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Review paper

The management of bridge structures – challenges and possibilities

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Abstract: Bridges are particularly vulnerable elements of transport infrastructures. In many cases, bridge structures may be subject to higher volumes of traffic and higher loads as well as more severe environmental conditions than it was designed. Sound procedures to ensure monitoring, quality control, and preventive maintenance systems are therefore vital. The paper presents main challenges and arriving possibilities in management of bridge structures, including: relationships between environment and bridge infrastructure, improvement of diagnostic technologies, advanced modelling of bridges in computer-based management systems, development of knowledge-based expert systems with application of artificial intelligence, applications of technology of Bridge Information Modelling (BrIM) with augmented and virtual reality techniques. Presented activities are focused on monitoring the safety of bridges for lowering the risk of an unexpected collapse significantly as well as on efficient maintenance of bridges as components of transport infrastructure – by means of integrated management systems. The proposed classification of Bridge Management Systems shows the history of creating such systems and indicates the expected directions of their development, taking into account changing challenges and integrating new developing technologies, including automation of decision-making processes.

Keywords: bridge, management, environment, diagnostics, BIM, Bridge Management System

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1. Introduction

The number of new bridge structures designed and constructed during a year in each country is usually about 1% of the total number of existing bridge structures. It means that about 99% of bridge population needs efficient management of their operation and maintenance, which is a real challenge. The main tasks in the development of bridge management technologies can be defined as follows:

– a balance between environment condition and bridge infrastructure construction, operation and maintenance, including ecological requirements of sustainable development of transport infrastructure (e.g. [1, 2]),
– more and more precise diagnostics of bridge condition, based on results of advanced Non-Destructive (NDT) and Semi-Destructive Tests (SDT) as well as technical systems for continuous monitoring of structure response to loads and environmental influences, focused on detection and identification of bridge defects and degradation processes (e.g. [3–6]),
– innovative techniques of bridge structures modelling in computer-based Bridge Management Systems (BMS) with effective technologies of decision-support Expert Systems (ES), using resources of data and knowledge bases with application of Artificial Intelligence (AI) [7–15],
– development of modern Bridge Information Management (BrIM) technology with elements of Augmented Reality (AR) and Virtual Reality (VR), e.g. [16–18],
– effective integration of bridge management with other systems involved in the management of the whole transport network [19, 20].

Accomplishing the goals mentioned above seems to be realistic thanks to the quick development of digitalisation technologies as well as the application of new unconventional techniques of structure condition testing and monitoring. Development of technologies of the transport infrastructure management in essential scope is stimulated by international research cooperation supported by the European Union, like "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Live" [21] or "Quality specifications for roadway bridges, standardization at a European level" [22]. It creates a chance for the integration of transport infrastructure management in the whole EU.

2. Bridge management and environment

2.1. Components of the environment

In the environment four main components can be distinguished (Fig. 1):

– lithosphere – the solid, outer part of the earth including the brittle upper portion of the mantle and the crust, the outermost layers of earth's structure,
– hydrosphere – the part of a planet that is made of water (oceans, rivers, lakes, clouds, etc.),
– atmosphere – the mixture of gases around the earth,
– biosphere – the global ecological system integrating all living beings and their relationships, including their interaction with the elements of the lithosphere, hydrosphere, and atmosphere.

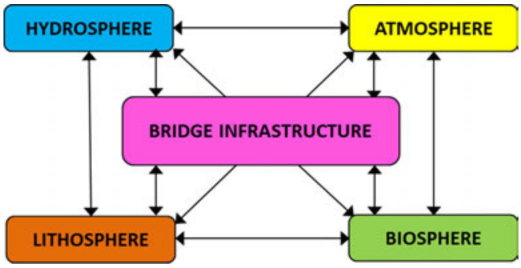

Fig. 1. Relationships between components of environment and bridge infrastructure

All components of the natural environment are mutually dependent as presented in Fig. 1. Natural environment means all living and non-living things occurring naturally, meaning not because of humans. Human civilization is changing the original environment and an element of the changes is also created by a transport network, including bridge infrastructure. On the other hand, bridge structures are strongly influenced by each component of the natural environment. The relationships between bridge infrastructure and environment are fundamental for the development of transportation network management, but also are very complex – some of the interactions are presented below for the basic components of the natural environment.

2.2. Lithosphere

The lithosphere is creating conditions for each bridge structure design, including foundation, taking into account the conformation of the terrain and ground conditions (Fig. 2).

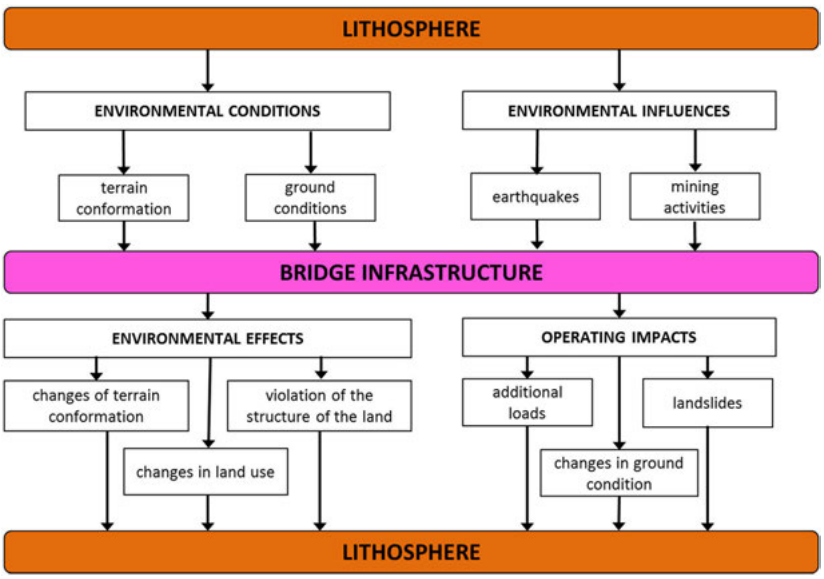

Fig. 2. Mutual relationships between lithosphere and bridge infrastructure

Some environmental influences of the lithosphere, e.g., earthquakes, effects of mining activities, are also significant for the design and safety operation of bridge structures.

Bridge infrastructure can modify lithosphere by (Fig. 2):

- changes of terrain conformation,
- violation of the structure of the land,
- changes of land use.

Bridge operation is also producing impacts transmitted to lithosphere – mainly additional static and dynamic loads resulting in higher stresses, what can provoke, e.g. landslides and changes in ground structure or in-ground condition.

2.3. Hydrosphere

Environmental conditions related to the hydrosphere, like navigation requirements, frequent floods and ice floats (Fig. 3), are of high importance for bridge design and management. In the management of bridge operation and maintenance also other hydrosphere influences in the form of degradation mechanisms have to be taken into account: leaching, erosion, blur, corrosion, and overloading (e.g., during a flood). On the other hand, the bridge infrastructure can cause environmental effects, like the disruption of water flow, changes in groundwater levels as well as the use of water for the construction. The most

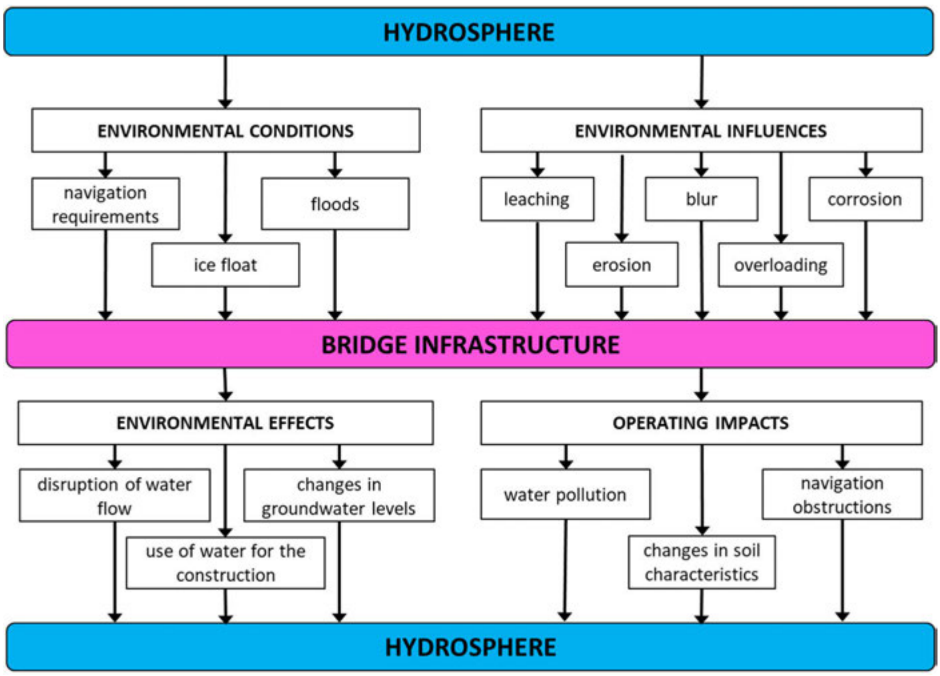

Fig. 3. Mutual relationships between hydrosphere and bridge infrastructure

common impacts associated with the operation of bridge infrastructure are the following: water pollution, navigation obstructions and changes in soil characteristics (Fig. 3).

2.4. Atmosphere

Atmospheric circumstances, like temperature, wind, air pollution, precipitation, solar radiation, etc., are very important for the condition of bridge infrastructure. The atmospheric influences are crucial for the initiation and development of degradation mechanisms: erosion, corrosion, carbonation, freezing/defrosting, chemical aggression (Fig. 4).

