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Mathias Artus, M. Sc.
Erfurt

Modeling Damage Information for the Operation Phase of Bridges

Reihe 04
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Modeling Damage Information for the Operation Phase of Bridges

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Bridges are prone to a high level of deterioration because of their frequent and heavy load. To ensure traffic and structural safety as well as durability, bridges are inspected frequently. Registering condition states, performing assessment, and preparing data for maintenance tasks are time consuming and error prone because of primarily paper-based workflows and manual copy-pasting. An improvement in digitizing bridge condition data could decrease the demand of manual work and helps to lower financial efforts for these tasks; therefore, makes inspection, maintenance, and repair more attractive. This dissertation aims to provide a data model that extends the known principle of Building Information Modeling to the operations phase of bridges. Damage information, such as geometries or photos, may be included in existing building models with this approach. Based on that, engineers are enabled to assess bridges based on comprehensive building models instead of analog reports.

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Dedicated to my wife Ulrike.

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Glossary

Application Programming Interface Communication interface for a computer program 73, X

as-built State of a model after the construction process 10, 85, 102, 115

as-damaged State of a model that includes damage information 2, 13, 37, 38, 45, 101, 102, 104, 114, 115

BIM Collaboration Format Data exchange format to communicate changes in model 28, X

Binary Large Object Is an entity of binary data as a single object, e.g., photos or videos. Depending on the storage type, i.e., database or file system, and the type of binary data, the kind on entity varies. 45, X

Boundary Representation Using the outer boundaries of a volume, a 3D shape is defined 42, X

Bridge Management System Formal definition of a bridge management system or guideline. Mostly, this systems are later implement via a software 96, X

Building Information Modeling A process and methodology to generate and exchange data about a building in the entire life-cycle 2, 24, VIII, X

buildingSMART Data Dictionary Online service of buildingSMART International for classifications, terms, nomenclature, and properties 10, X

buildingSMART International An open, neutral, and non-profit organization that aims to push on the digital transformation of the building asset industry 6, 8, 10, 85, VII, VIII

Constructive Solid Geometry Describing a solid geometry by combination of geometry primitives with subtraction, intersection, etc 98, X

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Damage Information Modeling Modeling defects and deficiencies related to building elements with geometric and semantic information 2, X

Digital Imaging and Communication in Nondestructive Evaluation Standardized data exchange format for non-destructive evaluation and testing results 18, X

Digital Shadow One way connected digital model of a physical entity 10, 11

Digital Twin Two way connected digital model of a physical entity 5, 10, 11

EXPRESS Modeling language for product data 96, 101

Finite Element Analysis Calculation of equilibrium conditions in several finite elements of a component or structure 23, X

geo-semantic information Information that is a combination of geometric and semantic parts. Images, photos, and colored point clouds are examples for this information type because a photo consists of several points (geometry) that have a color (semantic) 27, 42, 43, 45, 86, 88–90, 95, 114

Heritage Building Information Modeling Application of the Building Information Modeling method to heritage buildings 24, X

Industry Foundation Classes Data structure defined by buildingSMART International and used for exchanging building information 9, VIII, X

Information Delivery Manual Documentation about processes, actors, and data during a selected process or task in order to describe a business process 6, X

Level of Development Means the combination of and 8, X

Level of Geometry Geometric detail of a given geometric information 8, X

Level of Information Detail level of semantic information 8, XI

Machine Learning Adaptive computer systems for analyzing data. 16, XI

Model View Definition Particular use of Industry Foundation Classes (IFC) for a workflow ore use case 8, XI

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Non-Destructive Testing Group of analysis methods, which are used to evaluate material's parameters without causing damage 2, 18, XI

OmniClass Classification system for construction industry in the United States 10

photogrammetry Deduce information related to physical objects by taking and processing photos 16, 17

point cloud A collection of spatial points. Often retrieved from laser scans or 16, 17, 19, 21, 22, 25

Resource Description Framework Standardized model for linking data using triples 8, XI

Scan-to-BIM Generating BIM models from point clouds, which have been retrieved from photos or laser scans 10

SQLite File based SQL database system 8

Structural Health Monitoring Controlling bridge condition by continuously collecting sensor data with subsequent archiving, processing, and assessing 2, XI

Structure from Motion Generate point clouds of objects from a number of photos 102, XI

Structured Query Language Query language used to access numerous relational databases 39, XI

UniClass Classification system for the construction industry in the United Kingdom 10

Unified Modeling Language Set of diagrams to describe software design and behavior. 46, XI

Unmanned Aircraft System Autonomous flying vehicle or system 26, 37, XI

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Acronyms

AEC Architecture Engineering and Construction 5, 6, 8, 10, 11, 31, 57, 72, 96, 97, 99, 100

API Application Programming Interface 73, 99, 100

BCF BIM Collaboration Format 28

BIM Building Information Modeling 2, 4–6, 10, 11, 13, 14, 18–20, 24, 29, 32, 37, 38, 42, 45, 46, 52, 57, 58, 69, 85, 86, 88, 90, 91, 96, 99, 100, 102, 112, 114–116

BLOB Binary Large Object 45

BMS Bridge Management System 96, 116

BRep Boundary Representation 42, 103

bsDD buildingSMART Data Dictionary 10, 18, 91

CSG Constructive Solid Geometry 50, 55, 63, 67, 72, 74, 78, 98

DICONDE Digital Imaging and Communication in Nondestructive Evaluation 18

DIM Damage Information Modeling 2, 4, 5, 17–19, 21, 24, 27–29, 31–33, 38, 39, 59, 61, 63, 77, 85, 86, 88, 89, 92, 95, 96, 99, 103, 111, 114–116

FEA Finite Element Analysis 23, 36, 93, 109, 111, 112, 115

HBIM Heritage Building Information Modeling 24, 87

IDM Information Delivery Manual 6, 8, 16, 18, 23, 85, 86

IFC Industry Foundation Classes 5, 8, 9, 18, 19, 27, 28, 46, 52, 57–66, 68, 69, 71–73, 76, 77, 79, 82, 88, 96–101, 103, 104, 108, 109, 115, 116, VIII, XIII, XIV

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LoD Level of Development 8, 45–47

LOG Level of Geometry 8

LOI Level of Information 8

ML Machine Learning 16, 20, 102

MVD Model View Definition 8, 18, 85

NDT Non-Destructive Testing 2, 12, 17, 18, 24, 37, 46, 47, 88, 116

RDF Resource Description Framework 8

SfM Structure from Motion 102, 108

SHM Structural Health Monitoring 2, 18, 19

SQL Structured Query Language 39

UAS Unmanned Aircraft System 37, 115

UML Unified Modeling Language 46, 47, 49, 51, 54–56, 83

VR Virtual Reality 115

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Abstract

Bridges are prone to a high level of deterioration because of their frequent and heavy load. To ensure traffic and structural safety as well as durability, bridges are inspected frequently. Often, it is more efficient to demolish and repair a bridge because their maintenance and repair of them are expensive primarily due to high staff efforts. Furthermore, registering condition states, performing assessment, and preparing data for maintenance tasks are time consuming and error prone because of primarily paper-based workflows and manual copy-pasting. An improvement in digitizing bridge condition data would decrease the demand of manual work, helps to lower financial efforts for these tasks; therefore, makes inspection, maintenance, and repair more attractive. In the long term, this results in lower costs, building material demand, and also CO_2 emissions.

BIM aims to support the entire building life-cycle using geometric-semantic models of the building. Currently, acquiring, exchanging, and processing of building data during design, planning, and construction of buildings have been investigated. Studies about the efforts and effects of BIM show a big potential saving time and money as well as reducing construction errors. However, BIM lacks support of the longest phase of a building or structure: the operating phase. Using BIM during the operating phase has gotten less attention and a systematic and comprehensible methodical approach is missing to model data from the operating phase. In particular, this information is relevant for civil engineering structures, for example, bridges, because it helps to ensure traffic and structural safety as well as durability. During frequent inspections, deficiencies and defects are registered on paper and later manually transferred into table-based systems in the office. As BIM helped to reduce plans and reports during the design, planning, and construction phase, it is assumed that this reduction can also be achieved during operating phase.

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In order to use BIM during the operating phase of bridges, two geometric-semantic models need to be developed: one model for bridges themselves and one model of deficiencies and defects affecting these bridges. Numerous bridges are older than the concept of BIM, which means that there are no geometric-semantic models of these bridges. Some concepts, for instance Scan-to-BIM aim to generate geometric semantic models of existing buildings. As for the second requirement, a digital model for defects and deficiencies, a huge gap is evident. In situations where geometric-semantic models of damage and defects exist, they are incomplete and designed for specific applications. For this reason, this dissertation describes concepts and models to acquire, exchange and process geometric and semantic data of defects and deficiencies considering multiple use cases.

In the first step, an analysis of the as-is-state is performed; this contains reviewing current norms and guidelines and statistical analyses of bridge condition data from Thuringia. For the statistical analysis, damage types are defined and the frequency and severity are rated. The most frequent and severe damage types are selected for subsequent modeling and implementation.

Second, based on the selected damage types and use cases, the requirements for the data model are defined. To guarantee immediate and prospective usability, current norms as well as up-to-date methods from research need to be considered. The final data model is built to fulfill the defined requirements. This is achieved by synthesizing the existing approaches and extending the model where it is required. The result is an open-source data model for acquiring, exchanging, and processing bridge condition data. Additionally, by keeping the model flexible and open, further integration of information artifacts are possible later on, e.g., additional damage types can be integrated without changing the model structure.

Third and last, the resulting model is tested with an example scenario. The bridge inspection is the central point for the assessment and, therefore, has been selected for testing purposes. Considering current research results, a framework was designed that uses photos from bridge defects as input and processes them to generate defect geometries. These geometries are included in and aligned with the building model of the bridge before this model is enhanced with semantic information.

The final data model is an open interface to acquire, exchange, and process bridge condition data; furthermore, semantic, geometric-semantic, and semantic data are considered. Using

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established data formats from the AEC sector, the model is implemented via the IFC and verified by visualizing generated models in different IFC viewers. This approach allows easy integration of the given information model into existing software. Although the model is implemented using an open and established standard, numerous software applications show errors and problems during importing, visualizing, and processing the data. Future implementations of IFC software have to respect the IFC standard in its entirety.

By extending BIM with the provided Damage Information Model, it is possible to address the operating phase of bridges. This helps to extend bridges' life time, reduce material demands, and CO_2 emissions. Due to the availability of 3D building and damage models, the provided approach may improve transparency and communication of repair and maintenance actions. Improving the automated generation of structural models, development of durability analyses, and new methods for communicating bridges' states and maintenance are three examples for future research.

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1 Introduction

The Directorate-General for Mobility and Transport of the European Commission reported an ongoing increase in the transport load of goods and passengers in Europe [1, p. 21]. This goes hand in hand with increased demands on European transport infrastructure, including bridges. Analyses from Germany show that numerous bridges require maintenance and repair as well as strengthening because of the grown bearing load. Germany's country administration counts nearly 40 000 bridges, approximately 12% of which are rated as insufficient [2, p. 8 and 9]. Moreover, each state within Germany manages additional bridges that are not considered by the national report. In summary, the demands on bridges are growing and numerous bridges require either maintenance and repair or have to be replaced.

80% of the German Bridges mentioned above shall be replaced [2, p. 19] without providing information about the reasons for these decisions. It is striking that strategic, economic and technical aspects are considered, but environmental aspects, e.g. the emission of CO_2, are apparently not [2, p. 22]. On the one hand, it is conceivable that replacement is cheaper compared to repair because of lower staff efforts; thus, replacement is preferred. On the other hand, the current climate crisis requires us to lower the emission of greenhouse gases, including CO_2. Under the consideration that currently the cement industry is responsible for 5% of the global CO_2 emission [3], it would stand to reason that we should lower our demand of cement, i.e. of concrete. Accordingly, repair and maintenance of bridges should be preferred over replacement. In order to make these conflicting objectives, costs and CO_2 emissions, more compatible, two approaches are possible. The first would be to include the economic effects of greenhouse emission into the calculations for repair [4]. Secondly, lowering costs for repair and maintenance in order to make maintenance and repair more attractive to stake holders. This dissertation focuses on the task to lower the

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costs for maintenance and repair by improving the digital data acquisition thereby laying the foundation for automatic processing of bridge condition data.

To ensure traffic and structural safety as well as durability, bridges are inspected frequently. Registering condition states, performing assessments, and preparing data for inspection and maintenance tasks are time consuming and error prone because of highly paper based workflows and manual copy pasting. An improvement in digitizing bridge condition data decreases the demand of manual work, help to lower financial efforts for these tasks; therefore, make maintenance and repair more attractive. In the long term, this would lower costs and make repair and maintenance more attractive.

