State of the Art in Damage Information Modeling for Bridges

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Abstract. The Bridge collapse in Genoa let us take a closer look at the health state of bridges. Inspection and maintenance is essential to ensure the serviceability and safety of bridges. Current inspection on site is often done manually on paper, and paper is the medium to exchange condition information between involved stakeholders. After damage registration or information exchange, the data is processed digitally. The repeated digitalization is an error prone process and leads to redundant work. A dedicated information model, called damage information model, could provide a solution to improve the information exchange. This present paper investigates the state of practice and research in damage information modeling for bridges. After analyzing bridge damage data, it reviews different norms, guidelines, and existing research papers. Analyzing different national practices and synthesizing available research results form the basis for the presented achievements and challenges in the field of damage information modelling.

1. Introduction

On 14th August 2018 43 people were killed by the collapse of the Ponte Morandi Bridge in Genoa. Carmelo Gentile, a structural engineering professor, had suggested to '[…] perform a […] computer study […]' before the collapse happened (Glanz et al., 2018). With a detailed damage information model, a computer simulation like that, could have been done easily. However, the current state of practice for inspection is paper based or relies on bridge management systems (BMS) (Caltrans, 2017; Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2013). That means inspectors register defects and damages on site using paper and transfer the damage information to the BMS later in the office, which is an error prone practice. Furthermore, BMS store abstract data only, not considering any 3D models of the structure or damages. Instead, hand-made sketches, photos and textual descriptions are stored. This abstract data is difficult to understand without having a proper visualization. A damage information model (DIM) can support the inspection process and the later maintenance, to save money, to avoid errors and to help plan inspections and maintenance. This paper aims to identify significant damage types for bridges and to analyze the research that has addressed the information modeling of these types of damages.

Building Information Modeling (BIM) is the most common method to model buildings with a 3D-CAD model and additional information like material, processes and so on (Borrmann et al., 2018). The Industry Foundation Classes (IFC) represent a standard for implementing Open BIM providing a data format to share building information among several actors (ISO, 2013). Currently, BIM is being extended to the sector of civil engineering, e.g. Bridge Information Modeling (BrIM) (Costin et al., 2018). IFC-bridge, an implementation of BrIM, offers the possibility to model bridges with all their components (Lebegue, 2013). The current state of BIM and IFC allow to model damages on buildings with proxy elements and property sets, which might not be sufficient, as this approach lacks additional semantics, for example, damage types and taxonomies. Integrating and exchanging damage information in the context of BIM would support the operation and maintenance phase within the life-cycle of bridges.

2. State of practice

2.1 Bridge condition assessment

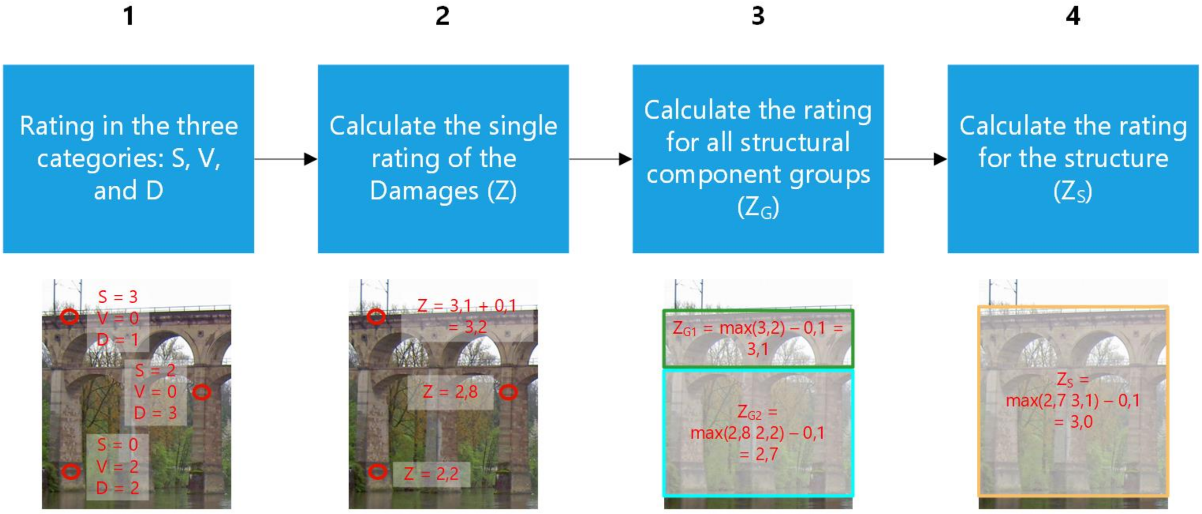
In Germany, the standard DIN 1076 regulates the inspection of all kinds of civil infrastructure (Deutsches Institut für Normung, 1999). Structures like bridges, tunnels, and similar, have to be inspected every 3 years. Within this interval the rough or plain inspection and the main in-depth inspection alternate. Inspectors have to inspect bridges within the range of the hands, to tap, to finger, and to take a close look. It is similar in California (USA) and Queensland (Australia). Both perform multiple types of inspection. The Unite States have a flexible period for inspection between 2 and 4 years (FHWA, 1988). Queensland defines an assessment score dependent inspection period between one and five years, e.g. intact bridges have a longer period than bridges with major deterioration (Department of Transport and Main Roads, 2016). For further information about guidelines of other countries, consider the paper of Hüthwohl et al. (Hüthwohl et al., 2018).

