stations and directly implemented into the ASHVIN platform. Similar PI related to the usage intensity for other types of infrastructure or buildings can be used, e.g. for airports # of flights per day and # of passengers, for buildings # of occupants etc.

3.1.5 (Un)availability of the asset and/or network during the maintenance / inspection works

The unavailability of an asset due to maintenance/inspection work should be distinguished between different types of assets, for transportation infrastructure and buildings, residential or industrial.

Residential and industrial buildings

The unavailability of a building due to maintenance can be measured by tracking the downtime of the building during the maintenance period. Here are some steps to measure the unavailability of an asset building due to maintenance:

- Define the maintenance period: Determine the start and end date of the maintenance period, which will help identify the timeframe for tracking downtime.
- Measure downtime: Track the total time the building is unavailable due to maintenance. Downtime can be measured by monitoring the length of time the asset building is not available for use or when it is operating at a reduced capacity.
- Identify the cause of downtime: Identify the root cause of downtime, which could be due to a maintenance issue, inspection, repairs, or upgrades.
- Calculate the unavailability rate: Calculate the unavailability rate by dividing the total downtime by the total time the building is expected to be available during the maintenance period. Multiply the result by 100 to get the percentage of unavailability.

Measuring the unavailability of an asset building due to maintenance can help identify opportunities to improve maintenance practices and reduce downtime. By tracking downtime, stakeholders can make informed decisions and prioritize maintenance work more effectively to minimize disruptions to the building's performance.

Transport infrastructure

Transport modelling is used to simulate transport disruption following an infrastructure failure (total or partial closure) due to performance of maintenance activities. It involves computing the number of trips, selecting the mode for travel and assigning traffic to the network. For freight transport, also production and consumption locations are modelled, as well as trade patterns and resulting logistic processes.

Delay times for transport users are computed due to maintenance activities (e.g. bridge, tunnel, slope) along the network. Such disruptions influence the functioning of the transport network. Transport modelling can be used to evaluate the impact of these disruptions, whereby the disruption is modelled as a reduction in capacity of one or more links, nodes or services along the network, for a certain time extent. The capacity may fluctuate over time until the problem is fully resolved (Tuin&Pel, 2019).

Unavailability of a certain asset in a transport network or a downtime, can be seen as the period of time that the road/railway/airport is unable to carry out its function, usually causing congestions and detours for users. Depending on the type of maintenance activities performed on a structure or a part of it, different traffic regulations can be applied to a network. Either total road closure (detour for users) or partial closure (closure of the lanes) causing longer travel time for users. In the case of a highway either transport modelling or more simplified calculations of detour length/time, decreased speed etc. per different types of users can be used as an input for analysis of other performance indicators such as the cost of the downtime. Cost of the downtime is the product of the time that the road is unavailable multiplied by the penalty which can be seen either as the agencies cost or the user cost due to not being able to use the road (Henseler, 2017). This PI is explained in paragraph 3.4.2.

Performance indicator unavailability of the transport infrastructure asset (e.g. closure of the lanes) can be expressed as a percentage of the asset which is unavailable for the usage or length (m, km) and number of lanes (#lanes) that closed during the maintenance activities. Indicator can also be used for buildings where a percentage of the building is taken into account as unavailable and then combined with the type and number of users of the building.

Availability of an asset or a structure is seen as the ability to perform its function in its full capacity during a certain period of time (ITF, 2019; Medeiros, 2008). For example, the availability of a road network can be taken in calculations as the percentage of the network that is available in full capacity per year. Some owners of the infrastructure network have defined their performance goal related to the availability, namely that the network has to be available in its full capacity 95% of the time (Stipanovic et al. 2016, RWS 2012).

Availability can be used as a performance requirement that corresponds to a functional requirement of the system. This availability requirement could be formulated to describe the performance requirement of the overall system (e.g. the main function needs to be available a certain percentage of time) or could be formulated for sub-systems (e.g. the roadway lighting needs to be available a certain percentage of time).

To calculate the availability percentage of a system, CENELEC (1999) gives the following formula. In this formula the availability percentage is calculated, but the availability performance of the system is expressed in the unavailability percentage of the system over a period of time.

$Planned\ unavailability = (1 - A_m)$ where A_m refers to maintenance

$Unplanned\ unavailability = (1 - A_r)$ where A_r refers to repair

$$A = Availability = 1 - [(1 - A_m) + (1 - A_r)]$$

Or

$$A = \frac{Mean\ Up\ Time}{(Mean\ Up\ Time + Mean\ Down\ Time)}; 0 \leq A \leq 1$$

Availability (A) can be used to calculate the resulting down time (d(T)) of the total mission time (expressed in T, e.g. 1 day of 1 year).

$$d(T) = (1 - A) * T$$

Data collection

Valuable data about buildings include the following information's: type of building, residential or industrial, number of occupants, type of occupants, period of time during the day when building is used (e.g. for industrial buildings during day) and similar.

Data about the unavailability of the asset for transport infrastructure can be collected from monitoring systems, i.e. from cameras, traffic management systems where the time of restrictions or special regulations are recorded, etc.

These data are used as input parameter into the RISA model, for the calculation of availability, unavailability and user delay costs, see paragraph 3.4.

3.2 Resource efficiency

The construction sector is the largest producer of waste, and a major consumer of natural resources. In the European Union (EU), the construction industry consumes about 50% of all materials and, in terms of volume, generates the greatest waste stream (35%) (Eurostat, 2022). Most of the resource consumption has been linear, with materials eventually being disposed away as waste. The approach has negative consequences causing amongst other higher carbon emissions and widespread environmental pollution. Given that glass, concrete, steel, and aluminium (or other metals) make up the majority of construction waste, the embodied energy and equivalent CO2 emissions in construction and demolition waste are very large.

3.2.1 Environmental impacts due to the maintenance and inspection works

3.2.1.1 Environmental impacts from maintenance works

During the maintenance works construction materials and components are being repaired and/or replaced. Due to the usage of new raw materials and machines to perform the works, those activities are creating environmental impacts, which can be evaluated using Life Cycle Assessment (LCA) models. The models are creating different performance indicators which can be used for the comparison of different maintenance solutions.

The determination of environmental impacts due to maintenance activity is based on two aspects. First, the environmental effect per impact category (EEi) based on material type can be determined using LCA models (Thinkstep, 2015). Second, the material quantity per kg produced for the maintenance activity is estimated (Mqj).

The example of environmental impacts per kg of construction material for impact category are given in Table 2. The environmental effect categories are based on the widely applied methodology which has been implemented in different software solutions allowing the estimation of the relevant environmental indicators. The impacts presented in Table 2 have been determined with the help of the LCA software GaBi or other literature sources. For the analysis, the quantity of all materials used for a certain maintenance activity needs to be calculated (e.g., quantity of concrete, steel, asphalt etc.). Quantity of a certain material should be then multiplied by the environmental impact per 1 kg, given in Table 2. This has to be performed for all materials used for a certain activity resulting in environmental impacts of a certain activity per impact categories.

Table 2 Environmental effect categories (TNO_MEP, 2004)

	Material								
	Steel	Concrete	Polyester	Glass fiber	Epoxy	Carbon fiber	Asphalt	Gravel	PVC
Impact category									
Abiotic depletion elements (ADP)	−4.93E-06	1.88E-07	4.47E-06	9.15E-05	3.26E-05	0.00E+00	5.96E-09	4.52E-10	1.71E-0
Abiotic depletion fossil (ADP)	6.54E-03	1.80E-04	3.66E-02	1.22E-02	5.79E-02	0.00E+00	9.00E-04	1.38E-05	3.07E-0
Global warming potential (GWP)	1.24E+00	1.21E-01	3.05E+00	1.97E+00	8.25E+00	0.00E+00	5.00E-02	2.28E-03	2.87E+
Ozone depletion potential (ODP)	1.11E-08	1.26E-12	8.42E-11	9.66E-11	0.00E+00	0.00E+00	2.80E-08	6.74E-13	0.00E+
Photochemical ozone formation potential (POCP)	5.49E-04	2.33E-05	1.66E-03	−1.69E-03	2.27E-03	0.00E+00	7.10E-05	1.53E-06	1.56E-0
Acidification potential (AP)	3.54E-03	1.83E-04	5.24E-03	1.10E-02	2.13E-02	0.00E+00	2.70E-04	1.47E-05	1.98E-0
Eutrofication potential (EP)	2.80E-04	2.57E-05	6.41E-04	1.38E-03	4.22E-03	0.00E+00	3.40E-05	2.42E-06	1.46E-0
Human toxicity potential (HTP)	2.01E-01	2.40E-02	1.07E-01	4.69E-02	4.87E-01	0.00E+00	3.80E-03	1.49E-04	6.29E+
Freshwater aquatic ecotoxicity potential (FAETP)	1.13E-02	1.54E-04	1.88E-02	2.32E-03	4.31E-03	0.00E+00	9.40E-04	1.23E-05	1.15E+
Marine aquatic ecotoxicity potential (MAETP)	3.05E+02	3.35E+00	1.11E+02	1.17E+02	3.05E+02	0.00E+00	1.50E+00	2.56E-01	2.04E+
Terrestic ecotoxicity potential (TETP)	4.92E-03	2.72E-04	1.82E-03	1.56E-03	1.08E-02	0.00E+00	4.90E-05	3.51E-05	9.51E-0
Source:	GaBI	GaBI	GaBI	GaBI	GaBI	no data	(VWB Asfalt)	GaBI	GaBI

Heavy construction equipment machinery is the primary source of Greenhouse gas (GHG), exhaust emissions, and air pollutions during construction works. Measuring performance of construction machinery through performance indicators lead to mission reduction strategies, improving equipment maintenance and operations. Due to a lack of measuring and monitoring data, it is difficult to quantify the precise amount of emissions. Fan (2017) discusses the factors affecting construction equipment emissions and propose to apply analytical approach to quantify the degree of impact from these emission factors, so that actions can be taken based on their priority in emission reductions and cost effectiveness. Overall, the factors affecting the construction equipment emissions can be categorized into four groups as seen in Figure 8.

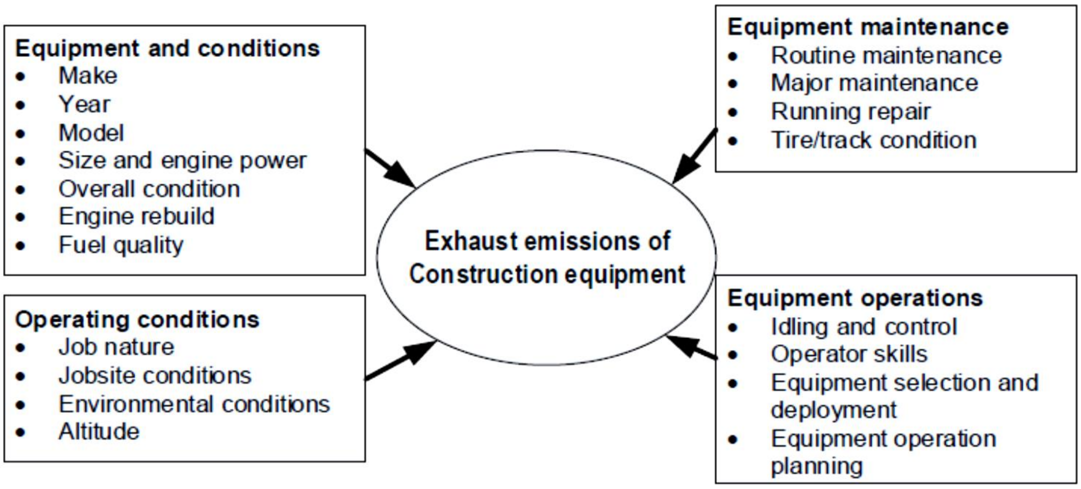

Figure 8 Factors of impact on construction equipment exhaust emissions (Fan, 2017)

The US Environmental Protection Agency (2010) published the NONROAD2008a, emission model for estimating emissions from non-road construction equipment. The emission factor is defined as the quantity of pollutants emitted by that particular type of equipment during a unit of service. The emission factor can be estimated as below:

i) For HC, CO, NOx, the exhaust emission factor for a given diesel equipment type in a given model year/age is calculated using:

$$EF_{adj(HC,CO,NO_x)} = EF_{ss}xTAFxDF$$

EF_{adj} - Final emission factor for HC, CO, NOx after adjustment (g/hp-hr) ['hp' is horsepower]

EF_{ss} – Zero-state, steady-state emission factor (g/hp-hr) – function of model year and horsepower category (technology type)

TAF – Transient adjustment factors (unitless) – vary by equipment types, accounting for the difference between the steady-state and the transient state of the engine.