Figure 1.1 shows an overview of several tasks for bridge inspection and maintenance. This starts with the bridge inspection (1), at which an inspector or engineer visits the bridge and notes all defects observed. Most of the defects are easy to spot; whereas others are may be identified by tapping with a tapping hammer. Later on, the collected defect data is used to directly assess the bridge condition. In case of uncertain failure modes or suspected defects under the surface, additional data acquisition, such as Non-Destructive Testing (NDT) or Structural Health Monitoring (SHM) may be considered. All retrieved data has to be analyzed in order to define the bridge rating (2). According to national standards, the severity and extent of the defects are rated based on defect parameters. Further analyses may be done by structural engineers. Next, bridge condition prediction may be done (3), like condition predictions of components or the entire bridge, simulation on damage propagation, or reliability simulations. Before maintenance actions can be executed (5), they need to be planned (4), which includes process, resource, and cost planning. All steps are related to bridge condition data from the structure gained by inspections, analyses, and simulations. Hence, this data needs to be exchanged in a suitable and structured way with semantic and geometric information. To address these requirements, a data model is required that includes both damage and building information. This results in the need for Damage Information Modeling (DIM). Damage Information Modeling (DIM) means to integrate geometric and semantic damage and building information. Resulting models of damaged bridges are called DIM models or as-damaged Building Information Modeling (BIM) models.

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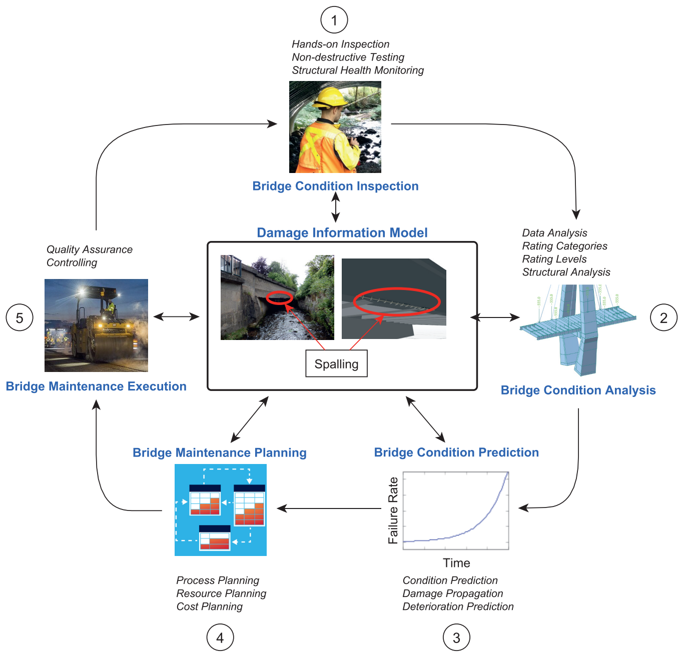

Figure 1.1: Process cycle and data exchange for bridges' assessment and maintenance. Photos and images that are part of this figure are from the "Thüringer Landesamt für Bau und Verkehr" as well as from the following references: [5]–[9]

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As shown by Borrmann, König, Koch, *et al.*, the information loss and time effort for information exchange during building design, planning, and construction phase may be reduced by automating information exchange using BIM [10]. The digital model includes semantic and geometric information required for subsequent processes. All data is saved in a digital format and sent to the targeted stakeholder. The same advantages are offered by DIM for the operating phase: data exchange is automated and accelerated.

Besides the simplified data exchange, a further advantage of digital models is that they can be processed automatically. For example, automatic clash detection helps to prevent construction errors, or automatic energy analyses help to reduce energy consumption [10]. Similar to that, DIM could offer new automated workflows in the operating phase, such as structural analyses, deterioration simulations, and maintenance planning.

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2 State of Practice and State of the Art

Generating a digital model of a building starts at the early design phase and should continue throughout the operating phase until the deconstruction. The current state of the art provides approaches to model building information starting in the design phase, update building models during planning and construction, and automatize as-is model generation. Based on these models, methods for analyses, inspection, and maintenance are elaborated. This chapter describes and discusses the existing work in order to identify the gaps in the current knowledge.

Numerous articles and conference papers about using BIM for different phases, tasks, and building types have been published. To identify existing problems and the objective, a literature analysis is conducted. First, concepts of BIM and Digital Twin are explained. Second, standards and research in the area of bridge condition data acquisition are explained. Third, based on the acquired data, a bridge assessment can be done. Fourth, to support the acquisition and assessment, several work about DIM is discussed. Fifth, besides IFC, several other data definitions exist that are described next. Sixth, several different damage types exist in practice. It would be too much to cover all damage types. Hence, a statistical analysis is performed to identify most frequent and severe damage types. This all results in the final problem statement and research questions.

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2.1 Building Information Modeling and Digital Twin

Traditional workflows in the Architecture Engineering and Construction (AEC) sector rely on plans and reports. During the creation of a building, the incorporated stakeholders exchange documents to share information about geometric and semantic information of the building or structure. Additional information, e.g., about material and processes, are exchanged in the form of reports or markers in plans. This information is analog and cannot be processed automatically by computers. Contradictory to that, several architects, engineers, and planners work with software tools and computers to generate their models and plans, which means they create digital models, generate plans and share them to digitize these documents again in subsequent tasks. This leads to information and time loss as well as errors because of doubled work.

The concept of BIM aims to promote digitization in the building sector. BIM is a concept and collection of multiple tools, which can be used to digitally generate, communicate, and process building information [10], [11]. BIM aims to cover the entire building's life cycle as shown in Figure 2.1 from the design stage up to deconstruction. All of these phases contain several tasks, e.g., cost estimation, pre-fabrication, monitoring, logistics and repair. Furthermore, these tasks are performed by different stakeholders that shall rely all on the same information. A digital geometric semantic model is the linchpin of BIM. Geometric information, such as the 3D representation of components, primarily allows proper visualization of the building but also are necessary for calculations based on geometric data, for example, areas that need plastering or the amount of concrete required for walls. Semantic information includes properties, relationships, descriptions and other data, that further describe objects, materials, processes, involved actors, or other building related information.

buildingSMART International has published several standards and guidelines in order to help software vendors and the AEC industry with digitizing their processes and implement BIM properly. To exchange and automatically process building information, three aspects need to be covered: processes, data models, and terminology [13]. Processes depend on companies and their domain. Data models and terminology should be defined independently from companies because a standard is necessary for communication between different stakehold-

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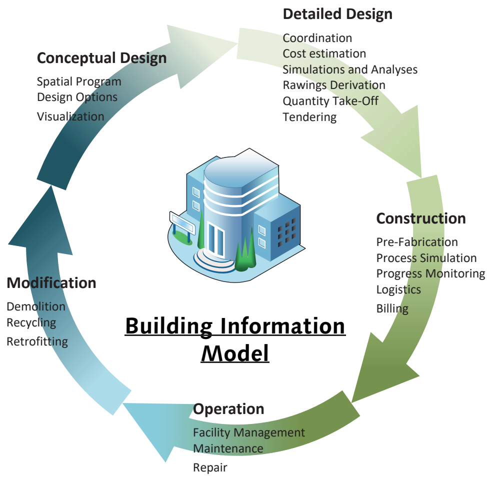

Figure 2.1: Building Information Model for the whole life cycle [12] (acc. [10]).

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ers. Readability and understandability of both rely on coordinated data formats and proper visualization; this is necessary to effectively support business processes in order to omit errors and save time. It is not feasible to specify on single process because existing processes can vary processes and additional processes or tasks may come up in future. Therefore, buildingSMART International offers a guideline to analyze and structure processes, actors, data, and requirements of processes [14]. The resulting information is summarized in the form of an Information Delivery Manual (IDM). Processes and related actors are described using process maps. Based on that, exchange requirements are used to outline information elements for later data exchange. During the development of a project, data is exchanged in different levels of detail, i.e. a building may be represented as a cuboid in an early planning phase. Later on, further details, such as windows, are added to the model. To be more precise, two terms are used in order to distinguish between the level of detail of geometric data and semantic data: Level of Geometry (LOG) and Level of Information (LOI), respectively. The combination of both is called Level of Development (LoD) [10].

buildingSMART International provides the IFC standard for data exchange in the AEC sector. IFC is published as official standard [15] and is available as open access document [13]. Using an object-oriented approach, this open and vendor-independent standard provides entities, relations, and concepts to exchange building information. Four layers constitute the IFC standard. The resource layer consists of resource definitions, like quantities, date, time, or actors, necessary for upper layers. Above the resource layer, the core layer is built, containing the kernel schema and core extensions. This layer includes definitions of basic structures, relationships, and concepts. Some entities are used across several domains but are not abstract basic elements, examples for this are doors, beams, and roofs. Such entities are part of the interop layer. All the way at the top, the domain layer provides definitions for domain specific elements, e.g., cable segments for the electrical domain or structural items for the structural analysis domain [10], [13].

With the IFC standard, buildings or structures are assembled of objects, attributes, and relationships. To illustrate the general idea of the IFC standard, Figure 2.2 shows a sample excerpt of an IFC file with a wall made of a frame and two precast panels. One of the attributes of the wall is the name 'Wall #1'. Additionally, an objectified aggregation (#156) is defined that shows that the wall is made of the frame (#148) and the two panels (#145 and #146). Objectified relationships allow to model relationships as individual objects