Independent from the country, it is necessary to register defects and damages for later assessment and maintenance planning. Modeling damages within a BIM context is a prerequisite to support the full life-cycle of built infrastructure. Aiming at modeling damage information it is important to know existing damage types and related parameters. To get an overview about damage types, an analysis of the German catalog of damages for civil engineering structures follows. The catalog of damages for civil engineering structures (Bundesanstalt für Straßenwesen, 2017) lists more than 500 types of damages. While grouping the damages related to components, the catalog lists damages of the same types several times, e.g. the superstructure and the substructure could have chloride penetration. This grouping is insufficient for later damage modeling, because a chloride penetration has the same parameters, independent from the component at which it occurs. Hence, all damages are grouped in categories, which are separated by semantics, for example material change, cracks, spalling, and divergences from specification/design and so on.

	D = 3					
	4	4.0	4.0	4.0	4.0	4.0
	3	3.3	3.5	3.7	3.9	4.0
S	2	2.8	3.0	3.1	3.2	4.0
	1	2.7	2.8	2.9	3.0	4.0
	0	2.5	2.6	2.7	2.8	4.0
		0	1	2	3	4
				V		

Figure 1: Matrix to calculate Z for D equal to 3 (see Haardt, 1999)

The condition assessment of bridges in Germany follows the algorithm developed by Haardt in 1999 (Haardt, 1999). Figure 2 shows an example for a bridge with 3 damages. Each single damage has its own assessment score within three categories: structural safety (S), road safety (V) and durability (D), like shown in step 1 of figure 2. The assessment scores within these categories range from zero to four. Using five matrices, a final assessment score (Z) is calculated. The Z-scores range from zero to four, too. Figure 1 shows an example of a matrix to calculate the Z-score of a damage. Assuming a damage has a D-score of three, S is equal to one and V equal to two, hence the final Z-score is 2.9. The inspector can decide to add a value of 0.1 to the calculated Z-value, due to a higher significance of the damage, or to subtract a value 0.1, due to a lower significance (Haardt, 1999).



https://commons.wikimedia.org/wiki/Bridge#/media/File:Bietigheim-Bissingen_Viadukt_02.jpg

Figure 2: Bridge assessment process in Germany

The highest damage score Z from all damages within a component group, defines the score of the whole component group. In Germany, 14 component groups are defined, e.g. superstructure, substructure, prestressing, foundation, etc. Figure 2 shows only 2 component groups for simplicity. Depending on the amount of damages within the component group, the Z-score of the group can be increased or decreased by 0.1. Both condition ratings have a decrease of 0.1, because they have less than 5 or 3 damages, respectively. Finally, the score of the whole structure is the highest score of all component groups. The decrease in figure 1 emerges from the fact that less than 3 component groups are affected by damages. In conclusion, the damage with the highest Z-score leads to the assessment score of the entire bridge (Haardt, 1999).