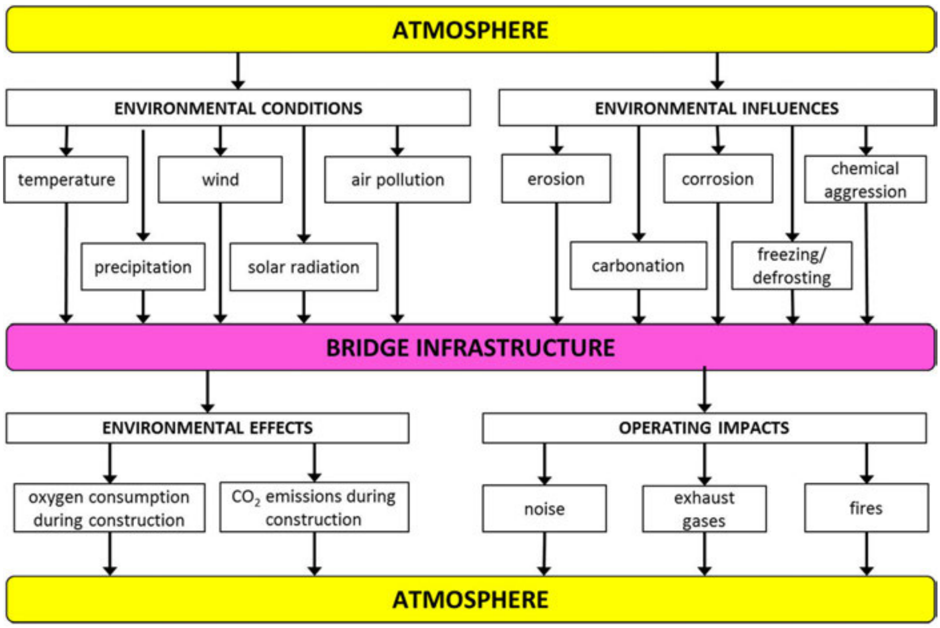

Fig. 4. Mutual relationships between atmosphere and bridge infrastructure

Bridge infrastructure can also modify the atmosphere because of oxygen consumption or CO_2 emissions during construction. Impacts on the atmosphere produced by the operation of bridge structures are usually related to noise, exhaust gases and fires, as presented in Fig. 4.

2.5. Biosphere

In the biosphere, two groups of factors influencing bridge infrastructure can be distinguished (Fig. 5): natural environmental bio-conditions (microorganisms, plants, animals) and influences related to human activities (operating loads, collisions, fires, vandalism, military actions, etc.).

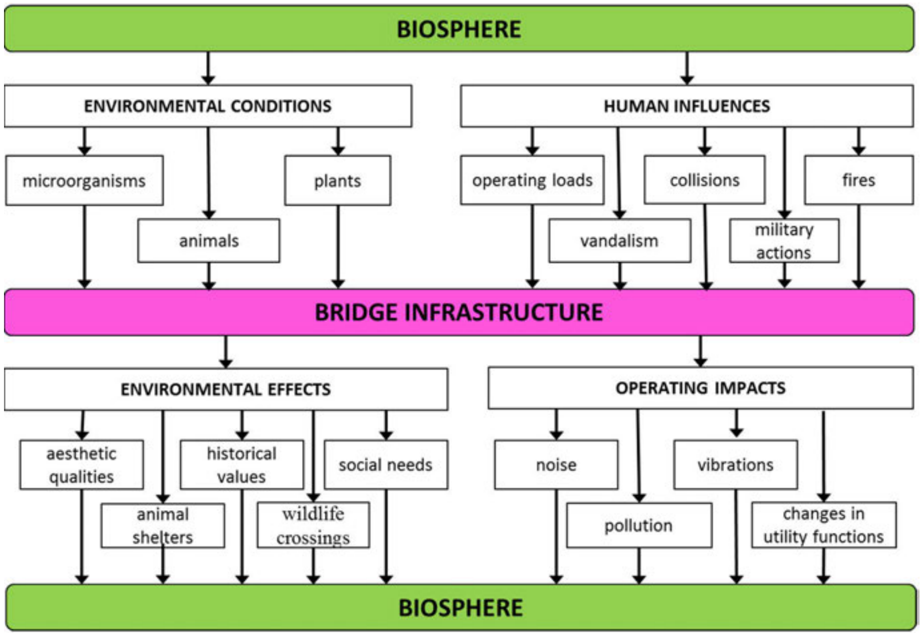

Fig. 5. Mutual relationships between the biosphere and bridge infrastructure

Interaction between bridge infrastructure and biosphere, as presented in Fig. 5, can be deliberated from the point of aesthetic qualities as well as historical values or generally – social needs. In some cases, bridge structure can also be an animal shelter or wildlife crossing. Direct impacts on biosphere because of bridge infrastructure operation are mainly focused on:

– noise and vibrations,
– various types of pollution,
– changes in utility functions of the structure surrounding.

3. Diagnostics in bridge management

3.1. Stimulators, mechanisms and processes of bridge degradation

Bridges are exposed to a harsh environment, rain, snow, de-icing salt, temperature fluctuations as well as they undergo a significant amount of cyclic loading. The condition of a bridge is typically diminishing in time due to degradation mechanisms activated during the operation of the structure. The final degradation process of a bridge structure usually consists of few mechanisms acting simultaneously. The effects of the structural deterioration are observed in the form of defects diminishing the condition of a bridge, as presented in Fig. 6.

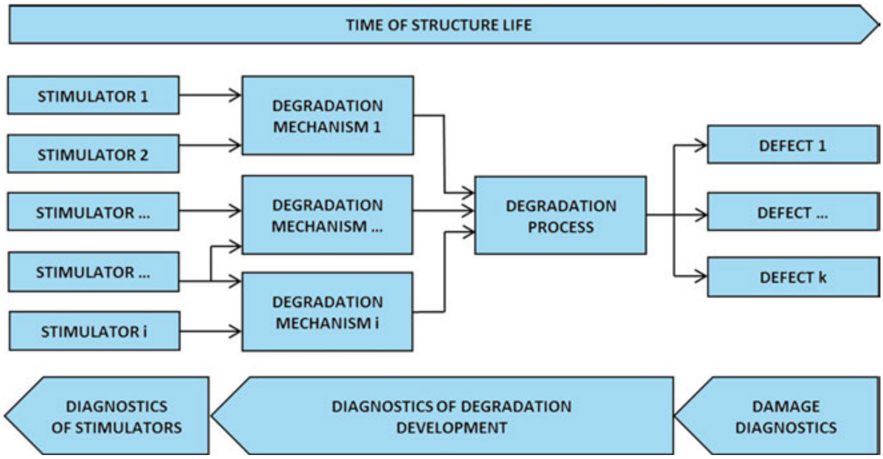

Fig. 6. General scheme of bridge degradation and diagnostic procedure

Information on structure condition, collected by means of various diagnostic technologies, are fundamental for effective management of bridge infrastructure. Three levels of diagnostic activities can be distinguished (Fig. 6):

– damage diagnostics – focused on detection and identification of existing defects,
– diagnostics of degradation development – concentrated on identification of active degradation mechanisms and finally on the identification of the whole degradation process,
– diagnostics of stimulators – focused on the identification of degradation stimulators.

Specific to bridge structures stimulators can be related to human activities (e.g., design or construction mistakes, operation and maintenance errors, collisions, war accidents, vandalism) or to influence of the environment (e.g., aging processes, water penetration, earthquakes, climate & weather conditions). Some of the degradation mechanisms can also be stimulated by simultaneous action of human and environmental factors (e.g. mining effects, fire, flood, pollution).

Degradation mechanisms can be divided into three groups (Table 1):

– chemical mechanisms – causing structure deterioration as a result of chemical processes: carbonation, corrosion, reactions between aggressive material components, etc.,
– physical mechanisms – when deterioration is a consequence of physical phenomena, e.g., erosion, overloading, fatigue, crystallization, extreme temperatures, freeze-thaw action, rheological effects,
– biological mechanisms – in the case of deterioration aroused by biological organisms: microbes, plants, animals, etc.

Activities of degradation mechanisms dominantly depend on the type of material used for bridge construction. Comparison of the importance of the basic chemical, physical and biological mechanisms to deterioration of various materials of bridge structures is shown in Table 1.

Table 1. Degradation mechanisms versus structural materials [4]

Degradation mechanism		Material of structure						
		plain concrete	reinforced concrete	prestressed concrete	steel	masonry	timber	soil
Physical	Accumulation of inorganic dirtiness	■	■	■	■	■	■	□
	Cyclic freeze-thaw action	■	■	■	□	■		■
	Erosion	■	■	■	□	■	□	■
	Crystallization	■	■	■		□		□
	Extreme temperatures/fire	□	□	□	■	□	■	
	Creep	□	□	□		□	□	■
	Relaxation	□	□	■	□			
	Shrinkage	■	■	■		□	□	■
	Overloading	■	■	■	■	■	■	■
	Fatigue	□	□	□	■	□	□	
	Geotechnical condition changes	■	■	■	■	■		■
Chemical	Carbonation	■	■	■		□		
	Corrosion		■	■	■			
	Aggressive compounds action	■	■	■	■	■	■	□
	Chemical dissolving/leaching	■	■	□		■		■
	Reactions between material components	■	■	■		□		□
Biological	Accumulation of organic dirtiness	■	■	■	■	■	■	□
	Activity of microbes	■	■	■	■	□	■	□
	Activity of plants	□	□	□	□	■	■	■
	Activity of animals	□	□	□	■	□	■	■

Legend: ■ – basic mechanism, □ – additional mechanism

3.2. Taxonomy of bridge defects

In the hierarchical taxonomy in each class of defects, few types of defects can be distinguished and within individual types, also few categories can be defined. An example of such a classification of defects of concrete bridges is presented in Table 2.