DF – Deterioration factor (unitless), related to technology type and age of engine.

ii) The particulate matter (PM) particles emitted from diesel engines are assumed to be smaller than 10 microns (PM10), among which 97% are smaller than 2.5 microns (PM2.5). PM emissions are dependent on the sulphur content of the fuel that the engine is burning and can be estimated by using an equation that is slightly modified from the one presented above:

$$EF_{adj(PM)} = EF_{ss}xTAFxDFxS_{PMadj}$$

EF_{adj} – Final emission factor of HC, CO, NOx after adjustment (g/hp-hr)

S_{PMadj} – adjustment to PM emission factor to account for variations in fuel sulphur content (g/hp-hr)

<u>Data collection</u>

Required data about the quantities of materials and machines can be collected from the bill of quantities from maintenance design project. The information about the construction machines trajectories (actual travel distance and duration of works) can be collected from GPS tracking devices, which can be visualized in the ASHVIN platform.

3.2.1.2 Environmental impacts due to the congestions caused by maintenance works

These impacts are primarily determined for the maintenance activities performed on transport infrastructure networks.

Alternative choices available regarding maintenance options for existing assets can have a very different impact on the users of the asset. An example is the choice between i) a less invasive maintenance treatment with less user disruption but leading to future interventions that are more frequent or ii) more invasive maintenance treatment procedure, such as renewal, which is very disruptive to users at the time of execution. The unavailability of the asset which is causing congestions or detours will cause an increase of the pollution due to the longer trips of the vehicles. The environmental impacts can be determined from changes in the levels of emissions from vehicles due to changes in speed and/or distance travelled. Depending on the type of traffic management required for carrying out the maintenance, vehicles, either trains or cars, busses etc, on the route may experience delays for the duration of the works. The impact on traffic can be determined from traffic models or by a simple traffic analysis. The change in fuel consumption is the source of changes in CO2 mainly due to changes in the average speed for the duration of traffic management. For the calculation of CO2 emissions related to delays caused by different interventions / traffic regulations additional km travelled are calculated for different types of traffic users (road/rail, freight/passenger). CO2 emission is expressed as quantity of CO2 per km per vehicle (ECTA, 2011; Barth& Boriboonsomsin, 2008; McKinnon&Piecyk, 2011).

User delay costs due to the works are presented in Chapter 3.4.2. The cost associated with emissions is calculated based on changes to emissions and standard costs of carbon (Barrett&Ramdas, 2018), explained in 3.4.4.

Data collection

This PI can be collected from traffic monitoring stations and directly implemented into the ASHVIN platform. The impacts can be then calculated based on the predefined environmental impact categories and unit impacts.

3.2.2 Energy consumption (before and after maintenance)

Primary energy consumption is the amount of the energy needed to meet the demand for heating, air-conditioning and mechanical ventilation, and to produce domestic hot water for its occupants. There are numerous measures, structural and non-structural, which can improve energy efficiency of a building. Replacing doors and windows to prevent energy loss to prevent heat escaping through cracks and gaps or a simple solution of bordering a frame with weatherstripping can create a barrier between indoor and outdoor temperatures. Enhanced building maintenance for increasing the energy efficiency of buildings can be achieved with the insulation of the exterior walls of the building. Energy consumption is assessed before and after the implemented maintenance measures and the result is expressed as a gain in kWh/(m^2year).

3.2.3 Energy demand covered by renewable use (before and after maintenance)

Implementing solutions for transition from non-renewable energy sources like oil, natural gas, and coal to renewable energy can be expressed in the range from 0 to 100%. Energy demand covered by renewables (PVs, solar thermal, biomass, mini-eolica, geothermal, biomass, heat pumps, etc) is calculated as a percentage of the total energy used by a household/building.

Data collection

Based on the initial maintenance design project the energy performance assessment should be done and compared with the actual as-built state using measurement data such as temperature and humidity, measured indoor and outdoor. These can be then visualized in the ASHVIN platform.

3.2.4 Recyclability and reusability of the maintenance solution

In the maintenance and repair processes deconstruction is the process of methodically dismantling structures to recover parts for recycling and reuse. Deconstruction can be used in various ways to recover useable materials and drastically reduce deconstruction waste. Different maintenance solutions are assessed from two aspects:

i. How much of recycling and reuse of the existing structure is applied in the using maintenance design solution;
ii. What is the whole life cycle impact of the maintenance solution, namely future recyclability and reusability of the actual maintenance solution that is being implemented.

There are three key requirements that must be satisfied for any recycling to be successful. It must be cost effective, be environmentally responsible, and perform well. Recyclability can be included in the design through material selection and modularity. There are facilities for recycling some materials more easily than others and putting them back into use. Steel for example is highly recyclable and is frequently recycled several times. Asphalt pavements are usually recycled. Reclaimed Asphalt Pavement (RAP) is the term used for removed and/or reprocessed pavement materials containing asphalt and aggregates, and generated when asphalt pavements are removed for reconstruction, resurfacing, or to obtain access to buried utilities[1]. When properly crushed and screened, RAP consists of high-quality, well-graded aggregates coated by asphalt cement. Although the majority of old asphalt pavements are recycled at central processing plants, asphalt pavements may be pulverized in place and incorporated into granular or stabilized base courses using a self-propelled pulverizing machine. Hot in-place and cold in-place recycling processes have evolved into continuous train operations that include partial depth removal of the pavement surface, mixing the reclaimed material with beneficiating additives (such as virgin aggregate, binder, and/or softening or rejuvenating agents to improve binder properties), and placing and compacting the resultant mix in a single pass.

[1] https://www.fhwa.dot.gov/pavement/recycling/rap/

The majority of the RAP that is produced is recycled and used, although not always in the same year that it is produced. Recycled RAP is almost always returned back into the roadway structure in some form, usually incorporated into asphalt paving by means of hot or cold recycling, but it is also sometimes used as an aggregate in base or subbase construction.

In the US around 80 to 85 percent of the excess asphalt concrete presently generated, is reportedly being used either as a portion of recycled hot mix asphalt, in cold mixes, or as aggregate in granular or stabilized base materials (FHWA, 1997).

Concrete can be 100% recycled after demolition. Recycling concrete from construction and demolition waste, C&DW, offers two main benefits: it reduces our dependence on primary raw materials and reduces the amount of waste sent to landfill. There are two main ways in which recycled concrete is reused: as a recycled aggregate in new concrete and as a recycled aggregate in unbound applications such as road construction and earthworks. The aim of the future developments is to increase the reusage of elements as a whole, which will also decrease the usage of energy and environmental impacts during the recycling processes.

The indicator for recyclability/reusability of certain construction material / element can range from 0 to 100% and is expressed as follows:

- % of the materials and components which can be recycled,
- % of the materials and components which can be reused.

Data collection

Data can be retrieved from the maintenance plan and implemented into a BIM or a digital twin model with the additional layer of information, which would describe the recyclability/reusability of certain material and element.

3.3 Health and Safety

Within this KPI two main aspects are observed, first one from the structural safety perspective and second one from the human safety perspective, either workers during the maintenance works, or users of the asset during the operation and maintenance phases.

3.3.1 Structural safety

Safety aspects for existing structures are provided in national and international standards and recommendations (Diamantidis & Bazzurro, 2007), including the guidelines of the American Concrete Institute (ACI, 2003), the recommendations by the Joint Committee on Structural Safety (JCSS, 2001), as well as the Swiss note SIA (1994). Required structural performance is usually related to the goals of structural safety and serviceability and, expressed as a target reliability, evaluated on the component or the system level. Indicators relating to structural performance in the context of safety, serviceability and durability often come with explicit definitions in relevant standards and codes of practice (Dette & Sigrist, 2011). However, a large disparity is noted within Europe regarding the way performance indicators are quantified with respect to the specification of goals. Several European projects have been working on the harmonization of standards and procedures for monitoring, maintenance and safety of transport infrastructure (see IM-SAFE, COST TU 1406, COST TU 1402).

In order to determine structural safety of the existing structures, the first step is to assess their actual condition. For that purpose, usually three levels of inspections are defined in order to assess the condition of existing structures ,as seen in detail in Figure 9:

- Preliminary investigation – collection of existing documentation;
- Regular visual inspection – performed by owner or by external experts, recording and classifying damages;
- Main inspection – performed by qualified experts from certified professional institutions, which includes detailed inspection with in-situ and laboratory tests, usually carried out when required.

Data gathered during a condition survey should therefore capture any changes related to the system's overall reliability, which is the crucial parameter for systems in use under challenging environmental conditions for lengthy periods of time. This suggests that the condition of a system under inspection should therefore be connected to the change in the system's or its components' reliability. Predicting changes of reliability through time can be used to inform planned maintenance and repair for a specific system. These methods offer maintenance managers a useful tool to cut down on maintenance expenses and increase asset value. The applicable standards and codes of practice across different countries frequently include clear definitions for indicators relating to structural performance in the context of safety, serviceability, and durability (Stipanovic et al. 2017, Strauss et al. 2016).