2.2 Analysis of frequency and significance of damage types

To analyze data from practice, we defined 23 damage categories based on the German damage catalog (Bundesanstalt für Straßenwesen, 2017). The data used for the statistical analysis has been provided by the Thuringian Department of Building and Transportation (Thüringer Landesamt für Bau und Verkehr). The data covers 25 610 damages at 2 953 bridges. Figure 3 depicts the ten most often occurring damages. The x-axis displays the different categories, whereas the y-axis shows the amount of damages. The number above the bars show the amount of the damage occurrences. *Cracks* occur most often at bridges. Right after that follow *divergences from specification and design*, which summarize defects, for example, regarding the thickness of layers, dimensions of components or wrong component types. The third place are *joint damages*. This category includes expansion gaps, as well as mortar gaps. Next are *waste, pollution and other foreign bodies* e.g. garbage, vegetation or formwork residuals. Corrosion, chloride intrusion and carbonation are examples for *material changes*. That group has two sub groups: with and without loss of substance, e.g. corrosion can lead to a loss of substance. The subgroup *without loss of substance* takes place 6. Changes, which are visible at the surface of concrete, e.g. efflorescence, take place 7. Similar, however a bit different, are *enclosures of foreign bodies, coarse grain or voids* within concrete. The last two places cover the lack of components or parts and their state and functionality, e.g. fixed or loose. To define a damage model, it would be sufficient to start from the most frequent occurrences, namely cracks, divergences and joint damage.

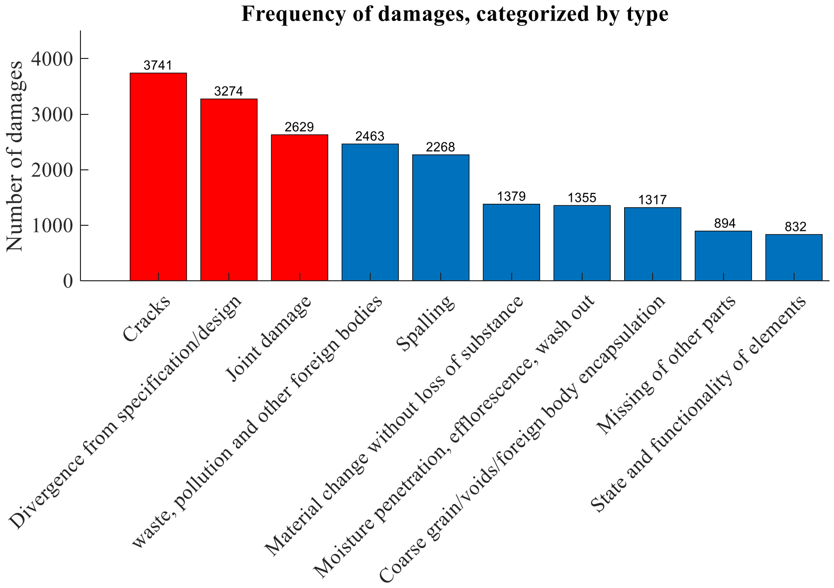


Figure 3: The ten most frequently occurring damage types (top three are red)

Beside the information about how often a damage occurs, it is interesting to know which influence has a damage on the overall assessment score of a bridge, e.g. cracks smaller as 0.2 mm in concrete are negligible for the structural integrity, and thereby for the assessment score, too. To answer which damage types are significant for the assessment score, it is necessary to consider the assessment algorithm, which is described above. Hence, to define the most significant damage types, the analysis only takes into account the damages with the highest Z-scores per bridge.