Bridge defect can be defined as a phenomenon diminishing bridge technical and/or functional condition as a result of a degradation process. Bridge technical condition can be described as a measure of differences between current and designed values of bridge technical parameters, e.g., geometry, material characteristics, while bridge functional con-

Table 2. Degradation mechanisms versus structural materials [4]

Class of defect	Type of defect	Category of defect
Deformation	Incorrect geometry of constructed element	Incorrect shape of concrete
		Invalid arrangement of reinforcement
		Invalid arrangement of prestressing tendons
	Change of the geometry of element axis	Excessive elastic deformation
		Permanent deformation
	Change of the geometry along the element length	Excessive elastic deformation
		Permanent deformation
Destruction of material	Change of the chemical characteristics	Change of concrete characteristics
		Change of reinforcing material characteristics
		Change of prestressing material characteristics
		Change of protective layer characteristics
	Change of the physical characteristics	Change of concrete characteristics
		Change of reinforcing material characteristics
		Change of prestressing material characteristics
		Change of protective layer characteristics
Loss of material	Loss of structural material	Loss of concrete
		Loss of reinforcing material
		Loss of prestressing material
	Loss of material of protective layer	Loss of material of concrete protection
		Loss of protection of reinforcing material
		Loss of protection of prestressing material
Discontinuity	Crack	Crack of concrete
		Crack of reinforcing material
		Crack of prestressing material
		Crack of protective layer
	Fracture	Fracture of concrete
		Fracture of reinforcing material
		Fracture of prestressing material
		Fracture of protective layer
Contamination	Inorganic	Aggressive
		Neutral
	Organic	Aggressive
		Neutral
Displacement	Incorrect linear displacement	Excessive movement
		Restricted movement
	Incorrect rotation	Excessive movement
		Restricted movement

dition can be defined as a measure of conformity between actual operational conditions and conditions required by users, e.g., load capacity, clearance, maximum speed.

Unambiguous and precise classification of bridge defects is one of the fundamental challenges in the development of bridge management systems. In the hierarchical classification of bridge defects proposed in [4] six basic classes of defects – common for all structural materials – are distinguished (see Table 2):

- deformation: incorrect geometry of constructed element as well as excessive changes of structure geometry during operation, with changes of mutual distances between structure points – incompatible with the design;
- destruction of material: deterioration of physical and/or chemical as well as structural features of material in relation to the designed values;
- loss of material: decrease of the designed amount of structural material;
- discontinuity: break of continuity of a structural material – inconsistent with the design;
- contamination – the appearance of any dirtiness or not designed vegetation on the structure;
- displacement: change of the position of a structure or its part – incompatible with the design, but without changes of mutual d istances between structure points (without deformation); also – restrictions in the designed displacement capabilities of the structure.

3.3. Monitoring of bridge condition

3.3.1. Monitoring strategies

Classification of strategies of bridge condition monitoring is presented in distinguished Fig. 7. In the diagnostic strategy of bridge structures, two main options can be distinguished (see Fig. 7):

- field-testing – a group of diagnostic tests performed in the field on existing structures,
- laboratory testing – a group of diagnostic tests executed in the laboratory on specimens or elements of a bridge structure as well as on small bridge structures or models constructed in the laboratory.

Field and laboratory testing are not alternative options, and very often, both these policies are applied together for effective bridge diagnostics.

Taking into account the “aggressiveness” of the tests three categories, presented in Fig. 7, can be specified:

- non-destructive tests – techniques and methods, which in any way do not breach the integrity of the tested structures – mainly applied during field tests,
- semi-destructive tests – techniques and methods requiring material samples to be taken for laboratory examinations or demanding any other minor breach of structural integrity during field tests,
- destructive tests – techniques and methods, which involve the destruction of an analysed structure or its elements during the testing procedure performed in the field or laboratory.

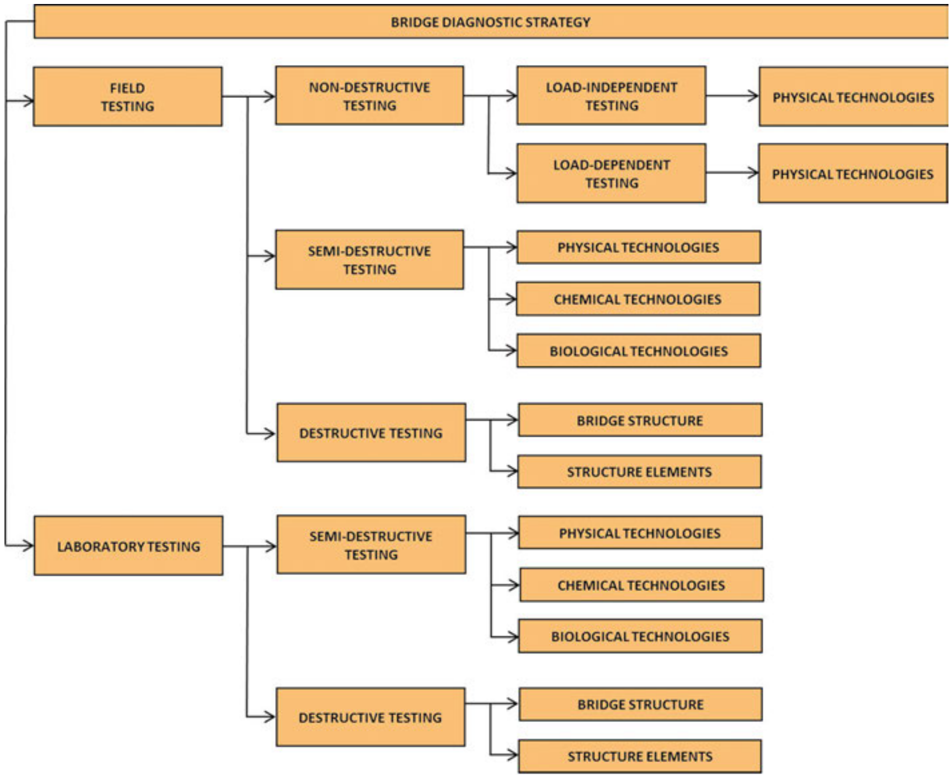

Fig. 7. Classification of diagnostic testing policies in bridge engineering

The group of non-destructive diagnostic tests is predominantly based on applications of physical technologies, whereas during semi-destructive as well as destructive tests of bridge materials and structures, various physical, chemical and biological technologies are applied as presented in handbooks and state-of-the-art analyses, e.g. [23–30].

The most important and popular diagnostic strategy is based on non-destructive field tests of bridges. In this strategy, two types of tests can be distinguished, as presented in Fig. 7:

– load-independent tests, which provide results regardless of loads acting on the tested structure (traffic loads, environmental influences, etc.),
– load-dependent tests, which are based on the effects of interaction between tested structure and loads (static or dynamic) acting on the structure.

The non-destructive diagnostic strategy offers condition evaluation of structural components without damaging them and can be applied during the whole life of the structure. The non-destructive field tests can be used for quality control during the erection of new structures, condition assessment of existing structures and quality assurance of repair works. Non-destructive testing is particularly useful for evaluating bridges in-service since the structures may remain open to traffic during the inspection and the evaluation period.

3.3.2. Load-independent NDT techniques

In the category of load-independent field tests, the following basic technologies are the most popular: acoustic, electrical & electromechanical, electromagnetic & magnetic, optic, mechanical as well as radiological measurements. In each technology, a number of specific techniques are available – addressed to requirements of bridge engineering, as presented in Table 3. The area of application of each technique depends on specific physical phenomena involved and on characteristics of materials of the tested structure.

Non-destructive load-independent field tests are applied during all types of inspections. Effects of load-independent diagnostic tests form a basis for evaluation of bridge technical and functional condition and – in the next step – for decisions in operation and maintenance of the structure.

Main goals of the load-independent tests can be categorised in three primary groups:

- identification of structure geometry, including the geometry of the whole structure as well as all its elements (thickness, location of reinforcement and prestressing wires, etc.),
- determination of material characteristics and quality, like strength, modulus of elasticity, homogeneity, permeability, humidity, temperature or chemical composition,
- detection, identification, and classification of all types of structure defects.

For selected, most encouraging, techniques comparison of their applicability in diagnostics of structure geometry and material characteristics is presented in Table 3. The testing technique is categorised as "basic" – when its applicability in tests of considered structural material is confirmed and "additional" – in the case of a supplementary technique.

Table 3. Geometry and material characteristics detectable by non-destructive load-independent diagnostic methods

Technology	Non-destructive testing technique	Geometry			Material characteristics					
		structure geometry	element geometry	reinforcement/wires identification	strength/modulus of elasticity	homogeneity	air/water permeability	humidity	temperature	chemical composition
	Chain drag technique					□				
	Electromagnetic acoustic transducer		■			□				
	Hammer sounding					□				
	Impact echo		■	□	■	□				
	Impulse response		□			■				
Acoustic	Parallel seismic		■							
	Phased array ultrasonic		■			■				

Continued on the next page

Table 3 – *Continued from the previous page*

Technology	Non-destructive testing technique	Geometry			Material characteristics					
		structure geometry	element geometry	reinforcement/wires identification	strength/modulus of elasticity	homogeneity	air/water permeability	humidity	temperature	chemical composition
	Time-of-flight diffraction					■				
	Ultrasonic surface waves				■	□				
	Ultrasonic tomography	□	■	■						
	Ultrasonic velocity		■		■	□				
Electrical	Electrical potential							□	■	
	Electrical resistivity					□	■	■	□	□
	Microelectromechanical systems							■	■	
Electro-magnetic & Magnetic	Alternating current field					■				
	Eddy-current testing					■				□
	Electromagnetic conductivity		■	□		□				
	Magnetic flux leakage					□				
	Magnetic particle testing					■				
	Radar techniques	■	■	■		□		□		
Optic	Closed-circuit television	□	□							
	Geodesy/GPS surveying	■	■							
	Infrared thermography testing			■		□		□	■	
	Laser techniques	■								
	Microscopy/endoscopy	□	■			□		□		
	Visual inspection	■	■			□		□		
Mechanical	Hardness testing				■	■				
	Liquid penetrant					■				
	Pressure techniques						■			
	Sclerometric techniques				■	■				
Radiological	Computer tomography		■	■						
	Gamma- or X-ray radiography		□	■		□				
	X-ray fluorescence									■
	Transmission radiometry				■	□				

Legend: ■ – basic technique, □ – additional technique

3.3.3. Load-dependent NDT techniques

Load-dependent field testing procedures involve the application of transducers for sensing physical or chemical quantities changes influenced by actions on structure, along with programmable electronic equipment for acquiring, processing and communicating data as well as utilization of algorithms that define how data acquisition, processing and communication is performed. In load-dependent field non-destructive examinations of bridges, two technologies can be used: static tests and dynamic tests. During the tests by means of installed technical measuring equipment, numerous techniques and sensors can be applied [31–35]. Information on the most effective load-dependent diagnostic techniques recently applied for static and dynamic tests of bridge structures is summarised in Table 4.