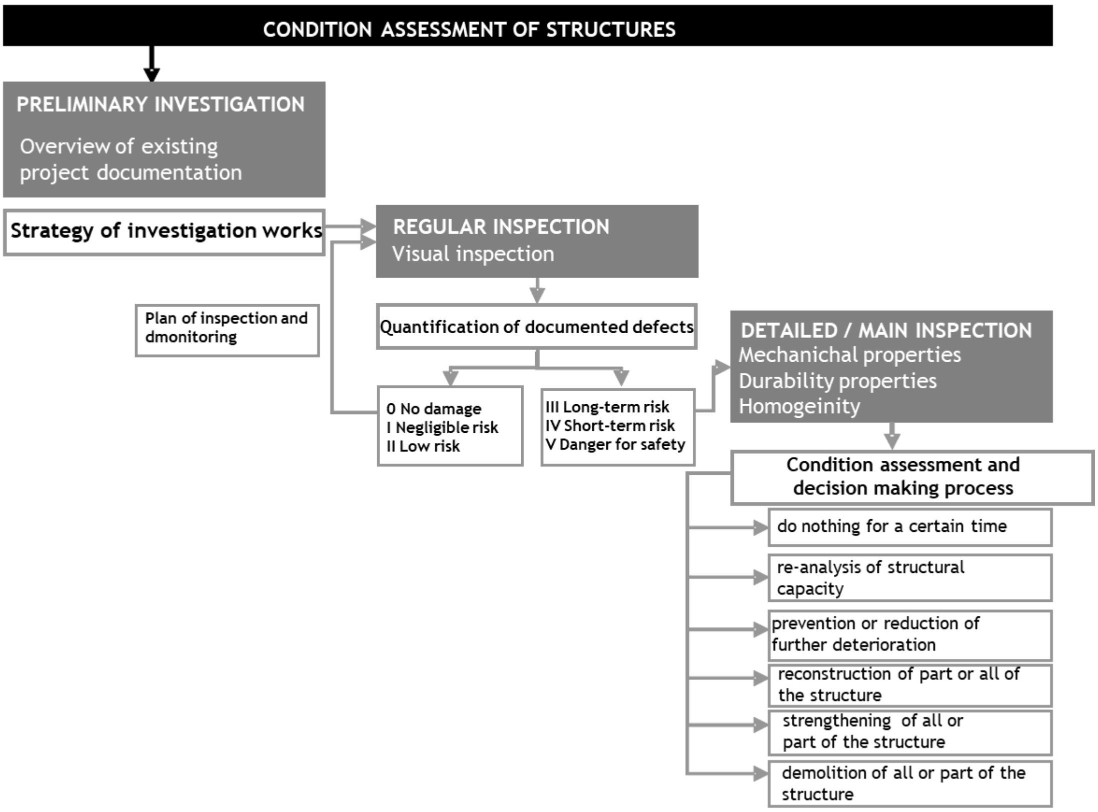

Figure 9 Condition Assessment procedure (Skaric Palic et al., 2012)

3.3.1.1 Condition Index

Condition rating is used in order to evaluate the structure's current condition compared to its condition at the time of construction. The condition is most often assessed by means of a visual inspection. Based on the results of visual inspection additional tests are performed and/or structural health monitoring (SHM) systems designed in order to collect data regularly over time.

Condition assessment methods differentiate from element to the structure/system level. Usual condition assessment is performed on the element level and then integrated and/or recalculated into structural level assessment. For example about bridges, element-level condition values must be aggregated to a single system-level condition value, namely the Bridge Condition Index (BCI). Practically there are numerous ways, varying by country and agency, to compute the BCI, aggregated from the element-level to the system-level, using worst element score, weighted average method, ratio scale (ATKINS, 2002; Chase, S. et al. 2016). These system level performance indicators may be then used for the prioritisation in the maintenance decision making process at the network level (Bukhsh et al., 2019).

Calculation of condition index takes into account different damages per type of structure and different coefficients that allow various attributes, such as importance of an element in the structure or importance of a structure in the whole network, taken into consideration. There are lists of typical damages for different type of structure or material which are available for practitioners involved in condition assessment of structures. Degradation of the structure is occurring with time (i.e., strength loss is occurring due to corrosion as well as fatigue damage accumulation) and, if a particular failure occurs, the specific consequences that may result are taken into consideration and used for risk assessment. More details can be found in Bigaj-van Vliet et al. (2022).

The condition survey as a part of condition control, which also involves condition assessment and condition evaluation, is one of the basic elements for the through-life management of structures. The results of the condition survey can help to obtain a guess or estimation of the reliability index view using performance indicators (PIs), see for instance the quality control plan concept of COST TU1406 WG3 (Hajdin, et al., 2018) and IM-SAFE project reports Appraisal of methods for safety evaluation and risk management (Bigaj-van Vliet et al., 2022) and Guidelines for data acquisition, processing, and quality assurance (Rodriguez, A.S., 2022).

In Table 3 is given as an example the Bridge Condition ratings in different countries.

Table 3: Bridge condition rating in different countries (Skaric Palic et al., 2012)

Different bridge condition rating in different countries									
Austria		**Croatia**		**Slovenia**		**Norway**		**France**	
Grade	***Condition***	***Class***	***Condition***	***Class***	***Condition***	***Class***	***Condition***	***Class***	***Condition***
1	Very good	0	No damage	5	Very good	1	Small damage	1	Good overall state
2	Good	I	Smaller defects from construction period.	4	Good	2	Medium damage	2	Minor structural damage. Non urgent maintenance needed
3	Satisfactory	II	Smaller defects from exploitation period.	3	Satisfactory	3	Large damage	2E	Minor structural damage. Urgent maintenance needed.
4	Faulty	III	Defects that in long term decrease durability	2	Bad	4	Critical damage	3	Structure deterioration. Non urgent maintenance needed
5	Bad	IV	Defects that in foreseeable future can decrease reliability	1	Critical	Defects are categorized by using the following system of letters and numbers and combined with the above classes: M=Environment, B=Load capacity, T=Traffic safety, V=Maintenance cost.		3U	Serious structure deterioration. Urgent maintenance needed.
		V	Defects that present serious danger to safety of traffic						
No clear correlation between component (element) condition rating and object (structure as a whole) condition rating.		Structure level condition is not determined from the above classes but from the influence of each elements functionality on traffic safety, mechanical resistivity, stability, durability and general condition of element. Structural level is then determined by combining maximum elements level grades.		Bridge condition is calculated as a sum of individual elements damage rating.		The element condition is related to the number of years before maintenance is needed, and the condition rating is not levelled. The structure condition is quantified by calculating a character using condition from the element condition.		For the structure level condition rating number of levels and categories are the same as for element level: 5 levels, 1, 2, 2E, 3 and 3U, and the structure level is the maximum of all element levels.	
Grades/Classes and conditions are not comparable between themselves for different countries in this table.									

3.3.1.2 Reliability Index

When evaluating the actual and long-term performance of various types of structures, the reliability-based method is used. It is based on two premises, the first of which is that the structure's performance degrades over time when subjected to environmental and structural loads. The second premise describes the concept of failure that occurs when the structure or a system can no longer support the demands and loads that it was designed for (some limit state is reached). Required structural performance is usually related to the goals of structural safety and serviceability, or expressed as a target reliability, evaluated on the component or the system level.

The selection of the critical limit states is the first step in the reliability assessment procedure. An experienced engineer performs the assessment utilizing cutting-edge analysis methods. The next step is to define the required reliability index, which is done with standardized values e.g. in EN 1990:2002 which defines serviceability and ultimate limit state (SLS and ULS). As a preliminary step, stochastic modelling of the load and resistance variables is carried out, which might be based on published probabilistic models in the literature. The reliability index for the system in issue is then determined for each limit state considered. Assessment of the structural performance (safety and serviceability) of the whole structure or of the structural elements is analysed before and after the maintenance intervention. SLS and ULS are standards for typical operational or functional use, and have defined threshold values for describing the acceptable values of structures performance.

The obtained reliability indices depend on the age of the structure and on the reference lifetime. These may be prescribed from the time of inspection t_{insp} to the end of the lifetime T, or it is further possible to define these with respect to shorter intervals, as for instance the time between inspections (Koteš and Vičan, 2012) or on a yearly basis, better indicated for the assessment of existing structures. Table 4 and Table 5 offer recommendations on target reliability indices according to different norms.

Table 4. Recommended target reliability indices for structures related to the specified reference periods at the ultimate limit state.(fib, 2013)

Ultimate Limit State	**Target β**	**Reference period**
Low consequence of failure	3.1	50 years
	4.1	1 year
Medium consequence of failure	3.8	50 years
	4.7	1 year
High consequence of failure	4.3	50 years
	5.1	1 year

Table 5. ISO 2394 Target values for the reliability index, for a design working life.

Relative Costs of Safety Measures	**Consequences of Failure**			
	small	**some**	**moderate**	**great**
High	0.0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

3.3.1.3 Risk reduction

Risk is defined as the possibility that certain hazard will happen and cause consequences. In our case we are relating the hazard to the probability of structural failure and potential consequences. Postponement of major repairs and replacements in operation and maintenance management causes increase of the value of probability of failure. The consequence of avoiding performance of certain interventions causes an increase of the risk value. Risk analysis is performed before and after the performed maintenance activity to determine the probability of failure and consequences of repair and rehabilitation decisions. Possible consequences of not performing a certain maintenance activity are direct and indirect, such as cost of structural damage (different levels of failure from decreased capacity to collapse), user delay cost, environmental impacts etc. The probability of failure is determined from in-situ collected data, SHM data, and numerical models. Steps for risk calculation are as follows:

- Identify risk (e.g. certain maintenance action),
- Define likelihood of occurrence or probability of failure,
- Define possible consequences,
- Calculate risk for all analysed alternatives before and after the performed maintenance activity,
- Compare risk levels for different alternatives.

One of the PIs related to risk-based design is for instance the robustness index, that according to Bakker, Schubert and Faber (2008) and Bakker & Klatter (2012), could be defined as:

$$I_R = \frac{R_D}{R_{ID} + R_D},$$

where R_D is the risk due to direct consequences, linked to damages in the constituents of the system for a given exposure loading event, and R_{ID} corresponds to the risk due to indirect consequences. Further risk indicators may be defined on the basis of the loading of the structure (exposure), the strength of the components of the structure (vulnerability) and the redundancy, ductility, effectiveness of condition control and maintenance (robustness) (Faber, 2009).

Data collection

Data acquisition for structural performance depends on the purpose of the data that is acquired. When the first level of data gathering is performed, then mostly visual inspections are taking place. In order to get better digital records of the actual condition and location of damages of civil engineering structures, visual inspections are performed using UAVs or LiDar scanners. Those technologies are also used to collect 3D-point cloud data and create digital twin models of existing structures. Image-processing techniques are then used for detection and classification of damages, see ASHVIN D3.1 Visual analysis for real sensing (2022). The results of data collection and analysis can be then visualised in the ASHVIN platform, using different tools, e.g. MatchFEM, DDT, GIS and RISA.

Different non-destructive techniques and monitoring sensors can be used to determine materials and structural properties, see ASHVIN D5.1 SHM digital twin requirements for residential, industrial buildings and bridges (2022) as well as the actual external loads and environmental actions. Based on the collected SHM data numerical models can be significantly improved. Consideration of monitoring data such as strain measurements, vibration and displacement (Rodriguez-González et al., 2022), water content or site testing allows a much more accurate calculation of the reliability, and will often show the infrastructure to have significantly greater capacity than previously calculated. Condition index, reliability index and risk (their increase or reduction after the maintenance intervention) are suggested PIs for calculation of structural performance as a PI for maintenance. These can be applied to all structures with data collection aimed at defining the difference in the performance before and after the maintenance intervention. Specific data depends on the type of the structure and the assessment method applied.

3.3.2 Human Health and Safety

It is hard to completely eliminate all safety dangers due to the nature of building operations and maintenance. However, by doing routine safety audits and having protocols in place to report, evaluate, and deal with potential risks, many common safety issues related to human health can be avoided. Implemented safety management procedures prepared for all high-risk construction projects before work commences highly increase the overall safety. The scope of the project is that any potential safety concerns, the risk management strategy and the procedures for safety management (e.g. responsibilities, check list, warnings, etc.) should all be covered in the Safety Management Plan (SMP). Safety management is required by law for construction activity but maintenance is often outside of these legally binding obligations. Therefore, it is important that SMP addresses maintenance activities while taking into account alternatives that can be used to safeguard both users, workers and companies involved from unnecessary risk if the main infrastructure system fails. One of the PIs can be the record of the existence of SMP for the maintenance phase.