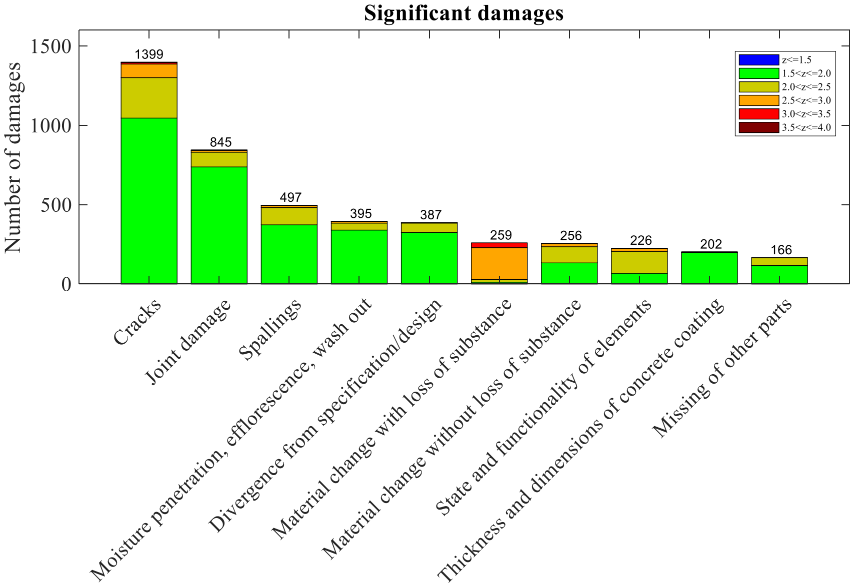


Figure 4: Significant damages with grouped Z-score

Figure 4 shows the result of the analysis on the significance of damage types. The x-axis lists the categories or types, whereas the y-axis shows the amount of damages within the category. The numbers on top of the bars show the amount of damages of the category. To give an overview about the Z-rating of the significant damages, the colors show six groups of damage Z-scores: lower than 1.5, between 1.5 and 2, between 2 and 2.5, between 2.5 and 3, between 3 and 3.5, as well as between 3.5 and 4. Some colors are not visible at the bars, e.g. blue. Two new categories are inserted into that graph: *Material change with loss of substance*, as well as the *thickness and dimensions of concrete coating*. As already described, the material change with loss of substance is mainly corrosion. Concrete coatings can be too thin or in a bad quality Material changes with loss of substance are interesting, because of the high ratio of Z-scores about 2.5 and above.

In conclusion, there are multiple damage categories, which are interesting to model, e.g. cracks, divergences from specification and design, spalling or joint damages. Future investigation on damage information modelling should care about multiple damage categories and focus on the most frequent and significant damage types.

3. State of research

The existing literature is systematically structured using two dimensions in order to form a two-dimensional matrix. Firstly, it is categorized according to eight damage types. Beside the six damage types with the most frequent occurrences, as discussed in section 2, two groups are added: *Other* and *Damages in general*. The category *Other* covers damage types aside from the top six, whereas *Damages in general* deals with literature that is concerned with a general approach to model damage information.

Secondly, the literature is structured according to the complexity of the modelled damage information. In this context, complexity refers to how much information is modelled at what detail, e.g. the concept only links raw data, it suggests an as-built model with damage parameters or it presents a comprehensive geometric and semantic information model for damages. Figure 5 illustrates these 3 complexity levels. Linked raw data are, for example, drawings, spread sheets, point clouds, textures, pictures, text or audio recordings, which are interlinked. The next category refers to a 3D as-built model of the bridge with damage parameters, e.g. crack width, spalling radius, corrosion depth etc. The highest complexity would be a geometric-semantic information model, which takes e.g. 3D damage model that includes relations to the bridge (component), influences on material data by this damage, repair recommendation, type of material for repair and so forth.

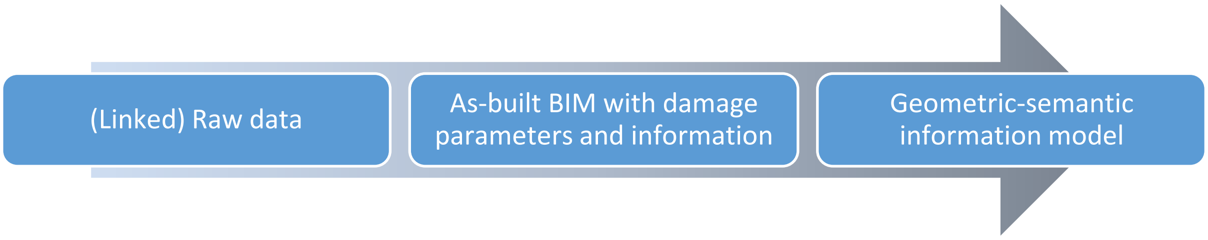


Figure 5: Complexity levels for DIM

3.1 Linked raw data

This section covers existing research approaches, which interlink raw data, e.g. point clouds, documents, pictures or others. In 2012, Adhikari et al. (2012) published a paper on automatic condition state prediction. The paper describes a method to automatically rate inspection results. An artificial neural network processes pictures of damages and predicts the rating for them. Even if the research does not show a data model, it deduces a first link between information: a damage has one or more pictures and a rating (Adhikari et al., 2012).

Matthew Torok (2014) worked on crack detection for post-disaster assessment. Besides photos, they use 3D-meshes for damage registration. Finally, the work stores the location of a damage. Even if there is no 3D as-built model, the position of a damage is the first parameter, which is important for further work. To evaluate the results, crack widths and depths are used. These parameters, damage position and dimension, are necessary for a comprehensive damage information model.