Table 4. Load-dependent techniques and sensors in static and dynamic field testing of bridges

Technology	Non-destructive techniques and sensors	Testing goals							
		linear displacement	rotation	strain	vibration velocity	vibration acceleration	vibration damping	crack development	load identification
Acoustic	Acoustic emission technique			□				■	
Electrical & Electro-mechanical	Anemometers								■
	Electrical capacity sensors				■	■			
	Electrical resistance sensors			■	□	□	□		■
	Electrochemical fatigue sensors							■	
	Inclinometers/tiltmeters		■						
	Inductive sensors	■			■	■	■	■	
	Load cells								■
	Microelectromechanical systems		■	■	■	■	■		
	Piezoelectric sensors				■	■	■		
	Weigh-in-motion systems								■
Mechanical	Hydraulic sensors	■							
	Mechanical sensors	■		□		□		■	
Electro-magnetic	Radar techniques	■			■	■	■		
	Vibrating wire sensors	■	■	■	□	□	□	■	■
Optic	Closed-circuit television								■
	Digital image cross-correlation	■	■	□	□	□	□		
	Fiber optics technique	■	■	■	■	■	■	■	
	Geodesy	■	□						
	Laser techniques	■	□		■	■	■		

Legend: ■ – basic technique, □ – additional technique

Depending on the goal of analysis, the following types of continuous technical monitoring systems can be distinguished:

– action monitoring – allowing assessment of the magnitude as well as the spatial and temporal distribution of specific forces acting on a structure or a structural component, including traffic loads and environmental impacts,
– reaction monitoring – allowing assessment of the state of displacement, stress/strain level and distribution in a structure as well as vibration parameters: frequency, velocity, amplifications, damping caused by traffic loads and other influences,
– performance monitoring – allowing to evaluate whether a structure or a structural component meets the performance requirements under specific or any actions, defined by the performance indicators,
– health monitoring – monitoring allowing the real-time assessment and prediction of the health condition of a structure or a structural component by means of their safety and serviceability indicators.

4. Digitalisation in bridge management

4.1. Modelling of bridge geometry

Bridge design and construction processes require making models of the structures and then bringing the models into reality. In bridge management, a reverse operation is necessary, i.e., creating computer models of already existing structures. Modelling of bridge structures in the computer-based Bridge Management Systems (BMS) is of great importance to the efficiency of the management process. The precision of the numerical representation of the structure geometry and defects influences the accuracy of the efficient assessment of the bridge condition and serviceability. In almost all contemporary Bridge Management Systems only non-dimensional models of bridge structures are applied, e.g. [4, 8–11, 17, 21, 22]. It means that the bridge infrastructure is geometrically represented by a set of non-dimensional points located on a map. Characteristics of each structure component (dimensions, material data, inspection data, etc.) are not oriented in the space, but are only assigned to the "name tag" of the structure, usually in the form of database. Classification of the models of bridge geometry which can be applied in BMS can be based on two parameters (Fig. 8), taking into account the conception presented in [11]:

– elements used for construction of a model – with possible application of non-dimensional (e^0), one- (e^1), two- (e^2) or three-dimensional elements (e^3);
– the dimension of the space needed for model creation – from non-dimensional space (s^0) to real three-dimensional space (s^3).

Presented taxonomy of the geometric models suitable for the Bridge Management Systems is shown in Fig. 8 on the example of the box girder bridge span. Columns in Fig. 8 correspond to the dimensionality of space used for model creation – from a non-dimensional point to the full three-dimensional space – accordingly. The rows indicate the

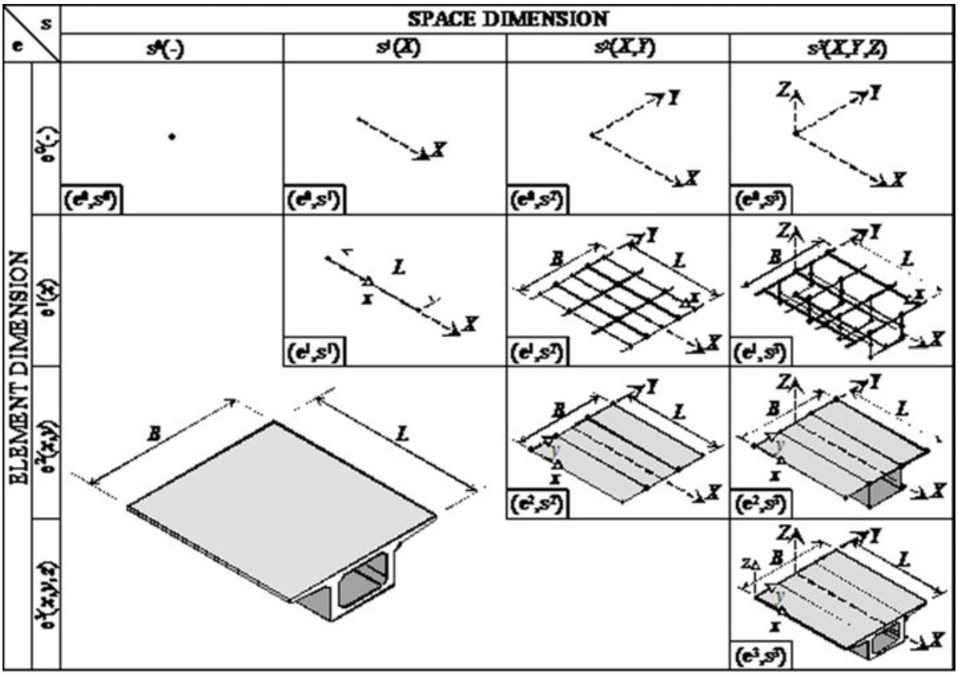

Fig. 8. Taxonomy of bridge geometry models – examples of various models of bridge box girder [11]

dimensionality of elements representing the bridge structure in the model. Combinations of the parameters (e^i) and (s^j) give ten basic classes of the considered models of bridge geometry denoted as (e^i, s^j), where "i" is the dimensionality of elements, and "j" is the dimensionality of space. The quick development of Information Technology (IT) enables in the near future wide implementation of fully three-dimensional geometrical models of bridge structures in contemporary management systems. Such models of the class (e^3, s^3) are applied in developed technology of the Bridge Information Modelling (BrIM), where a component of asset management is one of the fundamental parts [15, 18, 20, 39, 40].

4.2. Expert tools and artificial intelligence

One of the most important trends in the evolution of bridge management seems to be an extensive application of knowledge-based expert tools with artificial intelligence, e.g. [4, 12, 31, 37, 40–43]. The expert tools can be defined as software imitating human thoughts way of solving tasks based on the data and knowledge stored in the computer system. The variety of bridge constructions, complex and changeable environmental, operational and economic conditions require advanced tools making the systems intelligent by equipping them with the ability to learn, recognize, conclude, and even to choose and achieve goals.

The expert tools supporting the main decision processes in the Bridge Management Systems can fulfil the requirements mentioned above.

The preparation of the knowledge-based expert tools for the BMS needs close cooperation of civil engineers, knowledge engineers, computer scientists, etc. The procedure usually requires the following main steps:

– selection of the knowledge representation method, corresponding to the form of the available information,
– acquisition of the knowledge as a special type of information,
– construction of the computer knowledge base coupled with the system database,
– selection of the proper inference mechanisms for each particular application,
– creation and validation of the expert tool supporting decisions,
– analysis and interpretation of the results of computer reasoning and application of the conclusions in the decision processes.

Analyses of the information necessary in the procedures of bridge management confirm that decisions are very often based not only on relatively precise information (e.g., geometrical and material data) but also on fuzzy information (e.g., intensive defect, low aesthetics) or information of various degrees of uncertainty, e.g. [37–39,45]. Each type of information requires a specific method of numerical representation in the computer system – adequate to the level of knowledge precision or fuzziness necessary. The most popular technologies of knowledge representation applied in expert systems supporting bridge management are artificial neural networks, fuzzy reasoning, and classic mathematical tools. The integration of various knowledge representation techniques in one expert tool is possible by means of the technology of multi-level hybrid networks [45]. The hybrid network can be created – depending on the problem that needs to be solved and on the type of available information – by means of the following components:

– neural components, based on non-linear multi-layer artificial neural,
– fuzzy components, based on the fuzzy logic with the necessity of fuzzy inference,
– functional components that enable the implementation of various types of analytical functions.

The process of expert tool creation by means of the multi-level hybrid network technology is presented in Fig. 9. After the general analysis of the problem and the acquisition of the available knowledge – the architecture of the final network should be designed. Depending on the form of the accumulated information, the analyzed problem should be divided into sub-problems. In the next step for each sub-problem, a dedicated component of the network is created. All the components are prepared in the form of individually created elements that are stored in the library of the computer system and can be used in various networks. The selection of each component type depends on the quality, quantity and form of the available information. Every component has to be prepared individually and must pass all required tests before it can be applied as a part of the final network. In the last step of the creation process, the components are connected to form a multi-level network, which should be finally validated before application as an expert tool.