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```
#123= IFCWALL('2ucZRLBGP4uxZW$9i1VAZ8',$,'Wall #1',$,
      $,#153,#154,$,.MOVABLE.);
#156= IFCRELAGGREGATES('1fzLvTCX14ZPMFC2C3x$Zm',$,$,$,
      #123,(#145,#146,#148));
#145= IFCBUILDINGELEMENTPART('1dhqqYR5v9EPzs7Ts1dOEX',
      $,'Panel Forward',$,$,#358,#359,$,.PRECASTPANEL.);
#146= IFCBUILDINGELEMENTPART('3dca$PAJT1XA6b06dQW26g',
      $,'Panel Reverse',$,$,#383,#384,$,.PRECASTPANEL.);
#148= IFCELEMENTASSEMBLY('0tQt_zoibF6gdoecLxBvHT',$,
      'Frame',$,$,#186,$,$,$,.BRACED_FRAME.);
```

Figure 2.2: Excerpt of an IFC file. A basic wall (#123) has a name and is made of a frame (#148) and two precast panels (#145, #146) [13].

with two related elements. This has the advantage of being very flexible, for example, a relationship may be further classified by a an additional classification. On the other side, searching for parts of an object or the aggregation has a higher complexity, i.e., it needs more steps for calculation. In general, IFC aims to structure a building into several geometric and semantic objects. The IFC standard offers multiple ways to store building information, e.g., different file formats or databases. Most common are IFC files. Other possible file formats are archives or Resource Description Framework (RDF) files. Storing IFC data as SQLite database files has an experimental status [16]. In order to implement the data requirements, the IDM defines required information artifacts and the Model View Definition (MVD) defines how these artifacts are mapped onto the IFC standard [10]. IFC is still under development. Recent publications included alignment data, which is fundamental for bridge and tunnel design(IFC 4x1), and first suggestions for bridges (IFC 4x2 and 4x3).

Until now, there are numerous software applications that support IFC. Depending on the task and objective, these programs support different parts of the IFC standard. Firstly, there are the IFC viewers. Viewers are only meant to visualize IFC models on the computer possibly with additional options for displaying; whereas authoring tools also allow to edit these models. Several of them are free and may be categorized either as open source or proprietary applications. Table 2.1 shows a sample overview of proprietary and open source IFC viewers and libraries written in several different programming languages. Secondly there is also various authoring software, such as Autodesk Revit [17] and Archicad [18], and management software, for instance Desite BIM [19], which support IFC imports.

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The third important part for data exchange and collaboration are terms and a common nomenclature. One example are bearings that could be also called supports. A person is able to identify that these terms are synonyms. However, to automatically process data, a unique and standardized terminology is required. Furthermore, international building projects are increasingly common, causing the use of different languages in a single project. Dictionaries tackle both problems: defining common terms and providing translations for them. buildingSMART International provides the buildingSMART Data Dictionary (bsDD) as a service to register and query definitions, properties, classes, and terms. The bsDD has been defined as digital representative of OmniClass [28] and UniClass [29]. These two and other standards are also included in the bsDD.

Most bridges have been built before BIM had been established in the AEC sector. Hence, those bridges lack a proper BIM model, although there are promising approaches to use BIM for bridges. The manual creation of bridge BIM models is cumbersome and time-consuming. Considering the number of existing bridges only in Germany, this is not a viable option. Attempts to efficiently create/generate bridge BIM models led to concepts like Scan-to-BIM: a point cloud is generated using photos or with a laser scanner. Subsequent algorithms register building or bridge components, identify the mesh of the geometry, and add further semantic information [30], [31]. This simplifies and accelerates the generation of as-built models of existing bridges, which is a prerequisite to use the BIM concept in the operating phase.

buildingSMART International moved its focus from BIM to Digital Twins. A Digital Twin

Table 2.1: Sample of available Industry Foundation Classes viewers and libraries with the programming language in case of open-source software.

Proprietary	**Open Source**
usBIM [20]	xBIM Explorer (C#) [21]
BIMVision [22]	Java IFC Toolbox (Java) [23]
Solibri Model Viewer [24]	IfcOpenShell (C++, Python) [25]
	IFC.js (Javascript) [26]
	BIM surfer (Javascript) [27]

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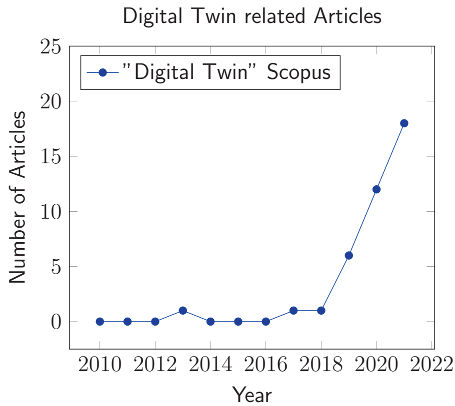

Figure 2.3: Number of articles per year having Digital Twin, bridge, and inspection in the title or abstract, as indexed by scopus. Articles have been checked manually to be also related to the AEC sector (April 2022).

is defined as a digital representation with an integrated two-way data flow between this digital representation and its physical counterpart [32]. Besides that, a Digital Shadow means that data is exchanged automatically only in the direction from the real world to the digital model. Figure 2.3 shows the number of articles related to Digital Twin, bridge, and inspection per year between 2010 and 2022, which are indexed by scopus. It is clear that the number of papers that refer to Digital Twin is growing. Although, 18 papers is quite less, the trend shows a growing interest. Such Digital Twins originate from the aerospace and manufacturing industry. Airplanes and manufacturing machines may have a digital representation and data between the representation and the physical entity are exchanged automatically, i.e., sensor data from the machine is sent to the digital representation and changes in the digital representation trigger actuators in the machine to perform a specific action or task.

In the case of buildings and structures, sensors are used more and more frequently, for example, smart home systems have been available for end users for some years and bridges are equipped with sensors to measure vibration [33]. This allows a time continuous ob-

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servation of buildings and structures. However, this cannot replace frequent inspections because sensors are placed on fixed locations, and hence, provide data of a discrete position only; whereas, bridge assessments require space continuous and heterogeneous data. To address the problem of the discrete localization of sensors, mobile monitoring robots have been developed. Such robots are able to take measurements and move along the bridge or in the building [34]. These robots are still not advanced enough to provide the broad variety of data that is gathered by an inspector.

The other data transfer direction may be addressed by using actuators like thermostats and window actuator in case of smart homes. Analogous actuators for bridges may be available in future, but currently actuators at bridges are not common. This means that currently, bridges have a Digital Shadow, rather than a Digital Twin.

To recap, BIM is important for the AEC sector to share data and communicate information during the life cycle of a building or structure. There are three requirements for collaborating on projects: processes, terms, and a data model. Although there are many publications regarding BIM, the design, planning, and construction phase are primarily covered by recent research; supporting the operation Phase wioth BIM has gotten less attention and needs further research.

2.2 Bridge Condition Data Acquisition

Bridges are inspected frequently to acquire data for later condition assessment. Besides visual inspection, NDT and sensor-based monitoring are possible data providers. Figure 2.4 shows a schematic overview of these methods including a partial overlap of NDT and sensor-based monitoring because NDT provides non-invasive acquisition of condition information. In the following subsections, all three methods are explained.

2.2.1 Visual Inspection

Figure 2.5 shows the overall process for inspection and maintenance. First, preliminary processes include the planning, i.e., what has to be inspected, and preparation, i.e., how

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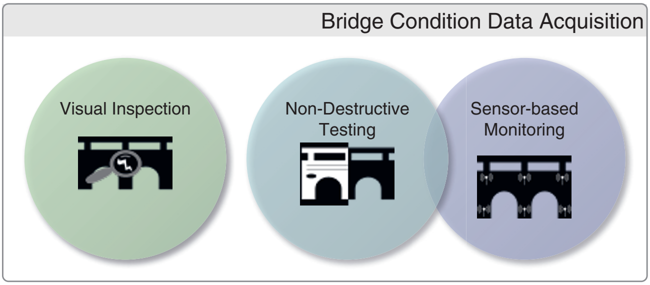

Figure 2.4: Methods used to acquire raw bridge condition data.

it will be inspected. Next, based on steps, information is acquired. A visual hands-on inspection provides an overview of existing defects and faults. Some circumstances may require additional material information, such as non-destructive testing, or structural analyses are necessary. These two processes are optional [35]. After all information has been gathered, the bridge is assessed. This includes the rating of the bridge, a rough estimation of maintenance and repair costs, as well as a decision if maintenance and/or repair is necessary. Last, if a decision for maintenance and/or repair has been made, they are planned, executed and approved. This thesis focuses mainly on the two green process groups Information Acquisition and Assessment.

In Germany, the norm DIN 1076 defines general outlines for bridge inspections, such as the frequency and aspects to be inspected [36]. Normally, bridges are inspected every three years, alternating main and basic inspection, considering a total of 13 different aspects. The Bundesministerium für Verkehr, Bau- und Wohnungswesen [Federal Office for Transport, Building and Housing] has listed all data gathered during inspections [37]. In practice, this data is noted manually by inspectors or engineers on-site. Similar approaches are also observed by Hearn for other countries [38]. Paper-based reports are used during inspections and subsequently digitized in the office. The definition of this data is centered on information about defects. Based on this information, the bridge is assessed and further decisions about maintenance actions are made. These approaches lack comprehensive semantic-geometric models for both bridges and defects. Sacks, Kedar, Borrmann, *et al.* came to the conclusion "There is currently no accepted, consistent or thorough way

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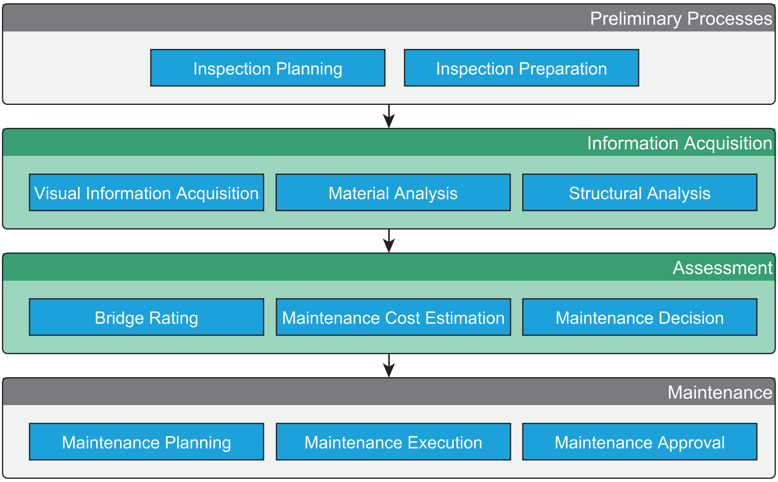

Figure 2.5: Overview of the process for bridge inspection and maintenance (acc. [12]).

to represent the defects that may occur in bridges" [39, p. 144]. Using comprehensive geometric-semantic bridge and damage information allows further automation in the case of data exchange, for instance by automatizing the transfer into structural analysis software. This could lower the costs for in-depth analyses of bridges in the operating phase, and hence, extend bridges life-time and improve their safety. A BIM model with related defects is called as-damaged model subsequently.

The catalog of damage examples from the "Bundesanstalt für Straßenwesen" has been used to define damage types [40]. Defects in the catalog are grouped by affected components. BIMwould allow to link defects to components, hence, a grouping into affected components would not be necessary. Instead, a grouping based on damage characteristics, like geometry or semantic effects, is preferred. This resulted in 22 damage types as depicted in Table 2.2. Some defects affect the geometry directly, i.e., cracks, spalling, thickness, and deformation; others affect semantic information.

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Table 2.2: Damage types deduced from the German damage catalog [40]. First published by Artus and Koch [12].

Nr.	Name	Description
1	Crack	Any visible crack at the surface, excluding cracks in coatings for wood or metal
2	Spalling	Spalling at the surface, excluding spalling at coatings for wood or metal
3	Joint damage	Damaged expansion or mortar joints
4	Loose, shear, break, or cutting of connection elements	For example, cut of screws, broken rivets
5	Broken element	For example, broken drainage
6	Material change without loss of substance	Chemical changes in the material, e.g. namely corrosion, carbonation, alkali-silica reaction without loss of diameter or similar
7	Material change with loss of substance	Chemical changes in the material, e.g. namely corrosion, carbonation, alkali-silica reaction with loss of diameter or similar
8	Moisture penetration, efflorescence, wash out	Concrete elements with moisture induced damages
9	Coarse grain/voids/foreign body encapsulation	several changes in the concrete
10	Divergence from specification/design	measured parameters, i.e. difference in height of a railing from specification
11	Missing of other parts	e.g, missing balustrade, traffic signs, etc.
12	Thickness of coating to thin or in bad quality the	meaning the coating of concrete over reinforcement
13	Waste, pollution and other foreign bodies	e.g. vegetation at the construction, bird excrement, pollution or waste

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14	Degradation of the surrounding environment	e.g. scouring