Every bridge is part of a particular environment. Thus, changes in the environment can affect the bridge condition, e.g. changes to the embankment can lead to impacts on the road safety. Due to this, Miyamoto et al. (2016) worked on the integration of environmental changes to a BIM database. After generating a 3D damage model of the embankment, the data is linked to a civil infrastructure information model.

Inspecting a bridge is time consuming and cumbersome. To address this issue, Omer et al. (2018) presented an approach that suggests inspecting bridges virtually via virtual reality (VR). Central for this is the acquisition of point clouds of the building. They use MATLAB (MathWorks, 1994) to process additional pictures that were taken on sight in order to highlight damages in the mesh. Finally, a head mounted display visualizes the point cloud with the highlighted damages. Again, this work shows some parameters of damages, like location and dimensions (Omer et al., 2018).

All of the work presented above lack 3D building models. They mainly collect independent data for visualization, simulation or planning.

3.2 As-built BIM with damage parameters

This section covers achievements that work with 3D models of the bridge and attach damage parameters and data. Sacks et al. (2016) describe an information delivery manual for bridge inspection. Central in the manual are parameters and semantics for bridges. After localizing damages, an algorithm groups them all by types, e.g. crack, spallings, scaling, efflorescence, corrosion or other. For that purpose, additional parameters are take, for example, the position. Upon this, a boundary shape representation is used to help visualizing damages (Sacks et al., 2016). However, further information, e.g. how to model the damage information, is not refined.

Sacks et al. (2018) extended their work on bridge inspection in 2018. Additionally to their information delivery manual, they published a model view definition. Every bridge element can have several element defects, whereas several element defects are part of a defect. Furthermore, every defect can be structural or not. Multiple damage types are specializations (child classes) of element defects and contain several parameters (Sacks et al., 2018). Even if the paper covers multiple damage types, there are still damage types, which are not covered, for example joint damages. Moreover, an inclusion of 3D damage models is missing.

During the construction process, defects, such as wrong dimensions of components or wrong placements, can lead to additional costs. Due to this, Hamledari et al. (2018) published a method on updating object data in IFC for as-built modeling. The idea is that every entity has a related type and a change in the parameters of an entity is done by changing the type with its parameters (Hamledari et al., 2018). This approach is comprehensible to some defects during constructions, e.g. installation of a wrong door. However, it is lacking links between defects.

In 2016, McGuire et al. (2016) developed a system to use damage information within structural analysis and for repair quantity estimation. Damage information from cracks, spallings and delamination have connections to bridge components. The paper also considers information about damage volumes. Last but not least, dimension parameters for the damages are defined

(McGuire et al., 2016). The next step would be a geometric model for the damages and links between damages.

Tanaka et al. (2018) started a work on damage information modeling in 2016. Based upon the IFC, they modeled degradations at bridges. Beside geometric information, images and measurements are part of the model. Additionally, Tanaka et al. integrated a time line to show the propagation of a damage. For this purpose, an extension of the IFC was necessary (Tanaka et al., 2016). However, the work lacks some data for a 3D model of a damage and relations between different damages. In 2018 Tanaka et al. extended their work with an automated data extraction from inspection reports (Tanaka et al., 2018).

3.3 Geometric-semantic information model

The section presents literature, which describes a damage model with geometric and semantic damage information, e.g. damage geometry, interlinking of damages, and effects of damages. Hamdan and Scherer (2018) published an information model for damages in 2018 that considers parameters and the geometry of damages. The information model contains some properties and documentation, too. Also, the decomposition of a damage into individual damages is suggested. What is missing is the relation between damages and influences on material parameters of the affected component. Furthermore, a definition of levels of detail or development is missing.

Hüthwohl et al. (2018) propose a second idea on modeling damages. Every damages is related to an inspection. Similar to (Sacks et al., 2018), Hüthwohl et al. disassemble a defect into several element defects and added several parameters. Additionally, the work contains data for inspection, e.g. time, type, inspector and weather. However, their approach lacks detailed 3D damage geometry and further semantic links and relations to represent damage histories.

3.4 Overview of the examined literature

Table 1 shows the summary of the literature examined. As clearly visible, several efforts have been made in the area of as-built BIM with damage parameters and information. However, so far only one research focuses on a more detailed model. None of the studies examined deals with links between damages, a level of detail or repair recommendations.