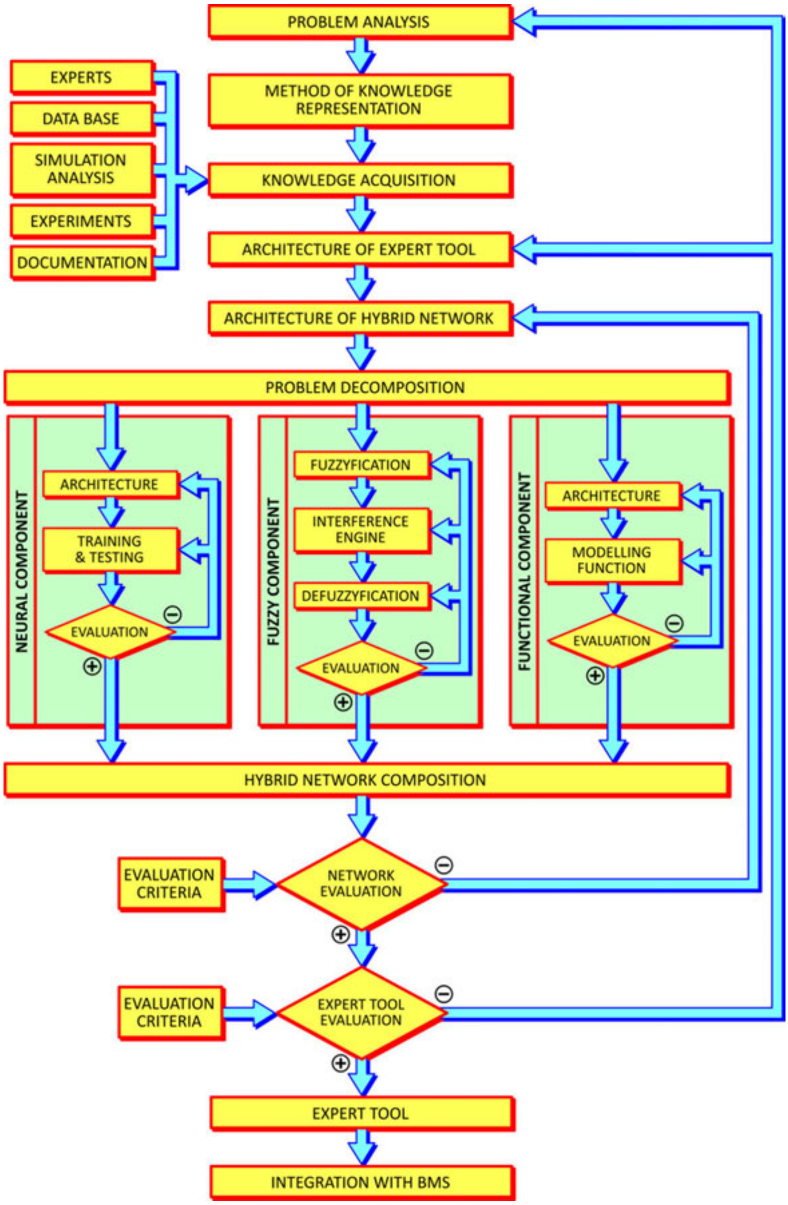

Fig. 9. Creation of an expert tool based on the technology of multi-level hybrid networks [45]

4.3. Bridge Information Modelling (BRIM)

CAD programs have typically been used by designers as only electronic 2D drawing boards. Neither the equipment nor the CAD program interface encouraged the use of 3D tools. This began to change when 3D technology started to be used in the design of increasingly complex and sophisticated bridges (Fig. 10). The development of these programs added more often contractual dimensions. The fourth dimension, time, can also be to create project animations as well as to prepare schedules and plans for the supply of materials [44]. The fifth dimension introduces a cost factor and allows for the development of model estimates [48]. The two subsequent dimensions are often combined and deal with the management of finished projects. These capabilities allow the use of BIM technology during the inspection of bridges [53].

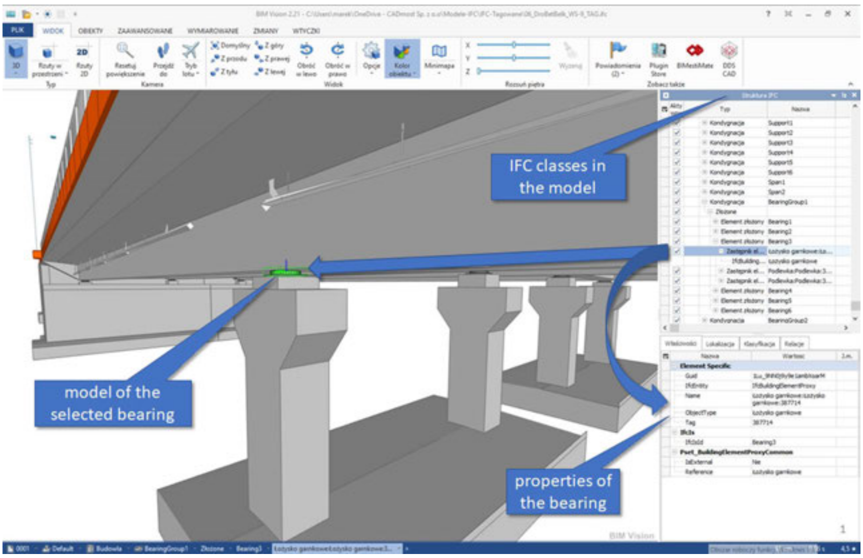

Fig. 10. Preview the BrIM model with the properties of the highlighted bearing

BIM technology is much better known in the construction industry (vertical BIM). It is used by architects, construction companies, and installers. Many public buildings are constructed with the use of this technology, such as hospitals, airports, office buildings, hotels, etc. BIM in infrastructure projects (linear BIM) is being implemented more slowly, for example, in the construction of roads, railway lines, bridges, tunnels, harbours, wharves, and dams. This delay may be due to the planning and realisation of infrastructure tasks.

The first fundamental issue is that the vast majority of infrastructure investments concern the public procurement sector. Unfortunately, public institutions belong to organisations that are resistant to the implementation of new technologies and improvements inefficiency. Another difficulty that delays the use of BIM technology in infrastructure projects is the slower development of BIM tools for infrastructure than for residential/commercial/industrial buildings. Finally, BIM itself still has problems, especially with regards to custom bridge geometries. This includes the overlapping of geometries in horizontal and vertical directions, transition curves, gradients, widening, and thickening [51]. This is especially problematic for monolithic concrete bridges. The most popular CAD programs that are not part of the group of BIM products can cope with these challenges, but they do not have the ability to maintain the proper relationships between model objects without full parameterisation, which brings further burdens to storage and management of additional information. Taking into consideration all the specifics of bridges and the nomenclature of their components, we propose introducing BrIM, Bridge Information Modelling or Management.

An example of the bridge used to create a BrIM model is presented in Fig. 11. It is a five-span bridge with a total length of 216 m, which runs over railway lines in Gliwice, Poland. It was constructed using the incremental launching technology in accordance with the traditional design documentation prepared in 2013. In the cross-section, it is a concrete box-girder with external prestressing. The bridge can, therefore, be classified as a mid- to a large-sized road bridge, whose inspection is typically time-intensive and important.

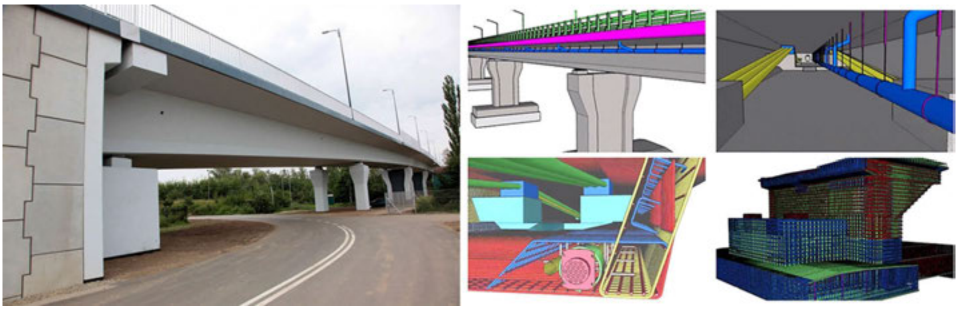

Fig. 11. The Hevelius Bridge and its BrIM model

The BrIM model of the bridge (Fig. 12) was developed in accordance with two procedures: based on the design documentation, and based on the cloud of points obtained in laser scanning. Both were compared and merged for further research. The first contains several details and information that are not available for scanners. There are supports with reinforcement, box girder with tendons and reinforcement, internal installations, and equipment. Everything was assigned to the appropriate thematic layers and marked with specific colours. In this way, the user of the model will be able to select the displayed objects.

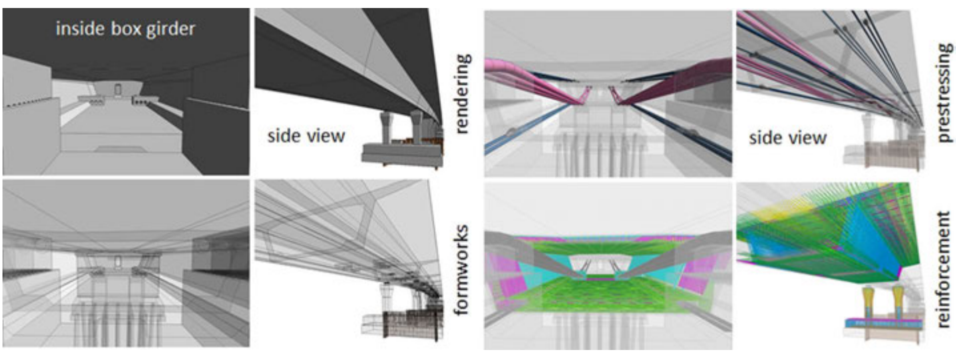

Fig. 12. Synthesis of real and virtual images on the example of the Hevelius Bridge BrIM model

4.4. Augmented and Virtual Reality

The solution here may be the use of Augmented Reality (AR). AR visualises cybernetic information against physical images and enables manipulation of cybernetic information by interaction with real and/or cybernetic objects [16]. AR can supplement and simultaneously use the BIM technology described above. AR is extremely promising. It allows combining the computer-generated world (virtual) with the real world (where the user is) so that they form one synthesised environment [16]. It is a continuum of the real and virtual world (Fig. 13), sometimes called also as Mixed Reality (MR).