3.3.2.1 Safety during maintenance works for workers

Due to irregular or non-routine operations, decreased barriers, leakage, pressure, electricity, etc., workforce involved in maintenance activities is exposed to hazards and experience poor ergonomics. On all types of construction sites from transportation infrastructure to buildings, especially regarding maintenance works which are taking place on structures that are in service, health and safety (H&S) for workers and users is a critical factor. There are numerous H&S indicators available in the literature and they are often required by law, but specific indicators for maintenance are scarcer (Stenströn, 2012; Carhart et al. 2016).

Performance indicators are applicable to all structures but depending on the type of works and the type of asset the safety issues for workers may vary. Maintenance activities performed on buildings are characterized by their limited environments and a preponderance of vertical construction tasks rather than horizontal ones, as in the case of roads and tunnels. The density of workers and structural elements and the complexity of the system may be higher. When maintaining transport infrastructure, especially with partial traffic closures, traffic poses a significant hazard for workers performing maintenance activities or inspectors doing the condition survey. In general, partial traffic closure can be perceived as an indicator of increased number of safety issues for both workers and users.

Three categories are frequently used to categorize accident causes: managerial problems, technological difficulties, and human factors. Human factors-related safety issues have received a lot of academic attention, and a number of studies have linked a lack of worker safety awareness to the high frequency of accidents (Meng et al., 2019). Some safety related issues in maintenance workplaces related to hazard as a source of possible safety issue and the potential harmful effects are listed in Table 6 6.

Table 6 Workplace hazards and potential harmful effects

Hazard – source of possible safety issue	Potential harmful effect
Equipment and powered hand tools	Using heavy equipment may result in strains and sprains Hand and eye injuries are the most common injuries resulting from use of powered hand tools
Electricity	Electric shock, electrocution Tripping hazards for people walking through areas where long electrical leads are in use
Work at height	Falls can result in serious injury or death
Hazardous substances	Irritation or burns to skin, dermatitis from continued use Nausea and headaches from breathing fumes
Vehicle traffic	Being struck by vehicles when working near roads, driveways, car parks
UV radiation	Where maintenance requires work out of doors, sunburn, and skin cancer present significant risks to health
Heat and cold	Fatigue, heat stress in hot and/or humid conditions. Diminished concentration can result in injuries if safety measures are forgotten
Manual handling	Musculoskeletal disorders, including sprains and strains

Data collection

Due to better implementation of safety related measures the near-miss approach is adopted in this work (Wright and Van der Shaaf, 2004). A near miss is an unplanned event that did not result in injury, illness, or damage – but had the potential to do so. For the near-miss approach to make sense there must be direct causal predictors of later, more serious, accidents. This assumption is based upon the common cause hypothesis or the assumption that near misses and accidents have the same relative causal patterns. The following historic/current data is collected and directly considered as a PI:

- # of workers accidents (fatal and non-fatal) during the maintenance works per day/week/month
- # of near misses for workers during the maintenance works per day/week/month

3.3.2.2 Safety during maintenance works for users

There are wide known safety and security measures for avoiding accidents to users around the construction sites. Maintenance works are performed most often on assets that are in use (full or partial) which sometimes makes it difficult to completely avoid adverse impacts on the surrounding environment. Access restrictions should not just be implemented to safeguard equipment against theft or damage. Security is essential both during and after work hours to safeguard pedestrians from potential construction risks. To improve pedestrian safety at busy intersections roads, motorways etc., separate entry and exit sites for heavy equipment and vehicles should be established. In the event of a safety incident or security breach, strict security and safety measures will also shield contractors from accountability and negligence.

Data collection

As for the safety of workers here also the near-miss approach is adopted. The following historic/current data is collected and used as PI:

- # of users accidents (fatal and non-fatal) during the maintenance works per day/week/month
- # of near misses for users during the maintenance works per day/week/month

3.3.2.3 Fire safety (or fire vulnerability) during maintenance

Construction sites are high risk areas for a number of reasons. One of these is undoubtedly the risk of a fire outbreak, as many construction sites contain multiple examples of the three things needed to start a fire: an ignition source, an oxygen source, and a fuel source. Fires in these settings have the potential to be extremely harmful, with consequences like material damage, construction delays, and potential life risks. Understanding some of the frequent causes may help safety managers prevent fires. The areas of refurbishment, demolition or reconstruction are at highest risk of fire hazards, due to the presence of old electrical cables, dry wood, activities such as soldering or sawing, causing higher likelihood of fire outbreak.

Five common causes of fire outbreaks on construction sites are[2]:

1. Flammable materials
2. Flawed fire protection measures
3. Arson
4. Power sources
5. Cooking

[2] https://www.cityfire.co.uk/news/5-common-causes-of-fire-on-construction-sites/

Data collection

Presence and quantity of these five items can be used as PI for fire susceptibility assessment. These can be also visualized in the digital twin during the maintenance planning and execution of the activities.

3.3.2.4 Indoor and outdoor air quality during maintenance

Two critical air pollutants that occur during works are nitrogen dioxide (NO_2) and fine particulate matter (PM) for managing pollution events and applying mitigation measures. PM stands for 'particulate matter' (also called particle pollution): the term for mixture of solid particles and liquid droplets found in the air.

Maintenance works include heavy equipment and materials prone to releasing large amounts of dust such as concrete, cement, stone, silica, and others. The dust consists of very small particles (PM 2.5) produced by construction and demolition activities which persists in the atmosphere for days. Various vehicles, generators and machinery involve the use of fuel causing exhaustion poisonous gases like carbon monoxide, carbon dioxide, nitrogen oxides, and hydrocarbons. Oils, glues, thinners, paints, treated woods, plastics, cleaners, and other hazardous chemicals are widely used on construction sites releasing noxious vapours that contribute to air pollution. Measurement of the potential air pollution during maintenance works is necessary for occupational safety and health administration.

PI indoor air quality is applicable for buildings while outdoor air quality should be measured at the site while performing maintenance activities for bridges, roads, or any other infrastructure. There are several metrics or units used to measure indoor and outdoor air quality. Here are some of the most commonly used:

For Indoor Air Quality:

- Particulate Matter (PM): PM2.5 and PM10 present the most commonly used metrics for the assessment of indoor air quality. It is a measure of size of particles in the air in micrometres (μm).
- Carbon Dioxide (CO2): The amount of CO2 in the air is expressed in parts per million (ppm). Poor ventilation may be indicated by high CO2 levels.
- Volatile Organic Compounds (VOCs): VOCs are a measure of the amount of organic compounds in the air and are expressed in parts per billion (ppb). Toluene, formaldehyde, and benzene are examples of typical VOCs.
- Radon: Radon is a measure of the amount of radon gas in the air and is expressed in picocuries per litre (pCi/L). When it builds up indoors, the naturally occurring radioactive gas radon can be harmful.

For Outdoor Air Quality:

- Particulate Matter (PM): PM2.5 and PM10 present the most commonly used metrics for the assessment of outdoor air quality. It is a measure of size of particles in the air in micrometres (μm).
- Ozone (O3): Ozone is a measure of the amount of ozone gas in the air and is expressed in parts per billion (ppb). Smog's main ingredient, ozone, can lead to respiratory issues.

- Nitrogen Dioxide (NO2): NO2 is a measure of NO2 gas concentration in the air and is expressed in parts per billion (ppb). The combustion of fossil fuels releases NO2, which might lead to respiratory issues.
- Sulfur Dioxide (SO2): SO2 is a measure of the SO2 gas concentration in the air and is measured in parts per billion (ppb). SO2 which can cause respiratory problems is produced by the burning of fossil fuels.

Data collection

National meteorological institutions or governmental bodies publish regularly data about the air quality. Real-time air quality index measured at meteorological or official air quality measurements stations can be seen here: https://aqicn.org/map/europe/. Meteorological measurement together with NO_2 and $PM_{(2.5 \text{ and } 10)}$ may be used for baseline comparison, and also for the site impact assessment if they are in the close vicinity to the site.

Significant construction sites including maintenance works should have continuous air pollution monitoring carried out, along with noise and vibration together with precipitation, wind speed and direction data. The concentration of PM and NO_2 is expressed in micrograms per cubic meter ($\mu g/m^3$).

Indoor Air Quality Monitors measure and display real-time levels of various indoor air pollutants. Passive sampling devices are devices that are left in place for a period of time to collect samples of indoor air. These devices can measure a wide range of indoor air pollutants such as formaldehyde, volatile organic compounds, and radon. They can provide a snapshot of indoor air quality over a period of time. Active sampling devices actively draw air into a collection device for analysis. These devices are commonly used to measure airborne bacteria and fungi. Personal monitors are worn by individuals to measure their exposure to specific indoor air pollutants. These devices can be useful for identifying sources of exposure to pollutants in the home or workplace. Finally laboratory analysis is used to analyse collected samples of indoor air. This can provide a detailed analysis of indoor air quality, including the identification and quantification of specific pollutants. However, this method is usually more expensive and time-consuming than other methods of measuring indoor air quality.

3.4 Cost

Cost as a KPI is one of the most widely used evaluation indicator for the comparison of different maintenance solutions. Costs can be divided into two main groups, direct ones, which are directly born by the owner during the entire life span of an asset and indirect costs which are related to the society, to the end users, environment, community etc. Since they are occurring along the whole life cycle of a structure, it is important to develop a Life Cycle Cost Model (LCCM) for the cost estimation of different maintenance alternatives. The main objective of the LCCM is to determine direct and indirect impacts (or costs) of planned and unplanned disruptions causing inspections and maintenance activities, which can then be used for the comparison of different maintenance strategies. (Stipanovic et al., 2017; Skaric Palic and Stipanovic, 2019).

3.4.1 Direct costs

Direct costs are expenditures that an asset's owner directly bears throughout the duration of its life. Costs associated with design and construction, maintenance, and end-of-life are the three categories into which direct agency/owner costs are typically subdivided. The method used to determine the agency's costs is based on Chandler (2004). Essentially, this entails decomposing the entire structure into various components and multiplying each component by the unit cost per component.

The acquisition of a new asset, such as one that is a part of a new development plan or a service need, is associated with the construction costs. This expense might also be incurred when an asset that has already reached the end of its useful life needs to be replaced. Labour, materials and equipment are all part of the construction budget. These costs are elaborated more in details in D2.1 (Krenn, 2021) and D4.1 (Lukaszewska, 2021).

3.4.1.1 Maintenance cost

For the calculation of maintenance costs first the maintenance scenario that most accurately describes the estimated required maintenance over the life cycle of the object has to be determined. This means determining the different necessary maintenance activities including inspections, their accompanying frequencies, and their estimated unit costs. Next, the unit cost of a certain maintenance activity (AUC_i), which includes workers and machines costs, is multiplied by the quantity of units related to that activity (Aq_i). All the years in the asset's life cycle during which that maintenance action occurs are given credit for the associated annual maintenance cost (based on the frequency attributed to that activity). As a result, a maintenance schedule is created, by which the total maintenance costs for each year of the life cycle may be determined.

The maintenance costs for one specific year are therefore calculated by:

$$MC_{t,nom} = \sum_{i=n}^{m} AUC_i \times Aq_i$$

Wherein:

$MC_{t,\,nom}$ = nominal maintenance costs for year t (€)

i = activity n until m

AUC = activity unit cost of activity i (€/unit)

Aq_i = quantity of units for activity i in year t (unit)

Summarizing, the maintenance costs of every year in the life cycle of the object gives the total nominal maintenance costs of the object. Because the maintenance costs are made in the year the maintenance takes place, the future cash flows have to be discounted to create a present value.