15	Deformation	e.g. tilt, bulging, shifting of components
16	Change in position	e.g. settlement of the whole structure
17	Liquid leakage	e.g. leaking drainage
18	State and functionality of elements	e.g. fixed bearing, loose screw
19	Damaged coatings	e.g. spalling, cracks, bubbles at coatings for wood or metal
20	Other changes in surface	e.g. gloss loss, change in color
21	Divergence of material measurements or state	e.g. quality of concrete,
22	Other	Defects, which could not assigned to any other group, i.e. notch effect, damaged seal profile etc.

Haardt developed an algorithm to rate defects at structures. All defects are rated in three categories: durability, structural, and traffic safety. A summarizing rating Z is defined based on the three categorical ratings and combined for component groups and the entire building. Briefly, the most severe defect determines the rating of the entire bridge with minor addition or subtraction. Based on these definitions, Artus and Koch have shown an overview of the most frequent and severe damage types in Thuringia on a dataset provided by the "Thüringer Landesamt für Bau und Verkehr" [12]. Important damage types are, for example, cracks, spallings, material changes, joint damages.

Other countries directly rate component groups in categories and deduct the bridge rating based on that [38], [42]–[46]. The rating differs also in the weighting of different damage types because common materials, environmental conditions, and construction practices differ, for example, humidity, temperature range, and natural hazards vary between countries [40], [47].

Besides the defect-based bridge rating, load indices are a common approach when assessing

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bridges [2], [48]. Variance analyses of loads allow assessment based on performances of the bridge. A comparison of actual and target loads may show inadequacies that are not caused by defects but by incomplete and/or incorrect assumptions during design time. This is primarily performed considering current traffic loads, including amount and classes of vehicle, and heuristic assumptions regarding permissible traffic loads deduced from design documents.

Sacks, Kedar, Borrmann, *et al.* have developed an IDM for the bridge inspection process that includes the generation of geometric and semantic bridge information in case of non-existent models, acquisition of point clouds for subsequent defect detection, calculation of performance indices, and maintenance action suggestions [39]. This IDM incorporates semantic information about the bridge, its components, and damage information, but misses geometric damage information. Singer and Borrmann published an attribute catalog for damage information based on the German standards. According to this catalog, defects may be represented with location, 2D, or 3D geometry [49]. Furthermore, several semantic information elements, e.g., damage type or description, are included, but geometric information and relationships between components and defects or between defects themselves.

Digitizing existing bridge condition data enables analyzing bridge condition and establishing novel analysis concepts easier. By using algorithms for text analysis, textual reports are transferred into digital machine readable formats [50]–[52]. This extraction may be done via rule based or Machine Learning (ML) models. Rule based methods rely on hand crafted rules that analyze syntactic and semantic features of texts. ML models are generated either with or without labeled training data to later on process new texts and infer additional information.

Current and future bridge inspections may be automated by evaluating photos taken manually or by drones with traditional image processing or ML algorithms. Providing initial guesses for defects, the work of inspectors and engineers could be simplified [53], [54]. However, this approach does not provide geometric data for visualization or structural analysis. photogrammetry and laser scans may deliver 3D point clouds that are processed to identify defects at bridges [55], [56]. Although, these approaches show the potential of automatically detect defects in point clouds, a structured data model is missing in order to exchange this data with further stakeholders.

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Engineers on site decide directly which defects are necessary to document during the inspection. Drones have less computing power because of their limited load bearing capacity, hence, they simply take photos during their flight and deliver them for subsequent processing. Thus, the photos have to cover the entire bridge. Seo, Duque, and Wacker as well as Morgenthal, Hallermann, Kersten, *et al.* describe a way for automatic flight plan creation [57], [58]. After the drone has followed the flight plan and acquired all photos, photogrammetry algorithms are used to generate point clouds of the structure including defects; and finally, a structural analysis is done based on the 3D model. Besides the method of photogrammetry, laser scans may be used to generate point clouds of structures with their defects [59]. Based on point clouds or photos, damage detection is done [55], [59], [60]. However, the use of this data is mainly limited to structural analysis and visualization.

Summarizing, traditional bridge inspection relies on paper-based and manual data acquisition, which is error prone and time consuming. Current national practices are highly subjective because numerical parameters and measurements are considered in a few cases only. Furthermore, these parameters are also based on rules of thumb because in-depth analysis, for example, structural analysis of strains and stresses are not common. Most countries conduct structural analyses or special surveys only on demand. However, in-depth analyses could reveal severe defects earlier and more reliable; additionally, they ease investigation in defect causes and effects. Novel approaches show that the automation of inspections is possible. Although gathering bridges' condition data has been investigated already, most systems rely on monolithic systems that impede general usage. A comprehensible DIM should be accessible for several use cases and software.

2.2.2 Non-Destructive Testing

Visual inspection methods may recognize defects too late for taking actions. NDT includes several methods that help analyzing buildings' and structures' internal condition without damaging them, for instance by using ultrasonic testing or radiography. Properties and characteristics of components or entire structures are utilized to test and visualize internal parameters. Wave-based methods utilize the natural law of reflection of waves at material borders. During a radar test, electro-magnetical waves are emitted into the component and

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are partly reflected at transitions between material layers. Such analyses enable engineers to measure material characteristics, like thicknesses of layers or entire components, localize tendon ducts, or detect voids [61].

NDT methods provide huge amounts of heterogeneous data. In the case of wave-based measurements, raw data consists of time variant signal amplitudes. These amplitudes are processed to create graphical representations that are called radargrams. Several radargrams of several component's layers may be combined to calculate a 3D volumetric model of the results. However, engineers require building data for proper interpretation of all of these NDT results. At this point, a link between building information and NDT result data is crucial.

Testing engineers primarily rely on plans and written building documents to plan measurements and assess results. The combination of NDT and BIM is promising in this circumstance but has gotten less attention yet. Niederleithinger and Vrana emphasized that there is neither a standard nor a common method to incorporate NDT results into BIM processes or software [62]. Contradictory to that, the demand of automation grows as well as the availability of sensors and interfaces. On the one side, Krieger published an approach to link NDT and BIM, however, they remarked in their study that BIM is too coarse regarding bridges, and hence, is not suitable for this task [63]. On the other side, Schickert, Artus, Lai, *et al.* outlined necessary steps to define an IDM, MVD, and a bsDD domain to combine NDT and BIM illustrating possible benefits. Similar to the IFC standard in the construction industry, there is an upcoming standard for the NDT sector called Digital Imaging and Communication in Nondestructive Evaluation (DICONDE), which tries to homogenize the data exchange in the NDT sector. This standard uses images and photos as the basis and extends them with additional meta-information. However, DICONDE does not consider BIM or building information in general, and hence, misses linking NDT results with the tested building or building component.

It can be summarized, that the construction industry and the sector of Non-Destructive Testing have been evolved more or less independently from each other and now both worlds need to be brought together. One problem with this task is that NDT delivers data related to several components and IFC operates object oriented and component-wise. Either, the data could be split up to relate each part to the related component, which worsens the

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interpretability, or all data is stored as a whole, which makes the relation to components more complicated. NDT information is out of scope for the DIM proposed here; however, future research should extend DIM to provide support for NDT information.

2.2.3 Sensor-based Monitoring

Fixed sensors in and on buildings or structures provide time continuous and space discrete information about them. Using sensors for condition assessments often refers to SHM. SHM consists of data collection, archiving, processing, and assessing [65]. This thesis considers only the data collection; hence, instead of the term SHM, the term sensor-based monitoring is used.

Several measured variables can be obtained via sensors, for example, displacement, temperature, or strain. Depending on the dynamics of measured variables and sensor's sampling rate, between dozens and millions of measurements are generated per day. To reduce the amount of data, some sensors deliver already pre-processed data. Still, sensor-based monitoring generates a large amount of numerical data that is normally stored in databases or binary files [66]. Besides fixed sensors, robotics may be used for mobile SHM [34]. Resulting sensor data is used for continuous damage detection at bridges [67].

The concept of time continuous sensor data conflicts with the IFC standard because IFC does not provide a suitable structure to directly include highly dynamic data. One possibility is to include only the sensor information into IFC and link it later to the related measurements [68, Chapter 31]. As sensor-based data is a complex topic, the DIM proposed in this thesis does not consider this data input primarily. Nonetheless, it is important for life-cycle management prospectively.

2.3 Bridge Condition Assessment

Using the German standard for bridge's inspection and assessment [36], analysis methods are subdivided into durability, structural, and traffic safety. Primarily, a proper visualization, which presents different and meaningful views to the engineer, supports bridge assessment

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processes in all three categories. Based on a BIM model, marking defect positions provides engineers a fast overview about existing defects [69]. Adding related descriptions and measurements, damage information is better interpretable [70]–[72]. By using the BIM model of a bridge, detailed information about defect positions may be provided, as well as color coding to highlight severe defects [73]–[75]. Such BIM models may be used to add further geometric data, like the defect geometry. For this purpose, point clouds of the structure inspected are generated and displayed to the user with highlighted defects [55], [76]. However, these point clouds have only a very limited amount of semantic information about the defect, and hence, visualizing semantic data, such as ratings, types, extend, or similar, is difficult.

Besides proper visualizations for manual assessments, automatic assessments may be performed. This could be done in general by calculate ratings or parameters of defects based on photos, for instance spalling diameters and severity [54], [77]. In this case, either image processing algorithms or ML models are used to process the images and extract the desired information. ML models used for assessment primarily rely on human labeled data, which may induce some bias.