Fig. 13. Continuum of the real and virtual world [52]

In contrast to the more popular Virtual Reality, in which the user is completely immersed in the virtual world, AR gives one the freedom to work in the real world while enhancing human perception with virtual objects. Modern visualisation techniques such as AR allow representing the virtual world in an extremely intuitive way by 3D objects with the ability to view them from any perspective, with textures that are indistinguishable from the actual textures of real objects and at any scale. Elements enriching reality using AR systems can also take forms beyond three-dimensional models, including subtitles, diagrams, photographs, films, and audio information [17, 47].

The increasing popularity of AR technologies is due to the benefits they bring. First of all, it is possible to supplement reality with information from a database and/or knowledge. Instead of completely replacing the world surrounding a person with an artificial, virtual world (as is the case with VR), AR enriches the real world by adding only the information necessary to enhance one's reliability (Fig. 14). This information can be delivered to the user of the system on demand [50]. The more common practical use of AR technology is

Fig. 14. The interior of the box girder seen in the continuum of the real and virtual world

on special devices such as helmets or glasses. For example, when assembling or inspecting technical equipment, an installer "sees" animations and information superimposed on real images to help them complete their task correctly.

4.5. Industry 4.0

The industrial revolution and technologies such as the steam engine from the late seventeenth century teach us that each subsequent stage of industrial development is shorter. In 2011 in Germany, a development strategy called Industry 4.0 (German: Industrie 4.0) was announced. This was a combination of automation, processing of big data, and intelligent manufacturing techniques. There are also cyber-physical systems, such as the Internet of Things and cloud computing. The idea is to create a modern factory that will carry out nearly the entire production process with minimum human involvement. New production management systems that use the components mentioned above will create an "intelligent" factory that will deliver tailored products according to an individual's needs.

As already mentioned, the construction industry is delayed in implementing new digital technologies, such as automation and robotisation. However, the development of digital technologies will eventually transform the construction industry. Many global corporations are interested in this industry as there are opportunities for profit by building faster and cheaper, as well as by lowering the cost of infrastructure maintenance and extending its lifespan. However, BIM technology is the first step to make this possible and effective. Without three-dimensional models and their connection with digital information at the construction site, changes will not be made.

One of the key components of today's industrial revolution is the so-called Cyber-Physical Systems (CPS). These are the mechanisms controlled or monitored by computer algorithms that are closely integrated with the internet and its users. Physical and software components in CPS are deeply interconnected with each other and operate in different time zones and at different scales. Examples of such systems include smart grids, autonomous vehicles, medical monitoring, process control systems, robotic systems, automatic avionics, and even Structural Health Monitoring (SHM).

Given the specifics of the construction industry and the fact development often occurs in open spaces, cyber-physical mobile systems with the ability to move and even work autonomously will be ever more important in this industry. Examples of such systems include mobile robotics, as well as electronic systems transported by humans or animals. The popularity of smartphones has increased the interest and potential of mobile CPS. These can be tablets and smartphones, but also smartwatches, helmets, glasses, or contact lenses. Together these devices are called wearable devices (Fig. 16). The most critical requirements for wearable devices are:

- significant computational and storage resources with large processing capacities,
- sensory input and output devices such as touch screens, cameras, GPS modules, speakers, microphone, gyroscopes, light sensors, accelerometers, and proximity sensors,

– communication mechanisms such as WiFi, LTE, and Bluetooth for connecting devices to the internet or other devices,
– high-level programming languages for rapid development of mobile software and simple mechanisms for application distribution,
– durable and reliable battery performance.

Nowadays, these requirements are met by a large group of commonly available smartphones, which can also be found at construction sites, although perhaps not always as a tool. Unfortunately, users of CPS such as smartphones do not have the ability to see and manipulate the information needed to make decisions about processes and their surroundings. They can use a smartphone to download documentation, and images can only be compared with drawings on the screen. In this way, errors arise from discrepancies between physical and cybernetic information.

The process of recording damage and saving in the BrIM model during the inspection is very intuitive (Fig. 15). The inspector equipped with the proposed mobile devices goes to the site. When examining the object (e.g., inside the box-girder bridge), the inspector looks for possible irregularities by comparing the BrIM with the actual object. Once the damage is found, qualitative and quantitative assessments are performed, and data is archived in the BrIM model. A report from the inspection is generated automatically and goes to the administrator's database together with the damage observed. From this point on, the damage is stored in the BrIM model and can be imaged during the next inspection.

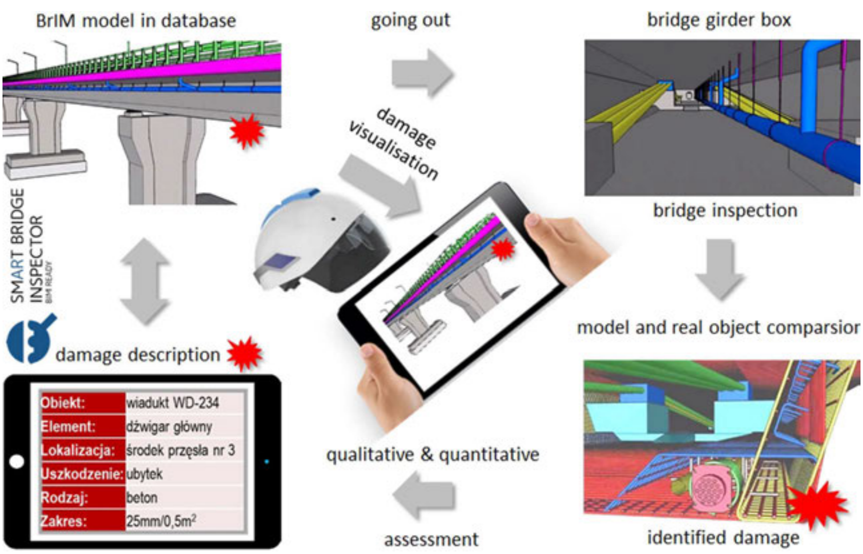

Fig. 15. Recording of damage in the BrIM model [18]

AR technology has an important place in the process of inspection in the above scenario. The inspector registering the damage works with the tracking system as one of the AR subsystems. When collecting data on identified damage, the inspector uses a wearable mobile device to take photos and record videos with text description labels (e.g., text labels to indicate important locations in the picture), graphics (e.g., graphic elements to indicate essential locations at the picture, e.g., arrows, lines, circles, etc.), and sound (e.g., voice recordings). In order to properly mark a location where the information was recorded or where the virtual object was imposed, it is necessary to use a tracking system. The location system allows saving recorded data in the BrIM model in the same location as on the real object. In the described system, two types of localisation are proposed: location based on a mobile device (accelerometer, gyroscope, compass) with SLAM support (simultaneous localisation and mapping) and GPS signal with hybrid location based on an independent localisation system (for localisation within objects). Properly saved data may be displayed again in the future during the inspection with the use of AR techniques. In this case, the user sees information regarding the current location (e.g., photos, text, sound information, sensory readings) which were saved during previous inspections and assigned to a specific location on the object on the helmet-mounted unit. Helmet integrated with Mixed Reality googles made by Microsoft and named HoloLens 2 is presented in Fig. 16.

Fig. 16. Cyber-physical mobile systems used for bridge inspection

In another application, once the mobile device is pointed at a specific place in the object and recognised the user's location and orientation, computer-generated 3D structural elements will be added to a real image. It is possible to display models of elements invisible to the naked eye. In both variants, the user selects the layer of information from the drop-down menu (according to the BrIM model such as installations, structural elements, etc.). In addition, it is possible to display information from multiple layers simultaneously (see Fig. 12). The latest use of AR techniques is integration with virtual instruments to measure identified damage. These tools are limited to simple instruments that allow measuring length (e.g. crack length) or surface area.

4.6. Integrated Bridge Management Systems

One of the most important elements of Bridge Management Systems (BMS) is the results of bridge inspections. These results are an essential source of information about the technical conditions and damages of a bridge [53]. In most countries, they are obligatory and are performed based on a systematic strategy to control the condition of transportation infrastructure. Instructions for conducting inspections in each country are described in detail. These documents also define the scope and layout of inspection reports, which currently are paper documents. Classic tablets or smartphones are neither comfortable nor safe for inspectors, and even electronic documents do not provide comprehensive support. However, introducing a new type of inspection interface based on AR eliminates the disadvantages of current inspector aid devices. Many publications [7, 44, 45, 49] have been written about the close connection of BMS with rapidly developing information technologies. These include the use of artificial intelligence, virtual and augmented reality, monitoring systems, algorithms supporting decision making, etc.

Given current trends [19, 46] and political decisions, it is increasingly likely that BIM technology in infrastructure, and BMS, will rapidly develop in the coming decades. Advanced bridge modelling methods will be required as the efficiency of this technique in BMS will depend on the virtual model of the bridge being inspected. The BrIM bridge model will be the most important element of the BMS database (Fig. 17). The practical use of BIM models is currently limited to the design phase (3D and 4D BIM) and sometimes to the construction process (4D and 5D BIM). The use of BrIM models for management and maintenance (6D and 7D BIM) occurs only in pilot projects and still requires research. This is particularly relevant to transportation infrastructures such as roads and rail bridges. Therefore, it will be necessary to develop procedures for creating bridge models for use in inspections and BMS.