The total maintenance costs for the object during its life cycle is therefore calculated by:

$$MC_{tot,disc} = \sum_{t=0}^{T} \frac{MC_{t,nom}}{(1+r)^t} \times (1+\chi)$$

Wherein:

$MC_{tot,\ disc}$ = the total maintenance costs during the life cycle of the object (€)

$MC_{t,\ nom}$ = maintenance costs for year t (€)

t = year in life cycle from 0 until end of life cycle T

r = the discount rate (%)

χ = an additional percentage to cover unassigned, indirect, engineering, and other costs.

Data collection

Required data about the quantities of materials and machines can be collected from the bill of quantities from maintenance design project. The information about the construction machines usage (actual travel distance and duration of works) can be collected from GPS tracking devices, which can be visualized in the ASHVIN platform. Similar approach can be adopted as for the collection of PIs for the construction stage, see D4.1 A set of KPIs to plan and monitor productive, resource efficient, and safe construction sites (Łukaszewska, 2021). Data about the duration of different activities can be collected by the usage of WT901 WIFI or WTGAHRS2 sensors, which are mounted on the equipment on construction site to gather data about the movement. By analysing that data, it is possible to determine the duration of activities.

Furthermore, pictures and videos can be taken manually, by fixed cameras or by an agile mobile robot. This information can help to evaluate and complement the collected sensor data. In addition, the pictures and videos can be analysed separately. In general, the collected data help to determine more reliable and precise data about the execution and duration of activities.

The unit costs for each equipment and workers have to be collected for each country individually by collection of historical data or through surveys.

3.4.1.2 Discount rate

Discount rate is function of both the interest rate and the inflation rate. In general, the interest rate (often referred to as the market interest rate) is associated with the cost of borrowing money and represents the earning power of money. Discount rate represents the real value of money over time and it affects how future cash flows would affect the overall LCC. This factor has a significant impact on the ultimate LCC result.

The terms discount rate and interest rate can both refer to a percentage number that is used to translate future costs and benefits accrued over the course of a project into a single time dimension. According to (Jawad and Ozbay, 2005), multiple variables are required to calculate the discount rate’s impact, mainly the present-day activity cost, the number of discount periods and the discount factor. The real discount rate can be estimated using the derived formula:

$$r = \frac{i - f}{1 + f}$$

Where:

f = Inflation rate

i = Nominal interest rate

r = Real discount rate—an interest rate that has been adjusted to remove the effect of expected or actual inflation.

The impact of the discount rate increases with respect to the number of years since the beginning of the life cycle. This inherently shows that the discount rate's impact is distributed exponentially. In general, fixed average discount rate for long-term monetary cost estimation can skew the accuracy of estimates so special attention must be given for the distribution bounds. Min and max boundaries should be set at the beginning of the analysis and perform sensitivity analysis to ensure consistent and economically justifiable results.

Data collection

The adoption of an appropriate discount rate that reflects historical trends over lengthy periods of time is stressed heavily by the FHWA (1998) as well as the majority of guidance on the choice of discount rate. Average and recorded historic rates should serve as the basis when deciding upon the discount rate for the analysis.

3.4.1.3 Total LCC

Life cycle costs include all maintenance and repair activities during whole life cycle of a structure together with initial construction costs and end of life for different scenarios. Calculation of total life cycle costs enables comparison of different investment alternatives based on the total costs that are associated with that alternative. Not only initial investment costs but also all costs that develop throughout the objects life cycle are taken into account. This entails costs made during operation as well as end of life costs. Depending on the level of analysis it can include direct or/and indirect costs. Direct costs are initial construction costs (€), nominal maintenance costs for year t (€) and nominal end-of-life costs (€). Indirect costs can include environmental costs and societal costs which can both be transferred into monetary units, explained in chapter 3.4.2.

The total discounted agency costs are the sum of the three sub cost categories and therefore calculated by:

$$Total\ Costs = ICC + \left(\sum_{t=0}^{T} \frac{MC_{t,nom}}{(1+r)^t}\right) + \frac{EoLC_{T,nom}}{(1+r)^T}$$

Wherein:

ICC = Initial construction costs (€)
$MC_{t,\ nom}$ = nominal maintenance costs for year t (€)
$EoLC_{t,\ nom}$ = nominal end-of-life costs (€)

t = year in life cycle from 0 until end of life cycle T
T = year in which life cycle ends
r = discount rate (%)

Initial construction costs include design and planning costs as well as direct construction costs such as materials, labour, and equipment expenses. More details can be found in D2.1 (Krenn, B. 2021). Usually indirect construction costs, such as risks, profit, general costs, execution costs and one-off construction costs are also taken into account. To determine the direct construction costs, different construction elements of the intended object must first be determined. The next step is to calculate the unit cost of each construction component and multiply it by how frequently that component appears in the design. The assigned construction expenses will be determined by repeating this process for each component of the structure and adding up their costs. The rest of the initial construction costs are calculated by taking a percentage of the direct construction costs. The percentage and the value with respect to which that percentage is considered should be based on the empirical / statistical data of the owner. These costs are claimed at the beginning of the life cycle, so they are not discounted. The initial construction costs are calculated by the following:

$$ICC = \sum_{i=n}^{m} CUC_i \times Cq_i \times (1 + \chi)$$

Wherein:

ICC = initial construction costs (€)

i = construction element n until element m

CUC_i = construction unit cost of element I (€/unit)

Cq_i = the quantity of construction element i present in the design (unit)

x = an additional percentage to cover unassigned, indirect, engineering and other costs.

The end-of-life costs include the costs of demolition and disposal minus the residual value and are calculated in the same manner as initial construction costs. The structure is divided into constituent elements with a unit cost for end-of-life and the amount of a certain building element is multiplied with the corresponding end-of-life unit cost. The equation is as follows:

$$EoLC_{disc} = \frac{EoLC_{T,nom}}{(1+r)^T} = \frac{\sum_{i=n}^{m} DUC_i \times Cq_i}{(1+r)^T}$$

Wherein:

$EoLC_{nom}$ = nominal end-of-life costs (€)

$EoLC_{disc}$ = are the discounted end-of-life costs (€)

i = construction element n until element m

DUC_i = demolition and disposal unit cost for element I (€/unit)

Cq_i = the quantity of construction element i present in the design (unit)

T = year in which life cycle ends

r = discount factor (%)

Data collection

Data about the quantities for initial construction costs are taken from the bill of quantities - as detailed as available at the design stage. The data can be then updated from the digital twin models.

For the calculation for maintenance costs over the life cycle, it is necessary to predict the service life of each unit / element, and these data can be updated based on the inspection and monitoring data. End of life costs require the information about the predicted service life of used materials / components, but it should be regularly updated with the information collected through inspection and monitoring, see chapter 3.3.1, about the actual condition, described with KPI Safety. Recyclability and reusability of the elements and materials can lower the end-of-life costs, since they would create a value at the end of the life. Required information is the amount and quality of reusable materials obtainable when structure is deconstructed.

3.4.2 Indirect costs

3.4.2.1 User delay cost

User delay costs are usually determined for the transport infrastructure networks. The calculation methods presented here are applicable for road networks, but they can be adapted for railway, waterway, or airport infrastructure.

The equations used for determining the user delay cost are based on the work of Sundquist & Karoumi (2012). The total user costs are a summation of the two sub-categories: freight delay costs and passengers delay costs. Because the user costs are made during the life cycle of the structure, future cash flows will have to be discounted to determine a total present value.

The total discounted user costs are determined using:

$$UDC_{tot,disc} = \sum_{t=0}^{T} \frac{TDC_{fr,t,nom}}{(1+r)^t} + \sum_{t=0}^{T} \frac{TDC_{car,t,nom}}{(1+r)^t}$$

Wherein:

$UDC_{tot,\ disc}$ = total discounted user delay costs (€)

t = year in life cycle from 0 until end-of-life cycle T

r = discount factor (%)

$TDC_{fr,t,\ nom}$ = nominal freight traffic delay costs in year t (€)

$TDC_{car,t,\ nom}$ = nominal commuters traffic delay costs in year t (€)

The traffic delay costs are the costs that represent the valuable time of the network users itself. This economic value of the user's time is dependent on several factors. The type of traffic (passenger vehicle or freight traffic), the amount of persons/cargo per vehicle and the type of cargo/person (business/leisure). The input data for the calculation of traffic delay costs should come from analysis of traffic flow models. The traffic model gives the values for additional travel time, depending on the traffic disruptions for two groups of users, namely freight and passenger's traffic. Different value of time is then used for each group of users. The traffic delay costs can be then determined by:

$$TDC_t = ETT \times ADT_t \times VOT_{user} \times N_t$$

Wherein:

TDC_t = traffic delay costs for year t (€), calculated separately for freight and for passenger cars,

ETT = extra travel time per type of users (hours)

ADT_t = the average daily traffic (separately for freight and for passenger cars) in year t passing the analysed section or bridge in question (PCE/day)

VOT_{user} = is a monetary value for the users time (€/hour), different values for different user groups, e.g. freight, business, leisure,

N_t = the duration of a certain maintenance activity for year t (days).

Data collection

Data about travel distance and extra travel time caused by maintenance activities should be determined by traffic flow models. Value of time should be determined from national statistical data. Data about the usage intensity (e.g. AADT) can be collected from traffic monitoring stations, see 3.1.5. Similar PI related to the usage intensity for other types of infrastructure or buildings can be used, e.g. for airports # of flights per day and # of passengers, for buildings # of occupants etc.

3.4.2.2 Environmental cost

Introducing environmental shadow prices provides a way of monetizing environmental effects which enables incorporation of these effects with all other monetary costs into analysis. For an explanation and in-depth discussion, the author refers to the report by CE Delft (2017) where the environmental prices provide average values for the Netherlands, for emissions from an average emission source at an average emission site in the year 2015. The different environmental effect categories and their corresponding prices are presented in

Table 7.

Table 7 Example of Environmental Cost Indicator per impact category, for use in LCA[3]

Impact category	**Unit**	**Weighting Factor** (€/ unit)
Global warming	kg CO_2-eq	0,05 €
Ozone depletion	kg CFC-11-eq	30,00 €
Acidification of soil and water	kg SO_2-eq	4,00 €
Eutrophication	kg PO_4^{3-}-eq	9,00 €
Depletion of abiotic resources – elements	kg Sb-eq	0,16 €
Depletion of abiotic resources – fossil fuels	kg Sb-eq	0,16 €
Human toxicity	kg 1,4 DB-eq	0,09 €
Freshwater ecotoxicity	kg 1,4 DB-eq	0,03 €
Marine water ecotoxicity	kg 1,4 DB-eq	0,0001 €
Terrestrial ecotoxicity	1,4 DB-eq	0,06 €
Photochemical oxidant creation (Smog)	kg C_2H_4	2,00 €

According to the authors, the environmental prices that can be used as weighting factors, values in the second column, in LCA are specifically suited for use in LCAs according to the ReCiPe methodology under the hierarchist perspective, while when estimating the external costs the values from the third column are used.

In the analysis, first the environmental impact of one kg of material is determined as a basic parameter of the model. Those values are then used to calculate the total environmental impact by multiplying it by the amount of material present in the construction or maintenance activity. The total environmental costs can then be determined using the following equation.

$$EC = \sum_{i=n}^{m} EE_i \times ECI_i$$

Wherein:

EC = environmental costs (€/functional unit, €/kg, €/m2 or €/total)

EE_i = environmental effects for impact category i (kg of impact category equivalent (IC_{eq})/functional unit (one bridge))

ECI_i = the environmental cost indicator for environmental effect category i (€/kg of IC_{eq})

i = environmental impact category n until m

[3] https://ecochain.com/knowledge/environmental-cost-indicator-eci/

Environmental costs incurred during the life cycle of the structure are not discounted as recommended by (Hellweg et al., 2003).