Table 2.3 shows an overview of the rating categories and different approaches for related simulations. Besides the groups regarding analysis objective, all methods may be grouped regarding the methodological approach: either probabilistic or analytic. In general, these approaches allow to objectify bridge condition rating in comparison to leave the rating completely to a single engineer. For structural analysis, a structural model is generated on the basis of the as-damaged BIM model [78]–[80]. This requires semantic data, e.g., information about material strength, and geometric data, such as profiles, lengths, or volumetric shapes. Using this data, structural bridge models are generated and simulated. An engineer could analyze resulting stresses and strains to assess the bridge. Biggest drawback at this method, is the time-consuming work of transferring data manually. Explicit interfaces between BIM and structural analysis would supersede this manual work [79].

Considering long term effects of defects, simulations for structures' durability are important. These simulations aim to predict the propagation of the overall bridge state or distinctive defects. A coarse estimation may be done based on probabilistic predictions of the condition rating using Markov chains or with ML methods [87], [88]. In this case, a state transition

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Table 2.3: Sample of some literature dealing with analyzing different bridge assessment categories with different method types.

Assessment category	Analytical Methods	Probabilistic Methods
Structural Safety	[78]–[80]	[81]
Durability	[82]–[86]	[87]
Traffic Safety		

matrix for ratings is generated based on historical bridge data. This matrix contains the probabilities that a bridge or defect ratings change from one to another rating within a specified period. Applying these probabilities onto existing bridges provides estimations for the condition propagation of a structure. This would be applicable for maintenance schedules and requires only the rating of the bridge or defect. A drawback of this approach is the huge requirement of bridge rating data to calculate the transition matrix properly.

Another possibility is to base durability assessments on propagation simulations of defects that estimate future parameters of a defect. Numerous work deals, for example, with the propagation of cracks [84]–[86]. Simulating this propagation may reveal severe cracks or defects that could be prevented with appropriate maintenance. Similar to structural simulations, the manual data transfer is error prone and time consuming, hence, it is less conducted in practice. This is far more relevant, in case of generating analytical damage propagation simulations of bridges because all data on individual defects has to be transferred manually.

Traffic safety is another criterion for bridges' assessment. Some defects influence the traffic on the bridge, e.g., a pothole can cause a driver to lose control of the vehicle. Numerous works could be found that analyze the impact of traffic on bridge condition. However, no study could be found at Elsevier, Wiley, Springer, or IEEE that describes methods to analyze impacts of defects on the traffic. This task currently remains to engineers.

Bridge condition analysis is a complex task that includes durability, structural, and traffic safety. Numerous methods exist to assist engineer in analyzing structural safety and durability. However, to apply these methods, data has to be transferred manually from plans or the bridge model into the used simulation software. Using these methods is uncommon in

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practice because the manual work is error prone, time consuming and expensive. Analyzing traffic safety including defects has not been covered yet. Enabling engineers to accelerate the creation of structural and durability models, a geometric semantic model of a bridge including defects is required.

2.4 Damage Data Modeling

Easing and accelerating data transfer may be achieved by suitable data modeling and open data formats. As shown by Table 2.4 from Artus and Koch, information gathered during a bridge inspection is very heterogeneous ranging from measurements and text to 3D geometry and point cloud [12]. Hence, a proper methodology for DIMhas to include all of this information. Again, this information may be split into geometric information, for instance 2D and 3D geometry, and others are semantic, such as typification or text.

As mentioned in section 2.2.1, the SeeBridge project has proposed an IDM for bridge inspection including basic semantic damage information, for example, width and orientation of cracks [39]. The basic requirement of affected components is also addressed by their study. This basic information is mandatory for inspection practice; however, their approach allows to visualize defects only as part of a component and not as a solely entity. Another drawback is that information for structural and durability analysis, for instance geometry, is missing.

McGuire used colored cubes to include geometry in the form of bounding boxes and type of defects. The Cartesian coordinate and bounding box of a defect are one possible representations of its geometry. Structural analyses need more geometric information, for example, if the defect geometry is subtracted from the component geometry for simulation [69], [78]. Colored boxes lack additional information for the visualization, such as textural information of photos. This is necessary because current norms and guidelines define this information as mandatory.

Hüthwohl, Brilakis, Borrmann, *et al.* respected inspection processes and defects including the damage rating in their data model. Furthermore, they included photos in the form of textures depicted on the affected element at the appropriate position [89]. This model is able

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Table 2.4: Damage information gathered during inspection [12].

Visual inspection	**Simulation**	**Condition Rating**
Images/Video	Influences on material parameters	Damage condition rating in categories
2D geometry	Influences on component geometry	
3D geometry	Related damages	
point cloud		
Mesh		
Audio recordings		
Text		
Measurements		
Damage Type		
Related inspections		
Linked components, component groups, and bridge		

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to cope with most national norms and guidelines as long as a single photo is sufficient, i.e., if multiple photos are included as texture, the resulting representation would either show only a single texture or several overlapping textures, both are insufficient. An engineer must be able to observe multiple photos of a defect. Additionally, textures require mapping information for proper visualization, which is not covered by existing data models.

Isailović, Stojanovic, Trapp, *et al.* added detailed geometric information to their data model; with these geometric defects, like cracks or spalling, may be represented by a spatial 3D geometry [60]. Furthermore, this approach subtracts the damage geometry from the component geometry. From a practical perspective, engineers require different views on a defect, e.g., multiple geometries or textures, which is not covered by their model. Also, as stated by the authors themselves, they mainly respected spalling but as evident from Bundesanstalt für Straßenwesen as well as Artus and Koch, there are more damage types to be considered [12], [40].

Hamdan and Scherer designed a data model that includes geometry data, documentation in the form of resources and further properties. This model considers that defects may affect multiple components by defining damage areas as well. Furthermore, this approach has been extended to be used of structural simulation with Finite Element Analysis (FEA) [80], [90]. This approach links different data from multiple sources via ontological definitions. Using ontologies for data exchange eases data modeling due to simple linking existing models. However, condition assessments also need to review prior inspections. Using a confined data model allows to store one entity or file per inspection. The proposed ontology would need additional triples to reflect that.

Under the consideration of defects changing over time, Tanaka, Hori, Onosato, *et al.* developed a DIM that includes timely aspects of a defect by linking it to the inspection [91]–[93]. This approach provides the possibility to track defects over time. Detailed information about defect geometry is missing and photos are not included within the model, which limits the use in practice.

Besides the infrastructure sector, the historical building sector has to deal with defects and register data related to that. Applying BIM to heritage buildings led to the concept of Heritage Building Information Modeling (HBIM) [94]. Khalil, Stravoravdis, and Backes categorized the information during inspections of heritage building as follows: archaeology,

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geometry, pathology, and performance. Some of this information is important for civil engineering structures others not. Archaeological data is only interesting for heritage buildings and performance data is relevant for houses or similar. Geometry data means the geometry of the entire building that is the basis for a DIM. Most relevant is the pathological data in this context that means material and structural defects. Proposed approaches for inspection in the HBIM sector primarily rely on semantic data and related reports from NDT analyses that are linked to the building model [96]–[99].

Table 2.5 shows an overview of literature until 2020 about DIM. The literature is grouped by the information that it addresses. Numerous publications related to textual information, geometry and point clouds exists. Most of them deal with the automated data acquisition. Only a few, [89], [93], [100], have a closer look at the data model. Also, many publications directly generate a rating based on raw data, like photos, and skip the information modeling resulting in closed monolithic architectures. Having a central model fed with data would decouple the information retrieval and processing. So, different information acquisition methods may be used for many different information processing algorithms. Furthermore, also combining different data, for instance geometry and parameters, for assessment processes would be eased [12].

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Table 2.5: Literature with relation to different information types [12].

Damage	Inspection	Simulation	Condition Rating
Text	[58], [90], [98], [101]–[107]		[98], [101], [102], [108], [109]
Images/Video	[70]–[72], [75], [89], [90], [98], [103], [108]–[112]		[98], [110]
Audio recordings	[103]		
2D-damage geometry	[72], [90], [113], [114]	[114]	[114]
3D damage geometry	[55], [78], [89], [90], [112], [113], [115]–[122]	[78], [79]	[69], [78], [112], [119], [123], [124]
point cloud	[55], [58], [115], [118], [125], [126]		
Mesh	[55], [127]		[98]
Measurements	[54], [70], [89], [90], [98], [112], [120], [121], [128]		[70], [110], [112], [128]
Other damage data	[129], [130]		
Damage type	[78], [89], [92], [110], [112], [119], [128], [131]		[78], [89], [110], [112], [119], [128], [131]
Rating(s)			[70], [71], [77], [89], [128]
Related inspections	[58], [91], [128]		[128]
Influence on material parameters	[98]	[78]	[98]
Influence on component geometry	[118]	[78], [79]	

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Related damages	[89], [105], [128], [132]	[128]
Linked component(s)	[69]–[71], [75], [78], [89], [91], [92], [101], [102], [104], [110], [112], [114]–[119], [123], [125], [132], [133]	[69], [70], [78], [114], [133]
Other semantics	[31], [103], [132]	

Another view on the literature is to group it by the addressed damage type. Table 2.6 shows such a grouping. Most literature focuses on cracks and spalling because those may be registered visually by using Unmanned Aircraft Systems and automatically processed with machine learning models [5], [60]. However, other important defects, like material changes or divergences have not been addressed.

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Table 2.6: Literature with relation to different damage types [12].

Damage type	Literature
Cracks	[55], [78]
Divergences from specification/Design	
Joint damages	
waste, pollution and other foreign bodies	
Spalling	[55], [78]
Material change without loss of substance	[128]
Moisture penetration, efflorescence, wash out	
Coarse grain/voids/foreign body encapsulation	
Missing of other parts	
State and functionality of elements	
Material change with loss of substance	
Divergence of material measurements or state	
Lower rated damages	[116]–[118]
Damages in general	[112], [119]

Summarizing, there are several approaches that cover some aspects of DIM, however, a comprehensive and open definition of interfaces for exchanging damage information between several stakeholders is still missing. This approach requires including geometric, geo-semantic information, and semantic data. Important are different geometry representations, relationships between defects and affected components as well as between different defects, measurements, material parameters, assessment parameters, and additional photos and documents.

2.5 Existing Data Definitions and Formats

