6 Summary and Outlook

Frequent inspections and assessments of bridges are necessary since they are exhibit to huge loads and all kinds of weather. Conventionally, bridge inspections are performed paper based and all information is manually exchanged between stakeholders, which is error prone and cumbersome. A digital data format would allow to acquire and share damage information automatically. Traditional processes may be eased and accelerated as well as novel processing concepts of as-damaged building models are enabled.

BIM has been widely evaluated to be beneficial for exchanging building information during design, planning and construction processes, however, it is not applicable in the operating phase. In order to extend the use of BIM to the operating phase, damage information need to be incorporated into the BIM concept. The resulting concept that extends BIM to the operating phase is called DIM. Several studies published frameworks and part models for damage information. However, a comprehensive DIM including geometric, geo-semantic, and semantic information has not been provided yet.

Based on analyses of data from practice, several damage types have been identified. Furthermore, frequency and severity of these damage types have been evaluated to focus on frequent and severe defects first. These analyses lead to 12 damage types and related data. This data consists of geometric information to visualize defects and damaged components, semantic data to include alpha-numerical information, and geo-semantic information data for photos, sketches, and videos.

In order to define a DIM, the object-oriented approach has been chosen. By sythesizing existing models and extended them with further geometric, geo-semantic, and semantic information derived from requirements and literature, a data model has been developed that consists of 15 classes and their related attributes. Central point of the model is a class for defects. Others are directly or indirectly related to this class.

Based on the object-oriented model, an implementation using the IFC standard has been developed. Mapping the developed classes onto existing IFC entities, an implementation that is interpretable by existing software could be achieved. However, several software applications showed issues in displaying the developed model. After extending an existing open source IFC viewer, all concepts of the model could be verified by checking the visualization.

Damage information is used as basis for subsequent steps of the inspection and assessment process. In order to proof the entire concept of the DIM, two workflows have been tested. First, an automated damage data acquisition using bridge photos has been developed and implemented. Geometry and geo-semantic data of defects could be obtained by this process; semantic data has been added manually. Second, the geometry of a damaged beam has been transferred automatically to a structural analysis software. Based on the geometric model, a exemplary FEA has been performed. Both case studies showed that the DIM helps automating data acquisition and transfer.

BIM is the basis for exchanging building information currently and enables automation and novel processing workflows. However, it lacks support for phases besides design, planning, and construction. This study showed how to develop an extension for BIM to add information for the operating phase of bridges. Future research may use this concept in order to further automate bridge condition assessment or public communications of inspection, repair, and maintenance.

With a DIM inspection, analyses, analysis and assessment are supported by BIM. Next, maintenance actions have to be considered for further development of BIM. The DIM could be a starting point for this goal. After that, modification and demolition may be addressed by further research

This study has focused on concrete bridges to develop a DIM. Future research should verify if this model may be to bridges made of other materials, such as wood or steel and if it applicable to other types of civil engineering structures.

Future inspections on-site could use smart devices, such as smart phones or tablets, instead of paper to register defects as shown by Lindenberg and McGormley [72]. Using UASs, remote inspections could be performed whereas a pilot controls the UAS and an engineer manually adds recognized defects to the BIM model [168]. Such digital inspection may use the as-built model as input and directly add the observed defects to it according to the proposed data model and implementation. The resulting as-damaged model may be used to be visualized in Virtual Reality (VR), which allows offline inspections in office, and hence, save time.

Generating defect geometries manually would be a cumbersome and error prone task; hence, automatic approaches, for example, for damage registration would lower the effort for inspection regarding cracks and spalling [5], [60]. Future work has also to consider methods for automatic registration of other damage types, for instance material changes and divergences from specification or design.

Bridges are inspected frequently, which leads to a history of a defect. Engineers need this history of defects for proper assessment. By reason of IFC has been designed to exchange single states of buildings or structures, it is necessary to extend the proposed model with damage progress data. This would mean to associate a state of a defect with an inspection. One arising question is what are state parameters, for example, the geometry or properties and how to encapsulate them. Based on that, it has to be identified if the IFC standard is still usable for that.

In general, the DIM provided here, adds a contribution to the current discussion about sustainability. In order to limit global warming and climate changes, the DIM helps to reduce CO_2 emissions. Based on the DIM durability analyses and simulations may be done that would help to extend bridges' service time, reduce replacements, reduce cement consumption, and therefore, CO_2 emissions. Analyses about how much CO_2 could be saved by extending bridges service time has to be done.

Conventional BMSs contain numerous bridges with related defects over time. If this data would be transferred into BIM and DIM models, big data analysis may be performed based on these models instead of using semantic data from databases only [105]. These analysis could help in bridge condition prediction or damage propagation in order to improve inspection scheduling or decide about maintenance actions.

Although the DIM may be used for analyses and NDT, a definition how to transfer results from these processes back to the owner or inspector has to be done. Results of analyses also consist of semantic, geo-semantic, and geometric data. However, these are registered on a sub-component level, i.e., a part of a component is analyzed or tested. Also huge amounts of numerical data, for instance huge matrices may be generated and required to make results transparent and reproducible. A proper definition of the required result data and a suitable modeling approach should be elaborated in future work.

Last but not least, infrastructure works are funded by taxes from citizens. Currently, maintenance and repair actions are sparsely communicated with citizens. DIM models offer a new way making maintenance and repair transparent to a broad audience. By using internet platforms as well as 3D digital building and damage models, many people would be able to access bridges' condition state, works planned, and scheduled. This would make states and decisions more transparent. Specific concepts for including citizens into decision making processes for infrastructure works have to be elaborated.