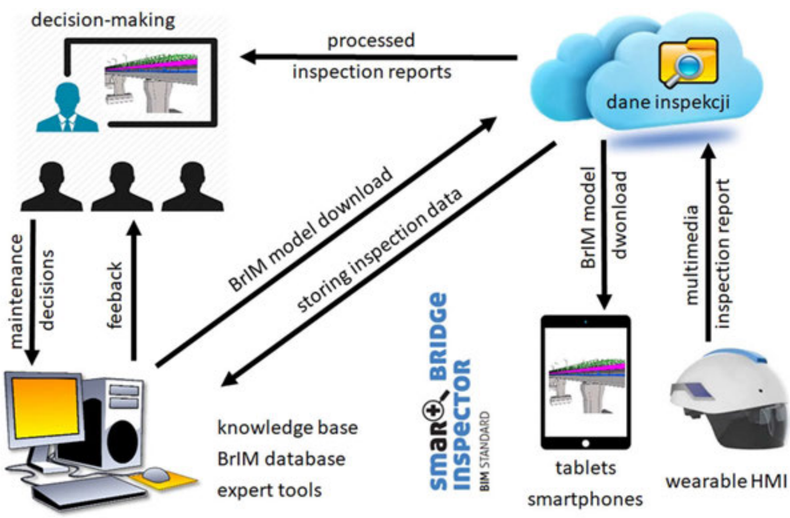

Fig. 17. Basic digital components of future Bridge Management Systems [18]

For existing objects that do not yet have such models, other procedures for bridge inspections will need to be developed, such as laser scanning and BrIM models based on clouds of points. These procedures must take into account dominant span lengths and hard-to-reach areas such as high supports and pylons, where unmanned aerial vehicles (UAV) can assist. The example of a Polish application for mobile devices aiding bridge inspections with the use o BrIM models is presented on Fig. 18.

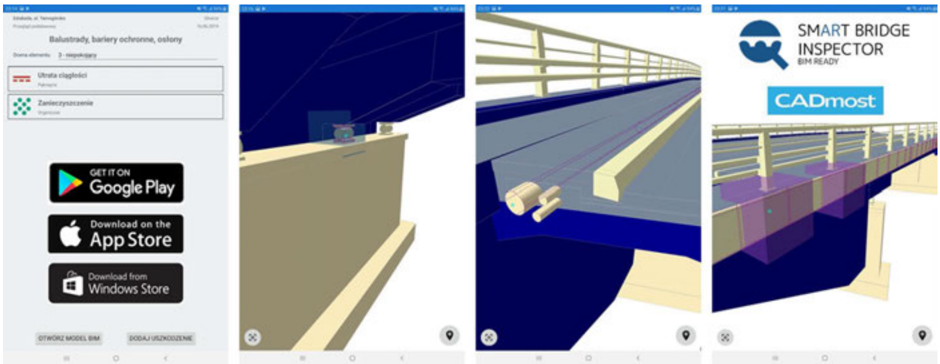

Fig. 18. User Interface of a Polish mobile application aiding bridge inspection with the use of BrIM models

5. Summary

In the coming years, the management of transport infrastructure as well as the whole industry of infrastructure construction, including bridges, awaits a revolution in design, construction, and maintenance of modern and demanding BIM technologies. Although this technology has already shown its advantages in building construction, there are still many difficulties and constraints for implementing it on a large scale for transportation infrastructure. The cyber-physical system for bridge inspections presented here can be used not only by owners and administrators of infrastructure. In many countries, bridges inspections are carried out by small private entities which are gaining popularity in the public procurement market.

On the basis of outsourcing, companies equipped with this type of equipment will be able to offer their services at a better value, which will also satisfy contracting authorities. Classification of important current and future generations of the Bridge Management Systems is proposed in Table 5.

Taking into account history of the Bridge Management Systems development as well as main challenges and possibilities in this area presented above, the following significant generations of BMS can be distinguished:

– I generation – systems based on simple applications of databases with rudimentary data processing,

Table 5. Generations of the Bridge Management Systems

BMS generation	Components of bridge management systems					
	data bases	decision algorithms	expert systems	BIM technology	integrated BrIM systems	automatic management systems
I	•					
II	•	•				
III	•	•	•			
IV	•	•	•	•		
V	•	•	•	•	•	
VI	•	•	•	•	•	•

- II generation – systems equipped with database and management procedures with pre-defined decision algorithms,
- III generation – management systems with intelligent expert tools based on a database and knowledge base implemented in the system, apart of decision algorithms,
- IV generation – systems equipped with BIM technology, based on 3D models of structures and tools supporting decisions – with elements of artificial intelligence offering an ability to learn,
- V generation – integrated management systems based on BrIM technology with the application of the augmented and virtual reality, cyber-physical systems, automation of diagnostics, etc.,
- VI generation – advanced management systems with the ability to take self-contained decisions based on the computer system's resources (including the database, knowledge base, advanced expert tools, results of automatic structure monitoring, etc.) and with the ability to direct automatic or semi-automatic control of bridge structure's parameters (e.g., automatic control of prestressing forces, traffic control).

The majority of currently functioned Bridge Management Systems can be classified into I or II generations. Some systems belonging to III and IV generation are in the phase of tests and pilot implementations. Extensive research activities are focused on management systems representing V generation [7, 15, 18, 20, 53] and initial steps can be observed in creation of a VI generation of BMS, e.g. [19, 47].

References

[1] B. Pang, P. Yang, Y. Wang, A. Kendall, H. Xie, Y. Zhang, "Life cycle environmental impact assessment of a bridge with different strengthening schemes", *The International Journal of Life Cycle Assessment*, 2015, vol. 20, no. 9, pp. 1300–1311.

[2] F. Biondini, D.M. Frangopol, Eds., *Bridge Maintenance, Safety, Management, Resilience and Sustainability*. CRC Press, 2012.

[3] S. Yehia, O. Abudayyeh, S. Nabulsi, I. Abdelqader, "Detection of common defects in concrete bridge decks using non-destructive evaluation techniques", *Journal of Bridge Engineering*, 2007, vol. 12, no. 2, pp. 215–225.

[4] J. Bień, *Defects and diagnostics of bridge structures* (in Polish). Warsaw: Transport and Communication Publishers, 2010.

[5] J. Hoła, J. Bień, L. Sadowski, K. Schabowicz, "Non-destructive and semi-destructive diagnostics of concrete structures in assessment of their durability", *Bulletin of the Polish Academy of Sciences, Technical Sciences*, 2015, vol. 63, no. 1, pp. 87–96, DOI: 10.1515/bpasts-2015-0010.

[6] J. Bień, T. Kamiński, M. Kużawa, "Taxonomy of non-destructive field tests of bridge materials and structures", *Archives of Civil and Mechanical Engineering*, 2019, vol. 19, no. 4, pp. 1353–1367, DOI: 10.1016/j.acme.2019.08.002.

[7] X. Wang, W. Dou, S. Chen, W. Ribarsky, R. Chang, "An Interactive Visual Analytics System for Bridge Management", *Computer Graphics Forum*, 2010, vol. 29, no. 3, pp. 1033–1042, DOI: 10.1111/j.1467-8659.2009.01708.x.

[8] P.D. Thompson, E.P. Small, M. Johnson, A.R. Marshall, "The PONTIS Bridge Management System", *Structural Engineering International*, 1998, vol. 8, no. 4, pp. 303–308.

[9] M.K. Soderqvist, M. Veijola, "The Finnish Bridge Management System", *Structural Engineering International*, 1998, vol. 8, no. 4, pp. 315–319.

[10] P.D. Thompson, A. Chetham, T. Merlo, R. Ellis, B. Kerr, "The New Ontario Bridge Management System", *Transportation Research Circular*, 2000, no. 498, pp. F-6/1–15.

[11] J. Bień, "Modelling of structure geometry in Bridge Management Systems", *Archives of Civil and Mechanical Engineering*, 2011, vol. 11, no. 3, pp. 519–532.

[12] T. Kamiński, J. Bień, B. Bień, "An expert tool for assessment of damaged masonry arch bridges", *Proc. 7th International Conference on Arch Bridges*, Trogir – Split, Croatia, 2013, pp. 691–698.

[13] J. Bień, M. Kużawa, "NDT-based bridge condition assessment supported by expert tools", *Proc. International Conference of Numerical Analysis and Applied Mathematics 2015*, American Institute of Physics, Rhodes, 2015, AIP Publishing, 2016, pp. 1–4.

[14] M. Vagnoli, R. Remenyte-Prescott, J. Andrews, "Railway bridge structural health monitoring and fault detection: State-of-the-art methods and future challenges", *Structural Health Monitoring*, 2017, vol. 17, no. 4, pp. 971–1007, DOI: 10.1177/1475921717721137.

[15] Ch.-S. Shim, H. Kang, N.S. Dang, D. Lee, "Development of BIM-based bridge maintenance system for cable-stayed bridges", *Smart Structures & Systems*, 2017, vol. 20, no. 6, pp. 697–708.

[16] R.T. Azuma, "A Survey of Augmented Reality", *Tele-operators Virtual Environ*, 1997, vol. 6, no. 4, pp. 355–385.

[17] J. Bień, M. Kużawa, B. Bień, "To See is to Know: Visualization in Bridge Inspection and Management", *Proc. 5th International Conference on Bridge Maintenance, Safety and Management*, Philadelphia, 2010, pp. 567–574.

[18] M. Salamak, M. Januszka, "BrIM bridge inspections in the context of Industry 4.0 trends", *Proc. of IABMAS 2018, Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges*, 2018, pp. 2260–2267.

[19] X. Wang, P.E.D. Love, M. Jeong Kim, C. Park, C. Sing, L. Hou, "A conceptual framework for integrating building information modelling with augmented reality", *Automation in Construction*, 2013, vol. 34, pp. 37–44.

[20] W. Chunfeng, Z. ZhenweI, L. Siyuan, D. Youliang, X. Zhao, Y. Zegang, X. Yefei, Y. Fangzhou, "Development of a Bridge Management System Based on the Building Information Modelling Technology", *Sustainability*, 2019, vol. 11, no. 17, DOI: 10.3390/su11174583.

[21] J. Olofsson, et al., "Assessment of European Railway Bridges for Future Traffic Demands and Longer Lives – EC Project "Sustainable Bridges", *Journal of Structure and Infrastructure Engineering*, 2005, vol. 1, no. 2, pp. 93–100.

[22] J. Matos, "An overview of the European situation on quality control of existing bridges – COST Action TU1406", *Proc. of the 40th IABSE Symposium*, Nantes, France, 2018.