Besides IFC that has been explained in detail in section 2.1, there are other possibilities that may be used to exchange building and/or damage information. Figure 2.6 shows an overview of the possibilities. First of all, there are proprietary data formats, such as

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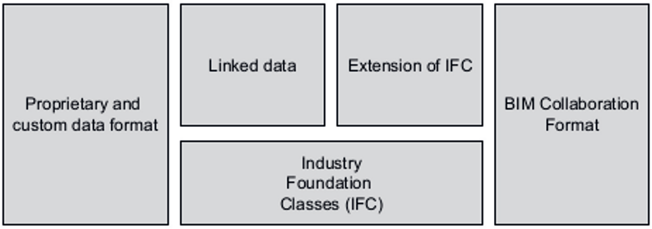

Figure 2.6: Possible approaches to model damage information.

Excel Spreadsheets. McGuire have used Excel spreadsheets for damage data exchange. Advantageous is that numerous software exists that can read this file format, however, an extension to proprietary file formats is not possible.

Based on the IFC, extensions may be defined for damage data. This has the advantage that existing concepts and software may be used. Nonetheless, additional effort has to be invested to develop and implement software extensions for the defined IFC extensions [91]–[93]. Such additional effort may be saved if existing formats may be utilized.

Also on the basis of IFC, a linked data model may be designed that links data from multiple sources [100]. Additionally, concepts like semantic web and ontologies support such solutions and also offer software applications for basic operations. Although, numerous software supports ontologies, they mainly visualize semantic data. Geometric visualization would need additional software development efforts.

In order to communicate change requirements of a building model between stakeholders, the BIM Collaboration Format (BCF) file format has been defined. This format includes information about view, highlighting, photos, and descriptions. This partly fulfills the requirements for damage information but lacks geometric damage information. Extending the BCF format would lead to a imperfect twin of IFC. Such a definition would be doubled and unnecessary work.

Existing IFC definitions are very flexible, offer numerous possibilities, and may include geometric, geometric-semantic, and semantic data. Furthermore, several software applications

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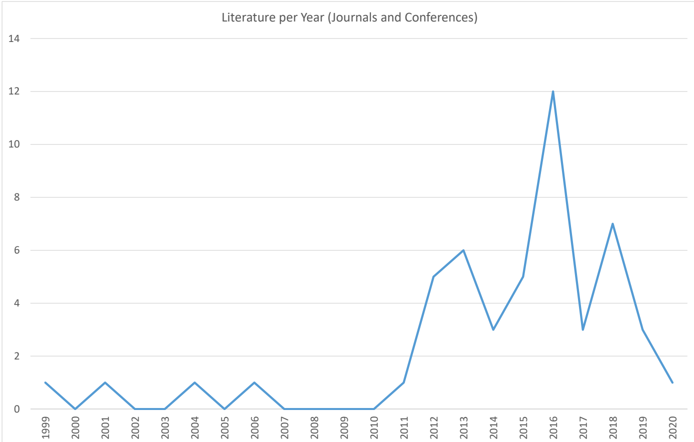

Figure 2.7: Year of publication of all literature [12].

exist that are capable of IFC. Hence, it is desired to first check if a DIM may be implemented by simply using IFC before checking further approaches.

2.6 Summary and Research Questions

Figure 2.7 shows the timely distribution of DIMrelated articles from 1999 to 2020 [12]. Eastman, Sacks, Lee, *et al.* have published the first edition of their BIMHandbook in 2008. Three years later, the first article related to inspection was published.

The literature shown in Figure 2.7 includes conference papers and journal articles until 2020 from Artus and Koch [12]. It shows a trend of growing interest in DIMȮverall, 29 publications have been identified since 1999.

Those can be split up and grouped by the related conferences and journals as shown in Figure 2.8 [12]. 14 journal articles have been published in Automation in Construction or in the Journal of Computing in Civil Engineering. Far the most conference papers

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have been presented at the International Conference on Computing in Civil and Building Engineering.

First, several damage types are defined by the different norms and guidelines. A definition of a comprehensive DIM should be done with an iterative process, for example, define a DIM for a subset of damage types and extend it later. To identify this damage related information, the following questions have to be answered:

- Damage information is related to different levels of the structure, i.e., component, component group or bridge. Which levels need to be covered?
- Damage information is related to different use cases and processes. Which use cases exist in practice and research and which processes are related to them?
- Requirements are the basement for a suitable data model. Which information elements are required for the identified processes and use cases?
- Different damage types require different data. Which damage types may be identified based on national norms and guidelines?
- To cover severe and frequent defects, it is necessary to analyze data from practice. Which damage types occur most often at bridges and have the biggest impact on their condition?

Second, national requirements and future needs require to include numerous heterogeneous data. After analyzing the requirements, a suitable object-oriented data model is required. This includes the following questions:

- Several approaches that cover parts of a DIM exist already and should be respected. How can the different models be synthesized and which changes need to be included?
- Existing approaches do not cover all necessary requirements. How to address necessary requirements for the object-oriented damage data model?
- A data model needs verification in order to proof it. How can such a data model be verified?
- A data model needs a proper implementation for verification. How to properly implement the data model using an established AEC data format?
- A first verification of the model is necessary before further steps may be taken. How to verify the data model using established AEC software?

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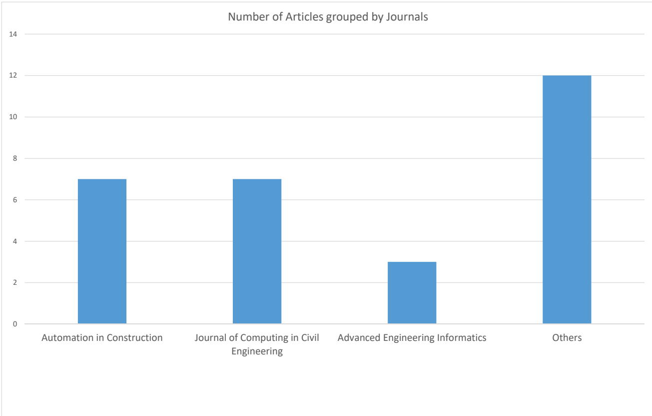

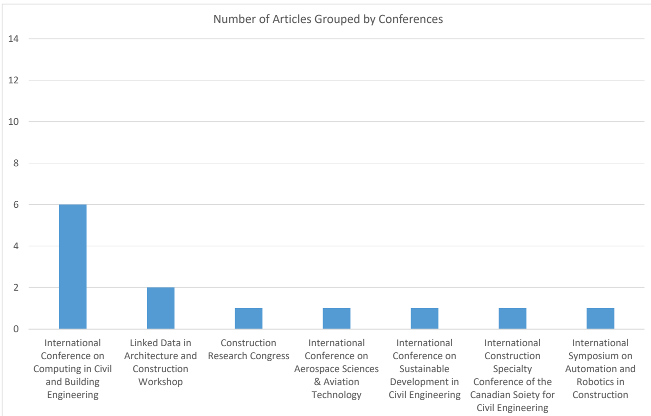

Figure 2.8: Number of journal articles (top) and conference papers (bottom) [12]

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Last, the first step in the damage data processing pipeline is the damage data acquisition, hence, the data model should be tested in order to automatically acquire damage data. Following questions need to be answered:

- Defects can be detected automatically. Can a proof of concept confirm that the developed model is appropriate in order to use it for automatic damage registration?
- The DIM relies on geometric damage information. Is it possible to automatically generate detailed damage geometry information including spatial shapes, positioning, and relationship?
- Further data, such as photos, documents, or measurements, have to be added to the geometric as-damaged BIM model. How can this be done?

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3 Object-Oriented Modeling of a DIM[1]

Figure 3.1 shows the process of defining the DIM for bridges. Based on the methods for system analysis by Booch and Shoval and Kabeli, the system requirements are analyzed and a suitable data model is defined [137], [138]. This includes analyzing existing norms and guidelines, statistical data from practice, as well as the current state of the art for bridge assessment. These steps result in use cases for the aimed data model. Subsequently, further investigation focuses on each use case to identify mandatory data. The data requirements are essential to design and implement the object-oriented DIM. Finally, a proof of concept of the model is performed by focusing on 3 scenarios: a discussion of bridge defects, a semi-automated defect registration, and structural analyses.

3.1 Inspection and Assessment Use Cases

As a first step, a requirement analysis for the data model is necessary. This requirement analysis must take current practice and up-to-date research into account. Current state of practice has to be considered to ensure the fulfillment of existing norms and guidelines; up-to-date research has to be considered in order to create a model that is also applicable in future use cases.

[1] This chapter contains republished work of a retracted article from ASCE [135]. The article has been retracted by the authors because of copy right issues [136]. All content, which was affected by the copy right issues, has been replaced.

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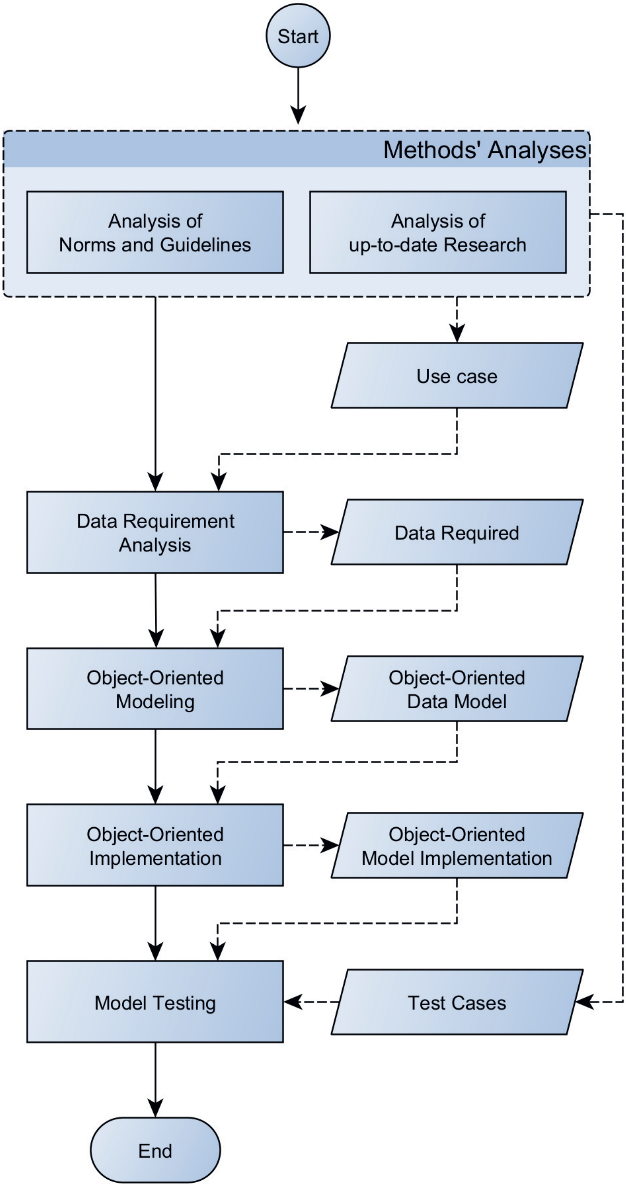

Figure 3.1: Process to define the final damage information model.

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3.1.1 Use Cases in Current Practice

As illustrated by Section 2.2.1, several standards and norms have to be considered for the practical application of the DIM. Primarily, DIN 1076 defines inspection outlines for inspections of civil engineering structures, such as bridges, tunnels, and retaining walls [36], for the public sector in general. This norm defines the frequency and type of inspections, required documentations, as well as components to be inspected.

Figure 3.2 shows an overview of the inspection process starting from inspection planning, up to the bridge assessment. Staff, equipment, routines, and traffic regulations have to be determined during the planning phase. Based on construction plans and preceding inspection reports, several aspects of the upcoming inspection are planned. Depending on inspections' type and size of the bridge, a proper team size for the inspection needs to be defined. During inspections, workers have to cross the road frequently and maybe stand on it. This leads to the necessity of traffic regulations. Some aspects of inspections, for example, inspecting the deck from below, require special equipment that has to be ordered from third parties. Furthermore, damage information and construction plans reveal locations and observations that need to be carefully observed. Figure 3.3 shows an overview of the emerging use cases during inspection, planning, and execution.

Next, on-site inspection is performed. Inspection guidelines focus on this visual inspection for condition data acquisition. The inspector or engineer registers defects and deficiencies manually and paper-based. Cracks, exposed reinforcement, corrosion, and other visual aspects stand in the focus. Also checking for loose concrete or air pockets is done by tapping components with a hammer. Additionally, measurements taken with a folding ruler or mechanic's level are taken and noted down. Besides the textual and numerical documentation of defects and deficiencies, photos have to be taken to provide a better visualization of the defects registered. The data registered on-site is later digitized in office for archiving purposes.

Beside visual inspections, methods for additional data acquisition exist. Those could be, for example, calculations or non-destructive testing. Figure 3.4 shows an overview of the use cases during in-depth analyses. Calculations focus on generating simulations to analyze the structural safety of a bridge. Two method groups are explained in the norms and guidelines

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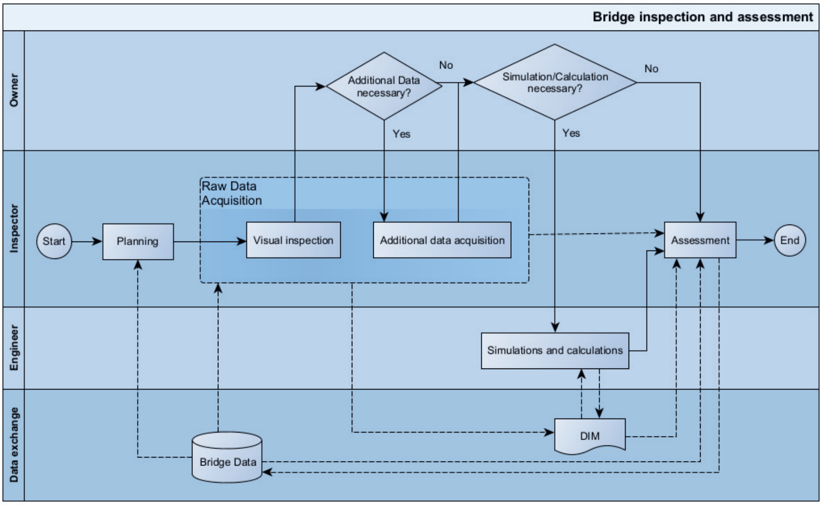

Figure 3.2: Entire workflow from inspection planning to condition rating. Dashed lines show data exchange. Consecutive processes are connected by solid lines [12].

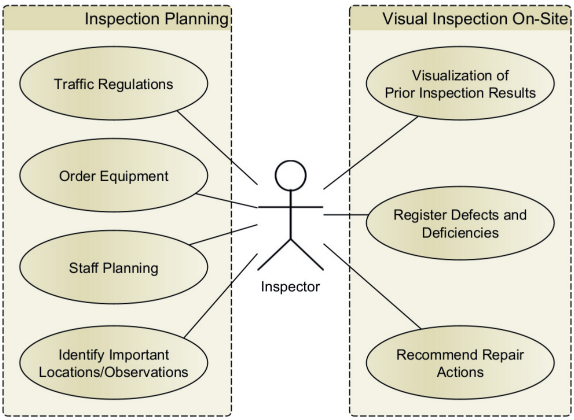

Figure 3.3: Use cases related to the inspector during inspection planning and execution.

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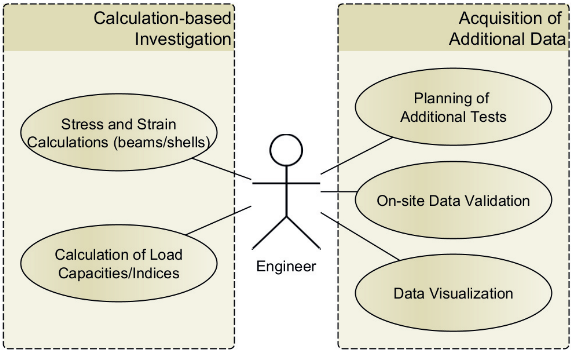

Figure 3.4: Use cases related to the engineer for in-depth analyses.

to analyze the structural safety: structural simulations based on equilibrium equations and heuristic calculations of bridges' load capacities that are compared to applied traffic loads. In case of equilibrium equation analyses, an engineer retrieves construction and damage information of the bridge being analyzed, generates the structural model, e.g., a FEA model, and performs experiments. All results of the experiments have to be documented and sent back to the owner or inspector of the bridge to reveal weak points and possible safety risks. The comparison of load capacities and applied loads, utilizes construction plans to estimate load capacities based on used materials, construction methods, and profiles [48]. Traffic loads may be deduced from traffic census and standardized load models [48], [139]. A comparison of capacities and loads results in the load index, which is used as additional parameter for assessment.

In-depth analyses that acquire additional data are primarily NDT methods. Similar to visual inspections, NDT investigations have to be planned. This planning requires comprehensive information about the bridge under consideration including information from the bridge itself, its planning, construction, and defects. Depending on the test objective and the bridge's condition, the testing engineer selects test equipment, methods, and parameters for the test. A visualization of test results on-site allows the engineer to validate the measurements and maybe perform another test with adjusted parameters. After performing the test, all results have to be included in the BIM model of the bridge. NDT primarily

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aims to assess the structural safety and durability of structures.

3.1.2 Use Cases from State of the Art

Figure 3.5 shows an overview of use cases within current scientific literature. Bridge inspections have received much attention in research last years. Unmanned Aircraft Systems (UASs) take photos based on which damage information, such as damage geometries, is generated. This information is stored in the form of an as-damaged BIM model.