4. Already published achievements and remaining challenges

Damage information modeling is a growing branch in the entire architecture, engineering and construction society, mainly empowered by the research on automated bridge inspection. Bridge management systems (BMS) cover the first level of damage information modeling. These management systems link raw data about bridges (or other civil engineering structures) to the related bridge or other components. 3D models are currently not part of these systems. Scientists are on their way to overcome this issue. First attempts show damage information models that include relations between damages and the bridge or their components. Another achievement are the first ideas to visualize damages, e.g. by overlaying a texture upon a component. Data, which is related to damages, for example the inspection parameters and information, is part of publications as well. Finally, one publication enhances the information model with a 3D model of the damage and properties (Hamdan and Scherer, 2018).

Table 1: State of research overview

Damage type	**(Linked) Raw data**	**As-Built BIM with damage parameters and information**	**Geometric-semantic information model**
Cracks	Adhikari et al. (2012) Torok et al. (2014)	Sacks et al. (2018)	Hüthwohl et al. (2018)
Divergences from specification/ design		Hamledari et al. (2018)	
Joint damages			
Waste, pollution and other foreign bodies			
Spallings	Adhikari et al. (2012)	McGuire et al. (2016) Sacks et al. (2018)	Hüthwohl et al. (2018)
Moisture penetration, efflorescence, washout		Sacks et al. (2018)	Hüthwohl et al. (2018)
Other	Miyamoto (2016)	Sacks et al. (2018)	
Damages in general	Omer et al. (2018)	Sacks et al. (2016) Tanaka et al. (2016) Tanaka et al. (2018)	Hamdan and Scherer (2018)

Taking a close look at the current state of the art reveals the lack of investigation in damage types. Different damage types need different parameters, e.g. a crack might have a 3D geometric model whereas corrosion is maybe only a material defect on the surface. Future investigation should focus on necessary parameters depending on the damage type. Another area may deal with the relations for damages, e.g. some damages relate to a component of a bridge and other maybe relate to the whole bridge. Moreover, more often than not, damages relate to other damages. Normally, this is written in an inspection report, whereas a comprehensive damage model should be able to represent this via data relations within the information model. The current work mainly focuses on inspection. However, inspections are usually followed maintenance, construction monitoring or destruction. Damage information has at least relations to maintenance, for example the damage geometry helps calculate the amount of material for repair, structural damages or defects can deliver necessary information for destruction. Finally, a definition for levels of details for the damages is currently not being considerd. Think about a maintenance manager, he or she does not need all the information about every crack in detail, but may need the overall amount and location of cracks and the type of the related material. Hence, a definition of different levels of detail are important to make BIM applicable for the whole life cycle of bridges.

5. Conclusion

For safety and operations, it is important to keep bridges in secure conditions. Inspections are a key process to identify problems and weaknesses at bridges, as well as for repair and maintenance. Besides, BIM is a well-known and applicable concept to manage civil infrastructure and related processes. Using BIM over the whole bridge life cycle leads to the necessity of a damage information model. To define the needs of a damage model, this paper analyzed the state of practice and deduced damage categories from the German damage catalog.

Statistical data from Thuringia helped identify the most significant damage types, which delivered categories for the reviewed literature. Most of the existing research work deals with damage modeling in the way of linking different data together and take a 3D bridge model as the basis for all damages. Less effort exists in advancing damage models to geometric-semantic models with relations between single damages, level of detail or repair recommendations. If BIM shall be applicable within the field of inspection and maintenance, a geometric-semantic damage model is necessary. Future work should focus on this area allowing the usage of BIM data all over the life cycle.

With digital information about damages, e.g. crack geometry and position, an automated assessment calculation can be done maybe via an artificial neural network. Hence, a big part of assessment can be automated: take photos of the bridge, extract damage types and parameters with the usage of image processing, calculate the assessment of the damages, components, component groups and the whole bridge by using artificial neural networks or defined algorithms. If an assessment reveals critical structural issues, the content of the DIM can be used by engineers for calculations, simulations and helps to identify possible damage reasons or effects. Hence, it becomes cheaper and easier to analyse the bridge state and prevent collapses.

Last but not least, register as much information about damages as possible, offers possibilities for data analysis to improve design, inspection practices, assessment and maintenance concepts, by using technologies from the fields of data mining, machine and deep learning.

6. Acknowledgement

We thank the “Thüringer Landesamt für Bau und Verkehr” for their support with knowledge from practice in bridge inspection and statistical data about bridges in federal state of Thuringia in Germany.

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