[23] J. Bień, J. Krzyżanowski, P. Rawa, J. Zwolski, "Dynamic Load Tests in Bridge Management", *Archives of Civil and Mechanical Engineering*, 2004, vol. 4, no. 2, pp. 63–78.

[24] A. Cunha, E. Caetano, F. Magalhaes, "Output-Only Dynamic Testing of Bridges and Special Structure", *Structural Concrete*, 2007, vol. 8, no. 2, pp. 67–85.

[25] H. Wenzel, *Health Monitoring of Bridges*. J. Wiley & Sons Ltd., 2009.

[26] J. Zwolski, J. Bień, "Modal analysis of bridge structures by means of Forced Vibration Tests", *Journal of Civil Engineering and Management*, 2011, vol. 17, no. 4, pp. 590–599.

[27] R. Helmerich, E. Niederleithinger, Ch. Trela, J. Bień, G. Bernardini, "Multi-tool inspection and numerical analysis of an old masonry arch bridge", *Structure and Infrastructure Engineering*, 2012, vol. 8, no. 1, pp. 27–39, DOI: 10.1080/15732471003645666.

[28] C. Middleton, P.R.A. Fidler, P.J. Vardanega, Eds., *Bridge Monitoring: A Practical Guide*. ICE Publishing, 2016.

[29] N. Bagge, C. Popescu, L. Elfgren, "Failure tests on concrete bridges: Have we learnt the lesson?", *Structure and Infrastructure Engineering*, 2018, vol. 14, no. 3, pp. 292–319.

[30] E.L.O. Lantsoght, Ed., "Load Testing of Bridges: Current Practice and Diagnostic Load Testing", vol. 12; "Load Testing of Bridges; Proof Load Testing and the Future of Load Testing", vol. 13. Series: *Structures and Infrastructure*, Dan M. Frangopol, Ed. London/Leiden: Taylor and Francis Group, CRC Press, 2019, pp. 299 + 376. ISBN 978-0-367-21082-3; 978-0-367-21083-0.

[31] M. Maksymowicz, P. Cruz, J. Bień, "Load capacity of damaged RC slab spans of railway bridges", *Archives of Civil and Mechanical Engineering*, 2011, vol. 11, no. 4, pp. 963–978, DOI: 10.1016/S1644-9665(12)60089-2.

[32] J. Zwolski, J. Bień, T. Kamiński, M. Kużawa, P. Rawa, "Experimental vibration analysis of concrete box bridge girders", *Proc. 5th International Conference on Experimental Vibration Analysis for Civil Engineering Structures EVACES 2013*, Ouro Preto, Brazil, 2013, pp. 193–200.

[33] J. Bień, T. Kamiński, M. Kużawa, "Validation of numerical models of concrete box bridges based on load test results", *Archives of Civil and Mechanical Engineering*, 2015, vol. 15, no. 4, pp. 1046–1060, DOI: 10.1016/j.acme.2015.05.007.

[34] M. Kużawa, T. Kamiński, J. Bień, "Fatigue assessment procedure for old riveted road bridges". *Archives of Civil and Mechanical Engineering*, 2018, vol. 18, no. 4, pp. 1259–1274, DOI: 10.1016/j.acme.2018.03.005.

[35] T. Kamiński, M. Kużawa, J. Bień, "Experimental and numerical assessment of an old backfilled concrete arch bridge", *Proc. 9th International Conference on Arch Bridges, Structural Integrity*, Springer, 2020, vol. 11, pp. 194–202.

[36] J. Bień, M. Kużawa, M. Gładysz-Bień, T. Kamiński, "Quality control of road bridges in Poland", *Proc. 8th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2016*, Foz do Iguaçu, Brasil, 2016, pp. 971–978.

[37] L.A. Zadeh, "Fuzzy sets and information granularity", *Advances in Fuzzy Set Theory and Applications*, M. Gupta, R. Ragade, R. Yage, Eds. Amsterdam: North-Holland Publ., 1979, pp. 3-18.

[38] S. Sasmal, K. Ramanjaneyulu, "Condition evaluation of existing reinforced concrete bridges using fuzzy based analytic hierarchy approach", *Expert Systems with Applications*, 2008, vol. 35, no. 3, pp. 1430–1443, DOI: 10.1016/j.eswa.2007.08.017.

[39] Z. Li, R. Burgueño, "Using soft computing to analyze inspection results for bridge evaluation and management", *Journal of Bridge Engineering*, 2010, vol. 15, no.4, pp. 430–439, DOI: 10.1061/(ASCE)BE.1943-5592.0000072.

[40] M. Kużawa, J. Bień, M. Gładysz-Bień, "Hybrid knowledge expert tool for load capacity assessment of railway plate girders with defects", *Proc. 11th International Conference of Numerical Analysis and Applied Mathematics (ICNAAM 2013)*, American Institute of Physics, Rhodes, 2013, pp. 1294–1297.

[41] B. Daniotti, et al., Eds., *Digital Transformation of the Design, Construction and Management Processes of the Built Environment*. Springer International Publishing: 2020, DOI: 10.1007/978-3-030-33570-0.

[42] S. Baumgartner, O. El-Mahrouk, M. Kop, M. Vill, "The development of a BIM data structure for bridge maintenance", IABSE Congress Ghent 2021 – *Structural Engineering for Future Societal Needs*, IABSE Zürich, 2021, pp. 949–954.

[43] V. Saback de Freitas Bello, C. Popescu, Th. Blanksvärd, B. Täljsten, "Bridge management systems: Overview and framework for smart management", IABSE Congress Ghent 2021 – *Structural Engineering for Future Societal Needs*, IABSE Zürich, 2021, pp. 1014–1022.

[44] A. Abdullah, O.B. Thai, "Personal digital assistants as a mobile inspection system at construction site", *Proc. of the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006)*, 5-6 September 2006, Kuala Lumpur, Malaysia, 2006, pp. D28–D38.

[45] J. Bień, P. Rawa, "Hybrid Knowledge Representation in BMS", *Archives of Civil and Mechanical Engineering*, 2004, vol. 4, no. 1, pp. 41–55.

[46] W. Carlson, "A Critical History of Computer Graphics and Animation", Ohio State University, 2013.

[47] M. Golparvar-Fard, "D4AR. 4-Dimensional Augmented Reality", *LiDAR Magazine*, 2012, vol. 2, pp. 11–15.

[48] M. Gołaszewska, M. Salamak, "Challenges in takeoffs and cost estimating in the BIM technology, based on the example of a road bridge model", *Technical Transactions Civil Engineering*, 2017, vol. 4, pp. 71–79, DOI: 10.4467/2353737XCT.17.048.6359.

[49] Y. Hu, A. Hammad, "Location-based Mobile Bridge Inspection Support System", *Proc. of the 1st CSCE Specialty Conference on Infrastructure Technologie*s, Ontario, 2005, pp. FR130.1–FR130.10.

[50] M. Januszka, W. Moczulski, "Acquisition and Knowledge Representation in the Product Development Process with the Use of Augmented Reality", *Proc. of the Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment*, J. Stjepandic, et al., Eds. London: Springer-Verlag, 2013, pp. 315–326.

[51] M. Jasiński, T. Płaszczyk, M. Salamak, "Visual programming and BIM technology in parametric concrete bridge design", *Proc. 12th Central European Congress on Concrete Engineering CCC 2017*, Tokaj, Hungary, 2017, pp. 130–138.

[52] P. Milgram, H. Takemura, A. Utsumi, F. Kishino, "Augmented Reality: A class of displays on the reality-virtuality continuum", *Proc. of SPIE - The International Society for Optical Engineering*, 1994, vol. 2351.

[53] M. Salamak, M. Januszka, "BIM models and augmented reality for concrete bridge inspections", *Proc. 11th Central European Congress on Concrete Engineering CCC 2015*, Hainburg, 2015, pp. 25–28.

Zarządzanie obiektami mostowymi – wyzwania i możliwości

Słowa kluczowe: most, zarządzanie, środowisko, diagnostyka, BIM, system zarządzania mostami

Streszczenie:

Obiekty mostowe są szczególnie wrażliwymi elementami infrastruktury transportowej. W wielu przypadkach mogą podlegać większemu natężeniu ruchu i większym obciążeniom, a także bardziej surowym warunkom środowiskowym niż te, na które je pierwotnie projektowano. Dlatego niezbędne jest przygotowywanie i wdrażanie do stosowania procedur, które zapewnią możliwie pełną kontrolę jakości obiektów mostowych na każdym etapie cyklu ich życia. Stosowane rozwiązania powinny też zapewniać systematyczne monitorowanie stanu technicznego infrastruktury mostowej oraz dobór skutecznych działań utrzymaniowych. W artykule przedstawiono główne wyzwania i pojawiające się możliwości w zarządzaniu obiektami mostowymi z wykorzystaniem nowoczesnych technologii. Obejmują one przede wszystkim: relacje pomiędzy środowiskiem a infrastrukturą mostową, doskonalenie technologii diagnostycznych, zaawansowane modelowanie mostów w komputerowych systemach zarządzania, rozwój systemów ekspertowych wspomagających procesy decyzyjne, które oparte są na bazie wiedzy z zastosowaniem elementów sztucznej inteligencji, a także wdrażanie metodyki BrIM (Bridge Information Management) z technikami rozszerzonej i wirtualnej rzeczywistości. Prezentowane działania skupiają się na monitorowaniu bezpieczeństwa obiektów mostowych oraz ich użytkowników w celu obniżenia ryzyka niespodziewanej katastrofy oraz zapewnienia możliwość realizowania sprawnego procesu utrzymania obiektów mostowych będących bardzo ważnymi elementami całej infrastruktury transportowej. Przedstawiona klasyfikacja systemów zarządzania mostami (Bridge Management Systems) pokazuje historię tworzenia takich systemów oraz wskazuje spodziewane kierunki ich rozwoju związane z uwzględnianiem zmieniających się wyzwań i integracją nowych rozwijających się technologii, w tym automatyzacją procesów podejmowania decyzji.

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