Current practice for structural analyses is to rely on shells and beams. This means that each part of the bridge is represented by a plate, slab, or beam and despite this being a simplified model of the construction, all calculations provide satisfactory accuracy. Defects are incorporated by either changing material parameters, such as Young's modulus or compressive modulus [79]. This approach could be based on more detailed data by generating 3D models based on the as-damaged BIM model. Exporting and importing geometric models from BIM software to simulation software in combination with automated meshing allows such automated model generation. A similar approach may be used for deterministic damage propagation simulations.

3.2 Data and Literature Analysis for Model Requirements

A comprehensive DIM has to cover all damage types. However, developing a full featured DIM from scratch would go beyond the scope of a single dissertation. Hence, the damage types in scope have been limited by analyzing existing damage data of concrete bridges from the bridge inventory of Thuringia. This data is stored in a database and managed with the Software SIB-Bauwerke [140]. A filtered extract of the database of Thuringia has been provided by the responsible department. Limiting the damage data analyzed to prestressed and reinforced concrete bridges was decided upon because approximately 87% of the bridge square meters in Germany fit in these categories [141].

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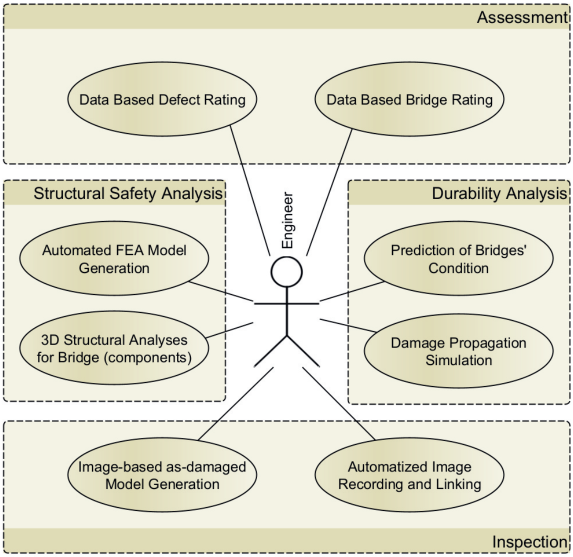

Figure 3.5: Use cases related to the engineer in recent literature.

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The database extract was provided as Excel spreadsheet with the identifier of the defect, identifier of the afflicted bridge, bridge type, type identifier for the defect type, additional descriptions, as well as the ratings in the three categories structural safety, traffic safety, and durability. This Excel spreadsheet exhibited problems during data analysis, e.g., long processing times and new views needed new pages in the spreadsheet. By transferring all data into a Structured Query Language (SQL) database, the data analysis could be simplified using SQL queries and views.

All damage types in the damage catalog [40] are organized according to the affected component groups, for instance bearing wall or pier. Under this category, cracks and other damage types are listed. This results in having the same damage type, like cracks, multiple times, e.g., cracks at piers and cracks at bearing walls are listed separately. In the first step, occurring damage type identifiers were grouped according to the generalized damage type, for example, cracks. Based on this grouping, the statistical data about frequency and ratings has been analyzed; whereby, ratings are used to determine the severity.

Using a data set provided by the "Thüringer Landesamt für Bau und Verkehr" with 2 953 bridges and 25 610 defect, a statistical analysis regarding frequency and severity of defects has been performed. All defects have been classified into damage types as shown in Table 2.2. Figure 3.6 shows an overview of the top ten most frequent damage types identified in Thuringian's bridge inventory. Cracks occur most frequently. Immediately after that, divergences from specification/design and joint defects follow. Further types are waste, spalling, and material changes. As mentioned in subsection 2.2.1, the data set consists of 2 953 bridges, hence, at least one listed crack, divergence and joint damage. Furthermore, about 15% of defects are cracks. Because of their high frequency, defects shown in Figure 3.6 are considered for the DIM.

In addition to the frequency of a damage type, the severity may be a characteristic to decide upon which damage types have to be covered. Germany has a damage catalog with standardized ratings for numerous defects. The German bridge rating system can be summarized as follows: the worst rating of a defect determines the final rating of the bridge with minor increase or decrease [41]. Simply using the rating from the catalog would not include the relevance of the defect, i.e. if a defect is severe but does not occur, it is irrelevant for practical purposes. Furthermore, it could be that two defects at a bridge both

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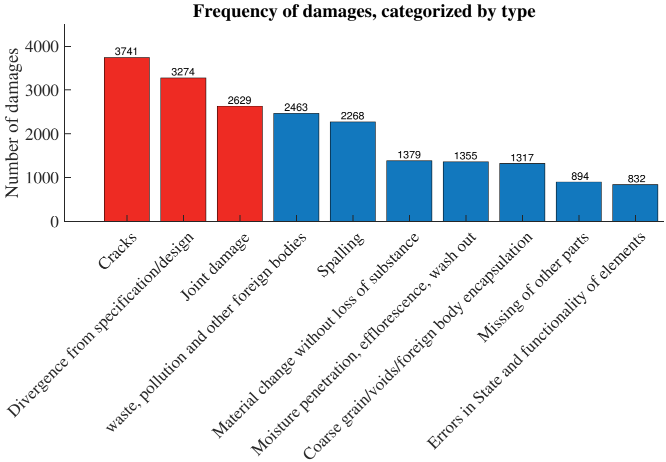

Figure 3.6: Top ten most frequent damage types in Thuringia. Top three in red [12].

have the highest rating. Therefore, it would be impossible to objectively decide which of them is more relevant. To identify relevant defects with high severity, all defects in the data set that are singularly responsible for the bridge's rating have been counted. This means that if two or more defects at the same bridge had the highest rating, none of them has been considered. If all defects that have the worst rating would have been considered, bridges with several similar rated defects would have a higher impact on the statistic, which would have led to a maximum estimation. Contrary to that, the approach proposed excludes several bridges and defects from the statistic and provides a minimum estimation. Assuming that defects with higher ratings occur less frequently than defects with lower ratings, the probability of multiple defects with higher ratings on a single structure is lower as compared to the probability of multiple defects with lower ratings. Thus, the selected single-defect approach provides a lower bound estimation for the impact of defect ratings on the overall structure rating. All defects have been counted and grouped into ranking bins for their rating and the resulting chart is shown in Figure 3.7.

Again, cracks are taking the pole position. Joint defects follow far behind them which is different compared to Figure 3.6. Also spalling show a higher importance regarding severity

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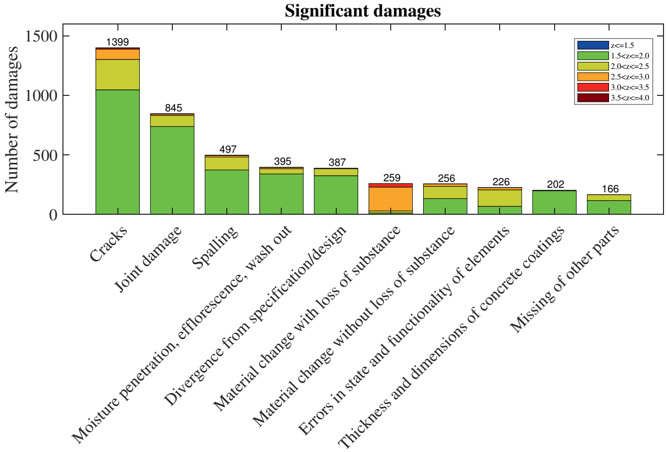

Figure 3.7: Top ten most severe defects at bridges in Thuringia, Germany, considering the severity. The colors display the Z-rating between one and four [12].

as compared to the frequency only. Apart from absolute numbers, material changes with loss of substance show a relatively high number of poor ratings.

Defects with a rating better than two are not interesting for authorities because of their minor impact to the structure. Hence, Figure 3.8 shows another view on the severity of defects, where only defects with a rating greater or equal to two have been considered. This reveals the importance of modeling material changes as they moved from the sixth position to the second. Also, most ratings are 2.5 ore worse. Hence, if a material change occurs, it is very likely that the severity is high and the condition of the bridge is deficient.

Due to the fact, that some bridges and defect are excluded by this definition, the results shown in Figures 3.8 and 3.8 provide a lower estimation of damage severity. The bars of the categories show the total number of defects considered. Lower parts of the bars, which are printed in yellow, are less severe; upper parts in red are severe defects. Obviously, cracks can be severe defects, depending on their location, orientation, and width. Highest relative number of severe occurrences are shown by material changes with loss of substance. Corroding reinforcement accompanying with a loss of diameter are part of this group.

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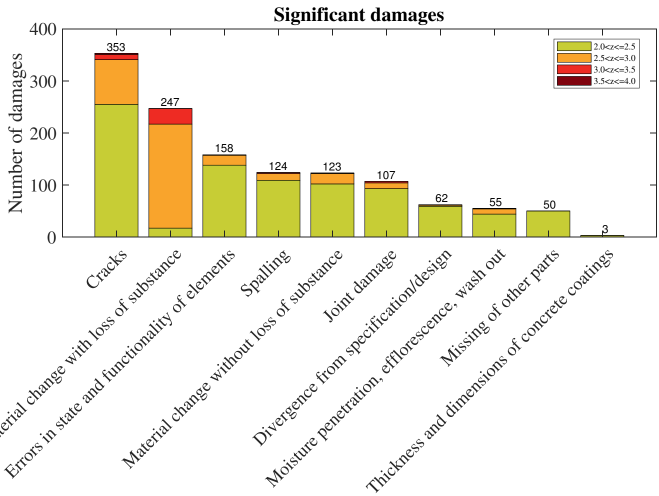

Figure 3.8: Top ten most severe defects with a rating greater or equal 2.0 at bridges in Thuringia [12].

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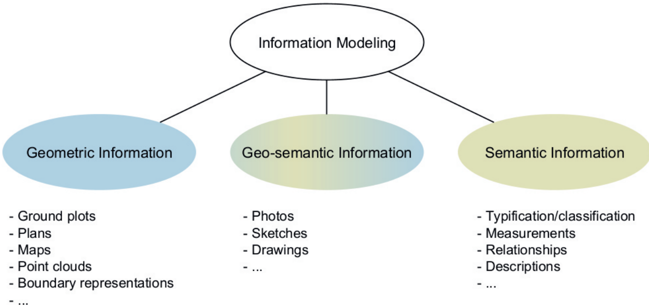

Figure 3.9: Conceptual illustration of the 3 subcategories of information modeling.

Both analyses, the analysis of frequency and severity, reveal the necessity to model cracks because they occur frequently and have a significant impact on numerous bridge ratings. Spalling also occurs in both charts; cracks and spalling could be combined into physical defects. Another interesting damage type are material changes, especially material changes with loss of substance. A loss of substance occurs in case of progressed corrosion. As a first step, a damage model should address physical defects, such as cracks and spalling, and material changes.

Borrmann, König, Koch, *et al.* have illustrated that BIM requires geometric and semantic information [10]. Geometric information means 1-, 2-, or 3-dimensional representations of objects. 1-dimensional representations are coordinates of object positions or lines. Planes are 2-dimensional representations and meshes or other volumetric representations in the X-Y-Z-space are 3-dimensional, such as Boundary Representation (BRep). Semantic information include elements, which further describe the meaning of an element or geometry. Measurements can be semantic, e.g., moisture, or geometric, such as a length. As inspections highly rely on photos and sketches that are neither geometric nor semantic information, this concept needs to be extended. Besides geometric and semantic information, geo-semantic information is required. Geo-semantic information is a combination of both geometric and semantic information. A geometric information, for example, a point in 2D, is combined with a semantic information, for example, the color. In this way, images, photos, or manual drawings may be described. Figure 3.9 illustrates this concept.

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A detailed description of data required for bridges' condition documentation in Germany is provided by the guideline "Anweisung Straßeninformationsbank Teilsystem Bauwerksdaten" [37]. These definitions include mainly semantic data. As aforementioned Germany calculates the rating of a bridge with a bottom-up method, i.e., all defects are registered and rated and based on these ratings component group ratings and finally the overall bridge rating is calculated. Other Nations directly assign ratings for component groups and the bridge rating depends on these ratings. Thus, using the German standard other standards are covered as well because the German standard includes damage, component, component group, and bridge ratings.

Table 3.1 provides an overview of the data used for the different aspects of inspection and assessment of bridges. The data is classified into the three mentioned categories: geometric, geometric-semantic, and semantic data. The second column shows different data aspects included in the data classification. Subsequent columns name the different processing steps of the data: inspection to acquire data, in-depth-analysis to provide deep insights into bridge condition, and assessment for the rating. All cells are marked with either p for produce data, c for consume data, or p/c for produce and consume data.

Most data is produced during inspection and in-depth analyses. Here, in-depth analyses require some elements of the inspection data, for example, component material to determine analysis methods. All data is consumed by the assessment at the end. Some semantic information, such as persons, is required to make processes and decisions reproducible for later review or in case of problems.

A first requirement drawn from standards is the necessity to have an object for a defect as container for all damage related data. This defect-container has a relationship to the affected component and possibly to related defects. Basically, a damage position at the damaged component is required to make it detectable for subsequent inspectors. To attach measurements taken by inspectors, this entity needs the possibility to add properties. Different damage types may have different properties; hence, a flexible concept of adding properties as own classes is desired.

In practice, geometric data covers only position information of defects, for instance 'crack on the right side at the bearing wall'. Using as-damaged BIM models, it is possible to provide

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Table 3.1: Overview of data required during the tasks of inspection and assessment. p = produce data; c = consume data; p/c = produce and consume data

Data classification	Data	Inspection	In-depth analyses	Assessment
	Defect position (1D)	p	p/c	c
	Defect orientation	p	c	c
Geometric data	Defect map (2D)	p	c	c
	Spatial defect representation (3D)	p	p/c	c
	Measurements	p	p	c
	Photos (1D)	p/c	c	c
	Videos	p/c	c	
Geometric-semantic data	Sketches	p	c	c
	Charts/Diagrams		p	c
	Textures	p		c
	Measurements	p	p/c	c
	Processes	p	p	p/c
	Tools/Equipment/Software	p	p	p/c
Semantic data	Persons	p	p	p
	Ratings			p/c
	Relationships	p		c
	Classification	p	p/c	c

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more detailed geometry information, such as a polyline for a crack at a wall. Volumetric defects, such as spalling, may include 3D geometry information.