The environmental effects per impact category can be determined using the following equation:

$$EE_i = \sum_{j=n}^{m} EE_{i,j} \times Mq_j$$

Wherein:

EE_i = environmental effects for impact category *i* (kg of impact category equivalent (kg IC_{eq})/functional unit)

$EE_{i,j}$ = environmental effect for impact category *i* per kg of material *j* (kg *ICeq*/kg material)

M_{qj} = material quantity per functional unit for material *j* (kg material/functional unit)

j = the different materials n until m

Data collection

Required data about the quantities of materials and machines can be collected from the bill of quantities from maintenance design project or BIM models. The information about the construction machines usage (actual travel distance and duration of works) can be collected from GPS tracking devices, which can be visualized in the ASHVIN platform.

4 MAPPING OF KPIS AND ASHVIN TOOLS AND METHODS

Accurate digital twins that represent the situation during operation provide the basis for analysis of different flexible predictive maintenance scenarios. Two interdependent tools, GISI and RISA, were developed to enable establishment of a risk-based predictive maintenance planning, a risk-based status assessment tool with KPI dashboard and a GIS integrator for digital twin-based asset management. A GIS application enables asset managers to monitor the anticipated state of various assets based on their digital twins using a set of asset management KPIs. Utilizing a visualization tool, maintenance schedules and interventions may be designed with a thorough understanding of an asset's status. The risk model considers different maintenance strategies and allows end-users to interactively review and utilize specific outputs of the risk assessment and the consequence modelling in the risk analysis. The GISI tool allows the visualization of condition assessment results and of risk calculated through the RISA tool following the next steps:

- Classification and quantification of documented damages – definition of threshold values for different classes – geo-positioning of all detected defects,
- Definition of failure modes,
- Condition assessment based on the detected defects (e.g. Pavement Condition Index PCI or Bridge Condition Index BCI),
- Projections of future degradation based on current condition,
- Quantification of risk by combining probability of failure and consequences – changes in risk over time – definition of threshold values for performing actions (maintenance options),
- Mapping of risk – geo-positioning.

4.1 GIS integrator for digital twin-based asset management (GISI)

In Figure 10, main components of the GISI tool are presented beginning with the acquisition of data with advanced technologies, with drone equipped with high resolution camera. Condition assessment of the asset is performed based on the analysis of photos containing main groups of damages. The photos are also used to develop 2D or 3D model of the asset to be used for presentation of results in the platform. Based on the failure modes (e.g. cracks) and predefined threshold values (e.g. width, length) damages are categorized and labelled to develop and train a damage detection model. The damage detection model was deployed using Deep Learning segmentation techniques under the framework of task 3.1 (see ASHVIN D3.1). The computer vision-based damage detection service receives images, automatically detects damages, and translates the pixel coordinates into geolocations for the GIS tool to display the results. The final result is the geo-positioned defects after applying the developed damage detection model on the 2D or 3D model of the asset.

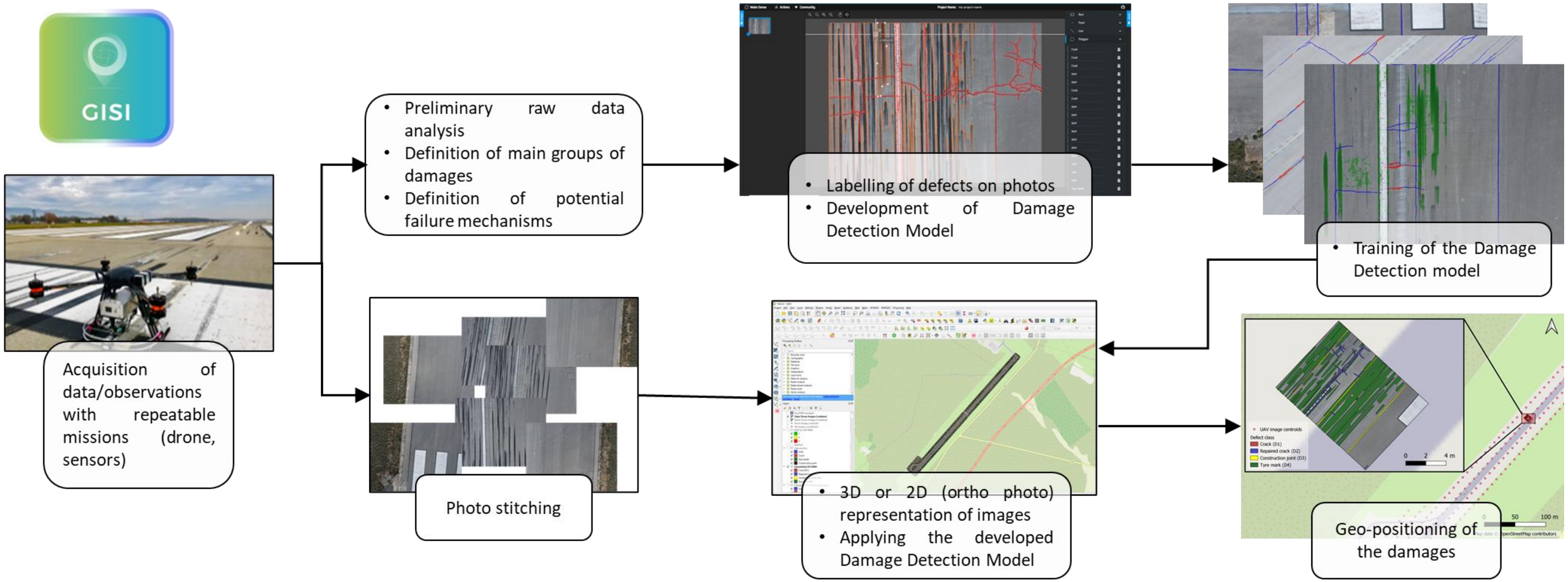

Figure 10 Structure of the GISI tool with main development processes

4.2 Risk-based status assessment tool with KPI dashboard (RISA)

The RISA tool uses the result of the GISI tool as a layer of assessed, categorized, and quantified defects. Selection of maintenance strategy can vary from no maintenance just monitoring, to minor or major repair and finally replacement. The RISA tool takes into account consequences of different maintenance options. Figure 11 shows the general risk evaluation framework using main project KPIs. Once the risk is calculated by applying the RISA tool, see Figure 12, the result is then returned into the GISI to visualize risk on the 2D or 3D model.

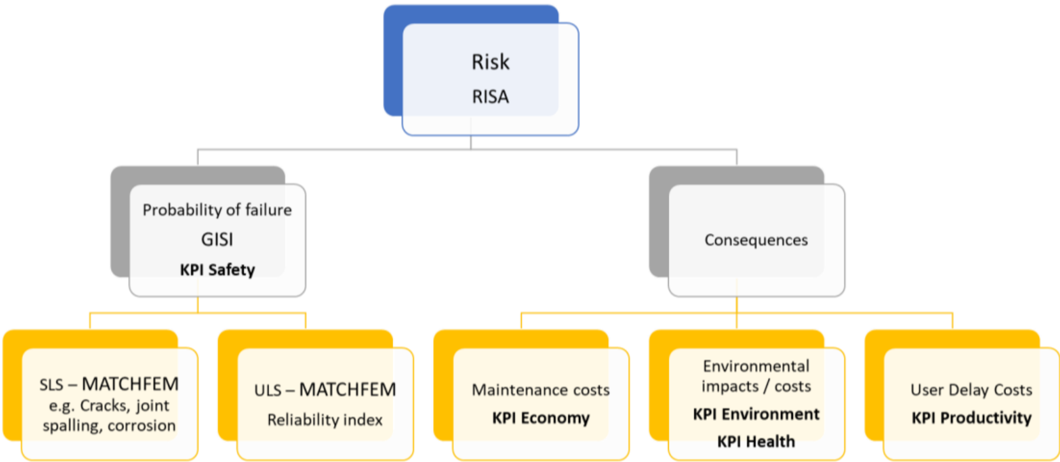

Figure 11 Risk evaluation using KPIs

The risk of failure is defined as the expected monetized consequences of an asset failure due to a certain threat scenario:

$$R = p_{FM}\ x\ Consequences = p_{FM}\ x\ (DC + IC)$$

Where:

p_{FM} - probability of an asset failure mode given the threat scenario magnitude

DC +IC - direct and indirect consequences i.e. monetized losses due to the failure mode for certain element / object / system.

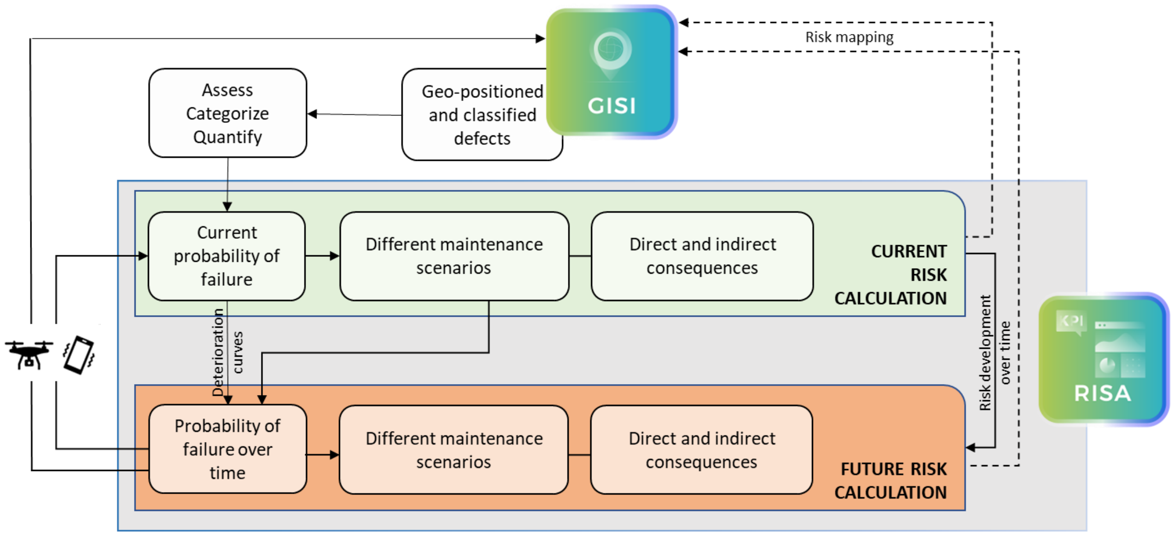

Figure 12 Structure of the RISA tool and the interactions with the GISI tool

4.3 Mapping of tools vs Performance Indicators

Table 8 shows the overview of the Performance Indicators (PIs) and ASHVIN tools and methods that contribute to the improved productivity, resource efficiency, safety, and cost of maintenance of an asset.

Table 8 Overview of Performance Indicators and contributing ASHVIN tools and methods

KPIs	Performance Indicators	ASHVIN TOOLS AND METHODS		
		GISI	RISA	ASHVIN DASHBOARD
Productivity	Duration of inspection and maintenance works		✓	✓
	Service life		✓	✓
	Prefabrication level		✓	
	Usage intensity		✓	✓
	(Un)availability of the asset and/or network during the maintenance/inspection work		✓	
Resource efficiency	Environmental impacts due to the maintenance and inspection works		✓	✓
	Energy consumption (before and after maintenance)		✓	✓
	Energy demand covered by renewable use (before and after maintenance)		✓	
	Recyclability and reusability of the maintenance solution		✓	
Health	Structural safety	✓		✓
	Human health and safety		✓	
Cost	Maintenance cost	✓	✓	✓
	Discount rate	✓	✓	
	Total LCC	✓	✓	✓
	User delay cost	✓	✓	✓
	Environmental cost	✓	✓	✓

5 IMPLEMENTATION ON DEMONSTRATION SITES

5.1 Demo sites - Bridges

5.1.1 Demo site #1 Bridges for high-speed railways in Spain

The branch of the high speed railway; Madrid-Bajadoz, has been under construction in recent years in Spain. The length of the double line from Madrid to Badajoz is 437 kilometres and it includes several viaducts, bridges, and tunnels, shown in Figure 13. The branch of the Highspeed Railway; Plasencia-Bajadoz is expected to open in the years to come.

Figure 13 Railway bridges on the line Madrid-Bajadoz

The bridges along this new railway line are being tested and monitored. The bridges vary in type from simple underpasses to complex arch bridges, including a top-5 world record bridge defined by a concrete arch (Almonte Viaduct). UPC has developed a digital twin simulation of bridge load tests (Chacon et al., 2023). Diagnostic load tests are meant to verify standards on the design and construction of the bridges. The load tests represent an ideal milestone for twinning bridges. On the one hand, specific, bespoke structural models are performed. On the other hand, measurements quantifying the structural response are taken. If both results are matched using not only basic comparisons but comprehensive digital twinning, the asset enters the service phase not only physically, but also virtually. The demonstrator #1 is aimed at establishing requirements and procedures for the generation of the most realistic virtual replica of the physical bridges that can be used during operation. Presently, current numerical methods focus primarily on the virtual reproduction of the assets. Models are generally calibrated with existing laboratory or real tests. The twinning of these bridges also includes the integration of data from sensors for model updating or hybrid simulations within the realm of such simulations.

Data to be collected (during load tests) include deflection, inclination, acceleration, environmental conditions (temperature and humidity), images and video (drone footage). This data is translated into the different performance indicators as indicated in the previous chapters. Several performance indicators are investigated within this demo. Using drones for inspection instead of manual visual inspection enables undisturbed traffic flows across the bridges along the entire railway line. Individual structures and the whole network are available with the consequence being the decreased or abolished user delay costs.

The overall aim is to use information from continuous monitoring for updating the safety and serviceability of the bridge and to combine the outputs from the model with the predefined threshold values. The thresholds values which represent satisfactory and non-satisfactory performance will trigger the action, such as detailed inspection, sampling, running numerical model with the updated information, maintenance, or repair activity, strengthening etc.

5.1.2 Demo site #7 Bridges in highway network in Spain

This demonstration site is the PR-04-B015 bridge, that is located within the Metropolitan Area of Barcelona (Spain). Its main objective is to connect two main road axes: the AP-7 Highway (heading North) and the A-2 Road (Heading West), Figure 14 PR-04-B015 bridge (Łukaszewska, A., 2021)Figure 14. This connection belongs to a strategic link for users of those axes whose aim is to avoid urban areas while crossing the Metropolitan Area of Barcelona. The link reduces the distance between roads by approximately 12 kilometres compared to the present connection. It is also a strategic asset for transporting goods from Barcelona port to northern Europe.

The PR-04-B015 bridge is a continuous beam drawn on a horizontally curved alignment, Figure 14. Two separated viaducts are defined by the driving direction (heading North or West). The structures allow bridging a river (Llobregat), a creek (Rubi), several roads and a railway line.

Both viaducts are supported by 12 piers with varying span. The cross-section is a composite bridge. Box section with variable web height (3,5 m-5,0 m) and a concrete slab with varying width (11,50 m-17,00 m). Longitudinally, the cross-section is provided with stiffeners and transversally, with stiffeners and diaphragms. The total length of the structure is approximately 840 meters.

Figure 14 PR-04-B015 bridge (Łukaszewska, A., 2021)

5.1.3 Maintenance Performance Indicators for bridges

For the development of life cycle management plan a service life of the structural elements and equipment needs to be predicted based on the inspection and monitoring data in order to optimize maintenance planning. In Table 9 a list of possible PIs that can be collected and integrated into digital twin for bridge demo sites is provided.

Table 9 Proposed maintenance performance indicators for Demo sites related to bridges

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI PRODUCTIVITY			
Duration of inspection activity	h, days	Duration of inspection affects users. For large bridges requires partial closures or full closures of a bridge. Time required for inspection can be used for the calculation of user delays (decreased speed, detour) through appropriate calculations.	Inspection time: drone flight vs. inspection with traffic closures, duration, user delay costs
Duration of maintenance works	h, days	Duration of maintenance activities affects users. Maintenance interventions require partial closures or full closures of a bridge. Time required for a maintenance intervention is transformed into user delay (decreased speed, detour) through appropriate algorithms.	Maintenance time: comparison of different maintenance options (e.g. Minor repair vs. major repair – duration of traffic closure records Benefit of SHM
Unavailability of the asset during the maintenance / inspection works	m, # of lanes/tracks, or section	Length and number of lanes or tracks closed during the maintenance activities. Bridge or section which can't be used or partly used (decreased speed, less availability) compared to undisturbed normal usage. PI is also used to calculate user delay cost in combination with duration of maintenance intervention.	Cameras Traffic data (# of trains per day, type of trains, load, AADT...)
Usage intensity (before, during and after the intervention)	AADT	AADT (per user group, freight, commute, leisure...) can be used in different forms for example for the whole year or for a part of the year to quantify the importance of a bridge in a network or to calculate user delay cost.	Cameras Sensors Traffic data (# of trains per day, type of trains, load...)
Service life of maintenance solution	years	Monitoring of maintenance measure performance (drones and SHM) to determine how long the intervention performs at the required level	SHM sensors, Drones, Meteo data (humidity, temperature) Sea water level data

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI RESOURCE EFFICIENCY			
Environmental impacts related to the usage of drones vs. vehicles	CO2, SO2, PO43, Sb,... €/kg, m2, unit or total	Different environmental impact categories for energy / fuel usage to compare for: Drone – battery size Vehicle type, duration of inspection	LCA model outputs Graphical representation (of comparison results)
Environmental impacts related to the usage of materials and machines during maintenance	CO2, SO2, PO43, Sb,... €/kg, m2, unit or total	Different environmental impact categories per kg of material and energy for machines used for a certain maintenance activity. From design solution the quantitites, materials source, technology, transport data are used as inputs in LCA model	LCA model outputs Graphical representation (of comparison results)
Environmental impacts related to the unavailability of the asset	CO2, SO2, PO43, Sb,... €/day or hour	Congestions of traffic or detours (longer routes than without traffic regulation for maintenance intervention) cause increased CO2 emissions which are transferred into monetary units allowing comparison of different interventions.	Traffic data / congestions / delays Cameras LCA
KPI COST			
Inspection cost	€/m2, unit or total	Includes cost of equipment, energy, and workforce. Comparison drone vs. conventional inspection	Cost data over time, graphs
Maintenance cost	€/m2, unit or total	Includes cost of all materials, equipment, energy and workforce.	Cost data over time, graphs
User delay cost	€/min, h	The traffic delay costs are the costs that represent the valuable time of the network/bridge users themselves.	Cost data per activity Can be visualised based on traffic data and duration time
Total LCC	€/kg, m2, unit or total	For calculation of total LCC a life cycle scenario needs to be developed with prospects of deterioration and timing of certain maintenance interventions.	Annual cost per scenario

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI HEALTH AND SAFETY			
Structural performance	Risk reduction – improvement in reliability /condition level	Assessment of the structural performance (safety in front of relevant limit states) before and after the maintenance intervention. Computational comparison of reliability levels before and after the maintenance intervention Condition assessment before and after the intervention	SHM sensors: Deflection, inclination, acceleration → visualisation in DT Drone images → visual inspection Automated detection of damages / cracks using AI → visualisation in DT
Safety during maintenance works for workers	# per day	# of workers accidents (fatal and non-fatal) during the maintenance works # of near misses during the maintenance works	Cameras
Safety during maintenance works for users (# of accidents, # of near misses)	# per day	# of users accidents (fatal and non-fatal) during the maintenance works # of near misses for users during the maintenance works	Cameras
Indoor and outdoor air quality during maintenance	g/m^3	Air quality monitoring stations - Specific construction site air pollutants are nitrogen oxides, CO2, CO, SO2, organic pollutants, particulate matter	Data about air quality – baseline scenario compared to the one during maintenance activities.
Fire safety (or fire vulnerability) during maintenance	% of present common causes of fire outbreaks on construction sites	Assessment of quantity and location of five common causes (Flammable materials, Flawed fire protection measures, Arson, Power sources, Cooking) of fire outbreaks, additional assessment of risk considering the number of users.	Location of flammable materials, power sources, arson and cooking devices on the site Movement of users and workers

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5.2 Demo site - Airport

5.2.1 Demo site #3 Airport runway in Croatia

Zadar Airport, Republic of Croatia, see Figure 15, was opened in 1969 as an addition to the existing military runway, and with the construction of a civilian runway, it became the only airport in Croatia with two runways. The airport had a steady growth of traffic during the 1970s and 1980s, when tourism in Croatia, and especially in Dalmatia, reached its peak at the time. However, this was abruptly interrupted by the war in Croatia in the first half of the 1990s, when the Zadar airport was occupied and destroyed, with severely damaged terms. After the war the airport was repaired.

Figure 15 Terminal building of Zadar airport

Airport infrastructure, which includes all operational areas for receiving and dispatching passengers and aircraft, was built, as already stated above, almost 50 years ago. In that period there were several partial renovations of asphalt surfaces, but no major reconstructions. This means that the essential infrastructure of the airport including runways is not in a very good condition degrading further rapidly, starting to influence the safety of traffic.

The goal is digitalization of airport infrastructure with the purpose of optimizing maintenance and operational planning. The main idea for this demonstration project is the use of images of operational areas of the airport collected with unmanned aerial vehicles (UAVs). In this demo, a digital twin is developed containing detailed structure information about the runway layout, materials, drainage systems and signage. It will be combined with the Airport Operational Database (AODB) and inspection data performed with Unmanned Aerial Vehicles (UAVs). Deep machine learning techniques are then applied on drone-based images for the automation of the visual inspection and damage detection procedures. The developed methodology for digitalization and automation of inspection and monitoring processes of operational areas, are then integrated into GIS based predictive maintenance tool. Collected data is transformed into single PIs and eventually combined into four KPIs productivity, costs, resource efficiency and health and safety. Final intention is to integrate use of UAVs into continuous monitoring practice and risk-based maintenance planning.

5.2.2 Maintenance Performance Indicators for airports

In Table 10 PIs are proposed for each KPI which can be collected for airport and implemented into digital twin platform.

Table 10 Proposed maintenance performance indicators for Demo sites related to airports

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI Productivity			
Duration of inspection activity	h, days	Duration of inspection affects users and operational planning. For airports means that runway needs to be closed for inspection for a certain period. Avoiding certain needed maintenance activities or choosing minor repairs instead of major could lead to need for more often inspections and closures.	Inspection time: drone flight vs. inspection with traffic closures, duration, runway not opened
Duration of maintenance works	h, days	Duration of maintenance activities affects users and operational planning. Maintenance interventions require partial closures or full closures of a runway. Time required for a maintenance intervention is time that the runway closed completely or closed for a certain type of aircraft.	Maintenance time: comparison of different maintenance options (e.g. Minor repair vs. major repair – duration of traffic closure records
Unavailability of the asset during the maintenance / inspection works	m, or section	Runway or section which can't be used or partly used (decreased length/width, less availability) compared to undisturbed normal usage. PI is used to calculate owner cost/loss due to unavailability of the runway in combination with duration of maintenance intervention.	Cameras, Traffic data (# of planes per day, type of planes, passengers, cargo...) No of passengers per year for Zadar airport
Usage intensity (before, during and after the intervention)	Average annual daily or monthly traffic data	Traffic data can be used in different forms for example for the whole year or for a part of the year to quantify the importance of an airport, or the importance of an airport in a certain period (e.g. Zadar airport very busy in summer) or to calculate owners cost/loss.	Cameras, Traffic data (# of planes per day, type of planes, passengers, cargo...)
Service life of maintenance solution	years	Monitoring of maintenance measure performance (drones) to determine for how long the intervention performs at the required level	Drones, sensors (e.g. optical fibers, corrosion sensor) Meteo data (humidity, temperature)

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI Resource efficiency			
Environmental impacts related to the usage of drones vs. vehicles	CO_2, SO_2, PO_4^3, Sb,... €/kg, m2, unit or total	Different environmental impact categories for energy / fuel usage determined for drone and for inspection vehicles.	LCA model outputs Graphical representation (of comparison results)
Environmental impacts related to the usage of materials and machines in maintenance solutions	CO_2, SO_2, PO_4^3, Sb,... €/kg, m2, unit or total	Different environmental impact categories per kg of material and fuel for machines used for a certain maintenance activity, data about quantities, materials source, technology, transport data are used as inputs in LCA model from design project.	LCA model outputs Graphical representation (of comparison results)
KPI Cost			
Inspection cost	€/m2, unit or total	Costs related to inspection activities include cost of equipment, energy and workforce.	Cost data over time, graphs Comparison drone vs. conventional inspection
Maintenance cost	€/m2, unit or total	Costs related to maintenance activities (minor and major repairs) include cost of all materials, equipment, energy and workforce.	Cost data over time, graphs
User delay cost	€/min, h	Costs of unavailability of the asset for the owner or end-user caused by inspection or maintenance activities. For airports can be different for different periods through the year.	Cost data per activity Can be visualized based on traffic data and duration time
Environmental cost	€/kg, m2, unit or total	Monetized environmental impacts related to the usage of materials and machines during maintenance	Cost data over environmental impact category, graphs

Performance indicators	Units	How to measure	Integration Into Digital Platform
Total LCC	€/kg, m2, unit or total	Life cycle costs are costs occurring during whole life cycle of a structure including end of life for different scenarios. For calculation of LCC a life cycle scenario needs to be developed with prospects of deterioration and timing of certain maintenance interventions.	Annual cost per scenario Total costs
KPI Health and Safety			
Structural safety before and after the maintenance works	Condition index	Condition of the structure before and after the maintenance based on inspection. Usage of standard e.g. ASTM D-5340 for determination of PCI	Visual inspection using UAVs Automated detection of damages / cracks, tyre marks using AI → visualisation in DT
Safety during maintenance works for workers	# of accidents per day # of near misses per day	Contractor and owner records of accident-related issues happening on site, number of workers accidents (fatal and non-fatal) during the maintenance works and number of near misses during the maintenance works	Camera – video Number and severity of reported accident issues, graph and location
Environmental pollution during maintenance works	PM (air pollution)	Measurement of the air, soil, or water pollution during maintenance works	Meteorological or air quality measuring station Mobile air quality stations
	Noise level (dB)	Noise level during maintenance works if close to populated areas	Noise Level Meter

5.3 Demo site – Building

5.3.1 Demo site #2 Residential building in Poland

Demo site #2 is a typical example of the residential building that needs intermediate renovation activities. This two-storey building, see Figure 16, was constructed in 1921, it has 7 flats and 16 building occupants and it is located in Gdynia in Poland (Lukaszewska, A., 20221). It is a public building that has a function of social housing.

Figure 16: Pictures of the demonstration case.

The building is owned by the City of Gdynia. The build-up area is 260m2 and the heat is generated by the tiled stoves (for coal and wood). The building envelope is not insulated. The building has very low energy performance estimated as 689 kWh/m^2 year, see Figure 17.

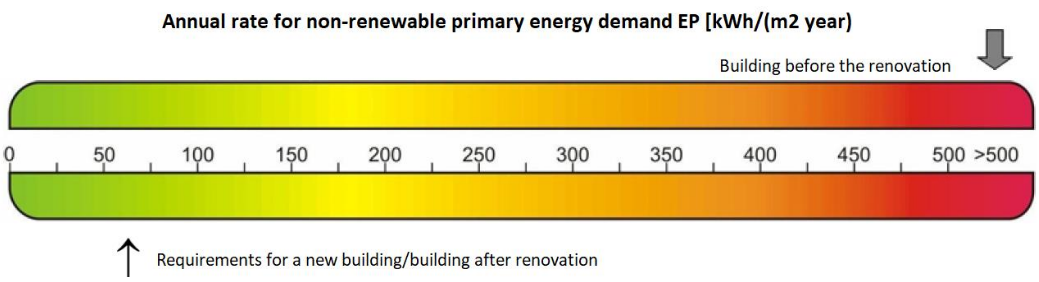

Figure 17: Energy Performance certificate for demonstration building.

5.3.2 Maintenance Performance Indicators for buildings

Building refurbishment aims to protect the building from heat loss and to drastically reduce the energy consumption needed to heat the building and water. In the vast majority of cases, excessive heat loss is one of the reasons for the high operating costs of buildings. These are the result of poor insulation of external walls, leaky windows, and insufficiently efficient heating systems. That is why many buildings need to be renovated (in some cases need to undergo the deep renovation). Renovation activities contribute to reduction of the energy demand of a building. Building refurbishment concerns already existing buildings, which due to their age and technical condition do not meet modern requirements.

In Table 11 PIs are proposed for each KPI which can be collected from the building renovation project and implemented into a digital twin platform.

Table 11 Proposed maintenance performance indicators for Demo sites related to buildings

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI Productivity			
Duration of maintenance works	h, days	Duration of maintenance activities affects users and operational planning. Maintenance interventions require partial closures or full closures of a building or its facilities. For building owner it means eventually moving out of the building and securing alternative housing. Time required for a maintenance intervention is time that the building is closed completely or partially.	Maintenance time: comparison of different maintenance options and final impacts on the energy usage
Service life of maintenance solution	years	Monitoring of maintenance measure performance to determine for how long the intervention performs at the required level	Sensors (e.g. humidity, indoor and outdoor temperature)
KPI Resource efficiency			
Environmental impacts related to the usage of materials and machines during maintenance works	CO2, SO2, PO43, Sb,... €/kg, m2, unit or total	Different environmental impact categories per kg of material and fuel for machines used for a certain maintenance activity, data about quantities, materials source, technology, transport data are used as inputs in LCA model from design project.	LCA model outputs Graphical representation (of comparison results)
Energy efficiency of the building before and after the refurbishment	kWh/m^{2}year	Energy consumption for heating and cooling before and after the intervention Environmental impacts related to the energy consumption and source	Energy consumption models LCA model outputs Meters for energy usage Sensors (e.g. humidity, indoor and outdoor temperature)

Performance indicators	Units	How to measure	Integration Into Digital Platform
KPI Cost			
Maintenance cost	€/m2, unit or total	Costs related to maintenance activities (minor and major repairs) include cost of all materials, equipment, energy, and workforce.	Cost data over time, graphs
Environmental cost	€/kg, m2, unit or total	Monetized environmental impacts related to the usage of materials and machines during maintenance Monetized environmental impacts related to the energy consumption	Cost data over environmental impact category, graphs
Total LCC	€/kg, m2, unit or total	Life cycle costs are costs occurring during whole life cycle of a structure including end of life for different scenarios. For calculation of LCC a life cycle scenario needs to be developed with prospects of deterioration and timing of certain maintenance interventions.	Annual cost per scenario Total costs
KPI Health and Safety			
Comfort for the users before and after the rehabilitation	Temperature, humidity	Deviation from designed temperature and humidity in the building	Thermocouples Humidity measurement
Structural safety before and after the maintenance works	Condition index Reliability Index	Condition of the structure before and after the maintenance based on inspection. Reliability-based structural assessment.	Visual inspection using UAVs Automated detection of damages / cracks, using AI → visualisation in DT
Safety of workers during maintenance works	# of accidents or near-misses per day	Contractor and owner records of accident-related issues happening on site, number of workers accidents (fatal and non-fatal) during the maintenance works and number of near misses during the maintenance works	Camera – video Number and severity of reported accident issues, graph and location

Performance indicators	Units	How to measure	Integration Into Digital Platform
Environmental pollution during maintenance works	PM (air pollution)	Measurement of the air, soil, or water pollution during maintenance works	Meteorological or air quality measuring station Mobile air quality stations
	Noise level (dB)	Noise level during maintenance works if close to populated areas	Noise Level Meter

6 CONCLUSION

The main objective of this report was to present a set of KPIs and PIs to plan and control productive, resource efficient, and safe maintenance together with guidelines for their applications. Four main KPIs have been agreed at the early stage of the project, namely productivity, resource efficiency, health and safety and cost and applied as a main structure of our KPI framework, which presents a basis for the development of the ASHVIN applications and tools, such as MatchFEM, GISI and RISA.

During the implementation of asset management strategies, maintenance actions are required in order to keep assets at a desired performance level. As the focus on an efficient delivery of asset (buildings and infrastructure) performance increases, so does the interest in the relations between economy, environmental and societal goals. The implementation of asset management should increase the integration of network, system network and asset performance requirements. In doing so, asset managers and owners face a number of challenges. Therefore, this report describes the quantification methodologies for each PI identified for four KPIs, in order to support decision making and development of optimized maintenance plan. The report presents also a continuation of the work presented in D5.1 SHM digital twin requirements for residential, industrial buildings and bridges (Casas et al., 2022), where the overview of SHM techniques is presented together with requirements for meaningful implementation of a physical asset into Digital Twin models.

The exemplary implementation of the KPIs on four selected demonstration projects with appurtenant performance indicators is provided.

Accurate digital twins that represent the situation during operation provide the basis for analysis of different flexible predictive maintenance scenarios. Three interdependent tools, MatchFEM (Chacón et al., 2023), GISI and RISA, were developed to enable establishment of a risk-based predictive maintenance planning, a risk-based status assessment tool with KPI dashboard and a GIS integrator for digital twin-based asset management. The GISI tool allows the visualization of condition assessment results using safety PIs. The MatchFEM tool enables digital-twin multi-physics simulations, which is used for the structural performance assessment and prediction. And finally the RISA tool uses the results of the MatchFEM and GISI tools as a KPI for the assessment of infrastructure performance. Selection of maintenance strategy can vary from no maintenance and just monitoring, to minor or major repair and finally replacement. The RISA tool takes into account consequences of different maintenance options and illustrates the risk for different maintenance strategies. Once the risk is calculated by applying the RISA tool, the result is then returned into the MatchFEM and / or GISI to visualize impacts on the safety on the 2D or 3D model.

The target group for this document are consortium partners and demonstration project owners, in particular infrastructure managers, decision makers, contractors, or consultants responsible for maintenance planning and execution.

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