Next, numerous guidelines define photos or sketches for defects as optional content [142]. This could be single photos, photo sets or videos. Depending on the size and amount of geo-semantic information, this could be integrated as Binary Large Object (BLOB) or referenced as external source. One exception in this category are charts and diagrams as they are produced during in-depth analyses and not during inspection. Photos and videos may need to be further processed to generate defect geometries. This is the reason photos and videos are marked with p/c in the table.

The identification of defect causes and effects require inter-defect relationships. This means that the inspector may document that a spalling is caused by the corrosion of underlying corroding reinforcement, which in turn emerged from missing or damaged joint tapes. So, the spalling is an effect of the corrosion, which is caused by the missing joint tape.

Classifications are required to add a damage or inspection type to damage or process data. This is necessary for organizational decisions, such as alternating basic and full inspection, as well as for later probabilistic analyses that are based on damage types. Furthermore, measurements need to be included in the data model with keys, values, and possible units.

Similar to LoDs at buildings [10], a definition of different information levels for defects is necessary. Inspection planning requires information about damaged components, damage positions, damage parts, and properties. The first level contains this information. An inspection review that discusses extent and severity of defects requires at least images, textures, and prior inspection reports in addition to level one, which leads to the second LoD. The third LoD aims to support structural analyses with volumetric geometries and material properties. Finally, level four focuses on the assessments and contains all documents from NDT surveys, structural, and durability analyses if available. During an inspection, in-depth analyses, like structural analyses, are optional, so, this data is not available for every inspection of the bridge. Table 3.2 shows an overview of the defined LoDs. These definitions are on a very abstract level because, for example, the results of analyses may be defined and classified in a more detailed manner. To make these LoD definitions more precise, further research is required.

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Currently, numerous research projects aim to extend BIM in different directions, also including definitions of additional LoDs. Taking into account that LoDs for the construction phase are under development in parallel to those in the operating phase, duplicate LoD definitions may occur if the existing schema is simply continued. Furthermore, the LoD for defects may vary from the LoD of the bridge. Hence, a different nomenclature for LoDs is used aside the established three-digit numbering style. The defined nomenclature uses the prefix DMG before the three-digit number to clarify the related domain.

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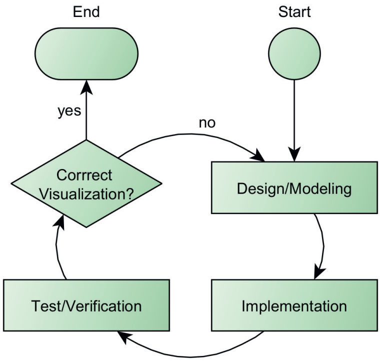

Figure 3.10: Iterative cycle for data modeling.

3.3 Object-Oriented Modeling of the DIM[2]

Based on the idea of object-oriented modeling [137], [143], an object-oriented data model is designed because the BIM concept also follows this approach [10]. The design of an object-oriented data model is an iterative process as shown by Figure 3.10. A first draft is designed and tested. Results of the tests lead to an adjustment of the model and another test cycle. This is performed until a satisfying data structure is reached. For developing the data model, Unified Modeling Language (UML) class diagrams have been used. Based on the diagrams, an implementation using IFC has been defined and tested by visualizing model example via existing IFC viewers. If the created IFC files were compliant to the IFC standard but the viewers did not visualize them correctly, modifications and extensions were made to the viewers. Further explanations about the modeling steps implementations are explained using the final results of the iterative process.

[2]This section contains republished work of a retracted article from ASCE [135]. The article has been retracted by the authors because of copy right issues [136]. All content, which was affected by the copy right issues, has been replaced.

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3.3.1 Semantic Data

Hamdan and Scherer and Sacks, Kedar, Borrmann, *et al.* have covered semantic data in their studies in the form of defect relations and measurements [39], [90]. The concepts presented in this paper are based on their work in a sense that relationships and measurements are included. Figure 3.11 shows the UML diagram for semantic defect data. Gray elements represent bridge parts and semantic damage data are depicted in blue. To address the target of a defect entity, a *DefectAnnotation* is defined, which consists of a name, id, and description. Relationships are the next point in the list of requirements. The relationship between the defect and the building product is designed via an objectified relationship *DefectProductRelation*. This relationship has two attributes: relatingProduct points to the affected bridge component and relatedDefect points to the affecting defect. Such an objectified relationship has the advantage that it can contain additional information, for example, the relation type. The *CauseEffectRelation* offers the possibility to represent causing and resulting defects. causingDefect points to the defect that is the reason for the resultingDefect. This relationship is an m to n relationship because a defect may have multiple causing defects and one defect may have several resulting defects. An objectified relationship has been used to cope with this requirement of an m to n relationship. Related documents may be referenced via the *DocumentReference* class. This points to a general object, because the documents may be related to a specific defect, such as photos of a defect, or to a building product, such as an ultrasonic survey of a bridge component. Furthermore, the class contains an identifier, name, description, and URI about the referenced document.

To address the requirement of a defect type, the *DefectAnnotation* is provided with the defectType attribute, which is of type *DefectType*. The *DefectType* class has a name and description. Possible names could be crack, spalling, corrosion, or similar. The defect properties are added by the class *Measurement* and grouped via a *MeasurementSet*. A Measurement contains a name, value, and an optional unit. In summary, this part of the model covers the requirements of modeling semantic data as shown by Table 3.1 bottom.

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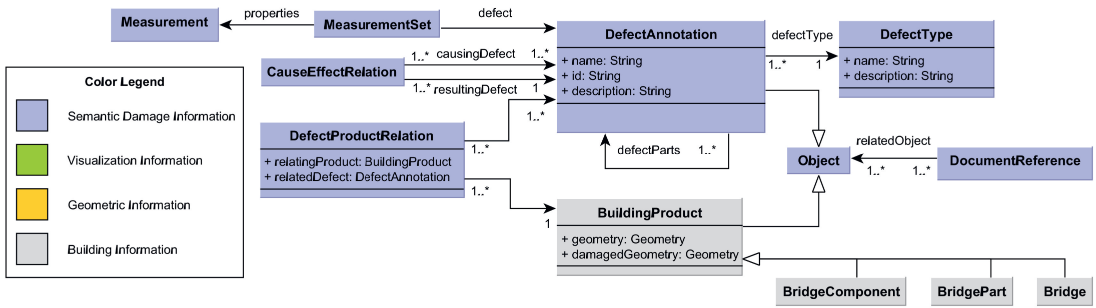

Figure 3.11: UML class diagram for the model of semantic data.

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3.3.2 Geometric-semantic Data

Images and photos are important information formats for defects. The are a combination of 2D-geometric information, i.e., the pixel position, and semantic information, i.e., the color of the pixel. Hence, information in the form of images, photos or similar are named geometric-semantic information. Hüthwohl, Brilakis, Borrmann, *et al.* have proposed defect representations using textures, however, their approach misses the requirement of including multiple photos and necessary texturing information [89].

Addressing the requirement of storing multiple photos, they can be referenced via *DocumentReference*. Figure 3.12 shows the concept of using of a photo as texture. The *DefectAnnotation* has a *Texturing* with the texture area, mapping information, and URI. A texture is applied to the texture area by mapping the image from the URI with the given texture mapping. *TextureMappingAlgorithm* is a subclass of *TextureMapping* and represents generic algorithms to calculate texture mappings, like the spherical texture mapping. *TextureGeometryMap* represents a point-based texture map also as subclass of *TextureMapping*. A *TextureArea* defines the location of a texture. This may be the entire geometry of a defect or component or it is a part of those geometries. Figure 3.13 shows the expected resulting output.

3.3.3 Defect Geometries

Physical defects lead to cutouts in component geometries. Either this is derived from the relationship between the damage and the component, or the relationship between the component and the damage is modeled separately from the geometry of the damaged component. The advantage of interpreting the geometry on the basis of the relationship between the component and its defect is that fewer entities are necessary, which entails less risk for incoherence. However, including multiple geometries is defined as a requirement, but calculating the geometry on the basis of the relationship does not offer to involve multiple geometries for a defect or damaged component. A distinction of relationships and geometries fulfills enables to include multiple geometries of defects and damaged components. For the sake of completeness, both methods are modeled, implemented, and tested.

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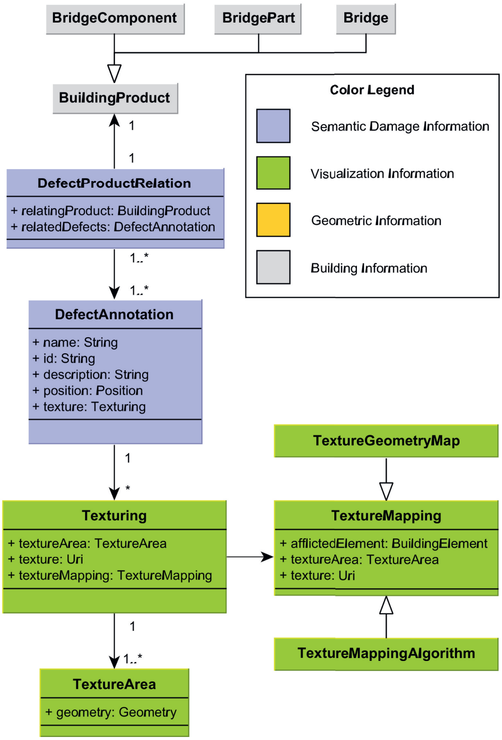

Figure 3.12: UML class diagram of the information model with additional textures.

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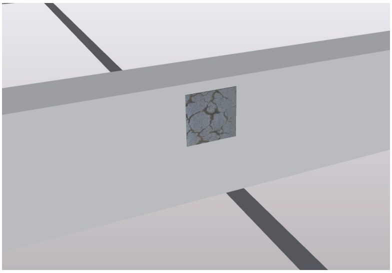

Figure 3.13: Visualization of an image applied as texture to a rectangular area.

These methods have in common that the defect and component have individual geometries; furthermore, the concept of Constructive Solid Geometry (CSG) is used to calculate the geometry of a damaged component for both approaches.

Relationship-Based Geometry

[60] have shown the integration of damage geometry into BIM models. However, their implementation has the shortcoming of using a surface feature for subtraction, which contradicts with the definition of IFC 4. The concept proposed in this paper is inspired by their work. Fewer relationships and entities are required if relationships between defects and components lead to geometric interpretations. Figure 3.14 illustrates this approach. *DefectProductRelation* has been replaced with a new relationship, namely *DamagedGeometryCutOut*, which is colored in blue and yellow because it combines the relation between a defect and the affected component and involves geometric data. buildingElement points to the affected component and defect points to the affecting defect. To model a crack in a wall, buildingElement would point to that wall and defect would point to the crack. Both objects, i.e. the undamaged wall and the crack, have a geometry. The geometry of the crack is subtracted from the geometry of the wall to create the geometry of the damaged wall.

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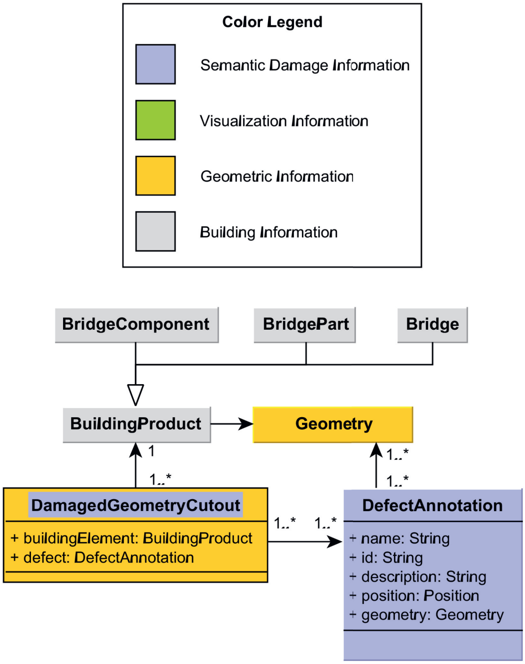

Figure 3.14: Class diagram for modeling the damaged component geometry with the component geometry and the defect geometry. The relationship *DamagedGeometryCutout* influences the geometry, hence, it is colored in blue and yellow.

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Independent Relationship and Geometry

The data model of [60] has a second drawback: it does not allow multiple geometries for a single defect which is required as explained in the Data Analysis for Model Requirements section. Using the following concept, this requirement is fulfilled. Figure 3.15 top illustrates how to independently model the geometry and the relationship between defects and products. This approach uses the *DefectProductRelation* from Figure 3.11 to represent the relationship between a defect and the affected component. The component and the defect have their individual 3D geometry. Figure 3.15 bottom shows the object diagram for this method. The defect has a geometry called **defectGeometry** and the damaged component has two geometries: the *componentGeometry* and the *damagedGeometry*. Cutting out the damage geometry from the component geometry results in the **damagedGeometry** of the component. Each geometry has a representation context to allow selecting the desired geometric representation.

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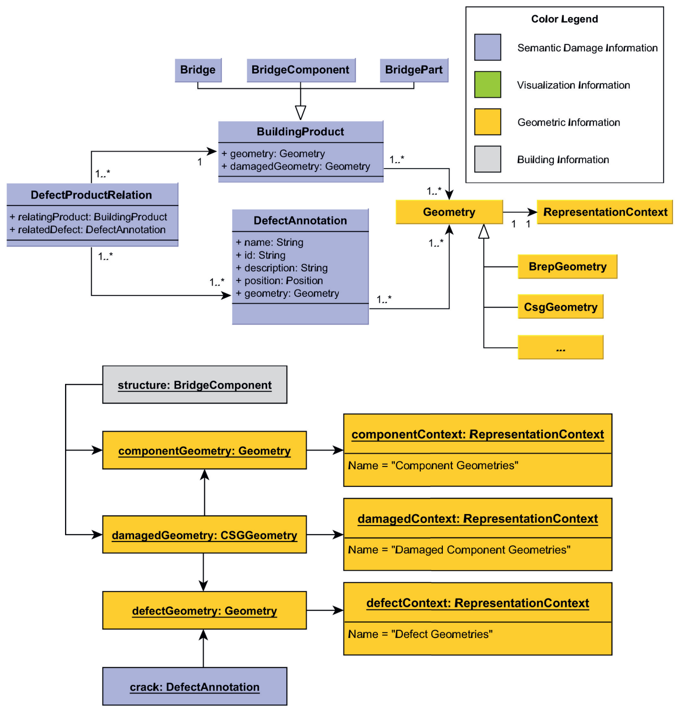

Figure 3.15: Top: UML class diagram for modeling the threefold geometry: intact component geometry, defect geometry, and damaged component geometry. bottom: object diagram for the threefold geometry model.

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3.3.4 Synergized Damage Model

Figure 3.16 depicts the entire UML model including both geometry modeling approaches. The geometry may be included by the *DamagedGeometryCutout* relation or by the *Defect-ProductRelation* in combination with CSG geometries.

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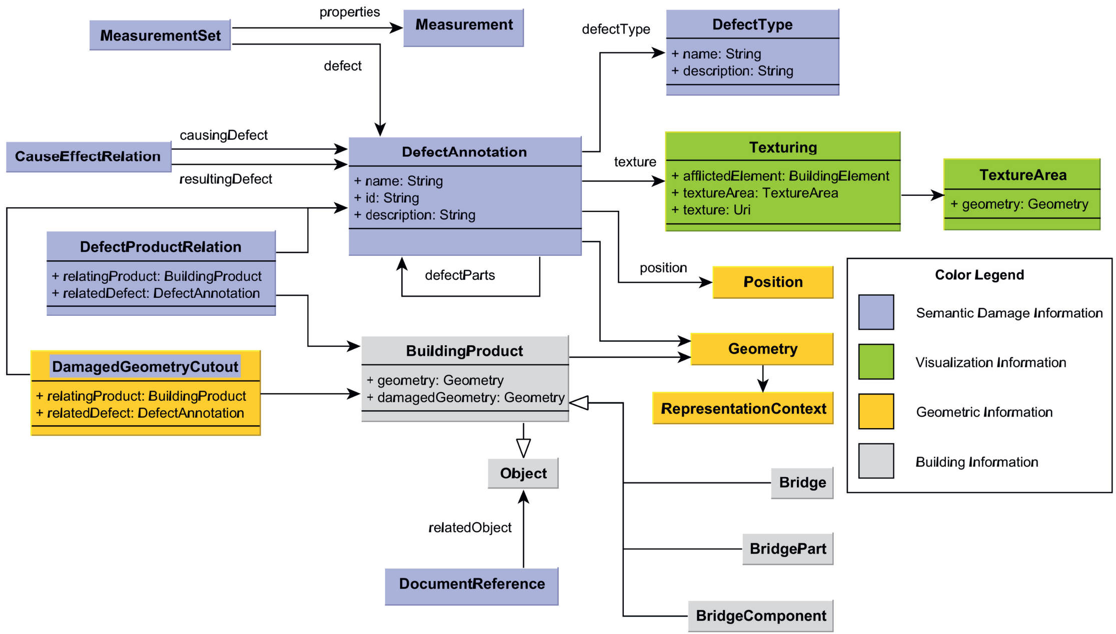

Figure 3.16: UML model including both variants A and B with the relationship-based geometry and the distinct geometry and relationship.

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4 Object-Oriented Implementation of the DIM[1]

After the definition of the information model, a proper implementation in form of a data model has to be done. As BIM relies on IFC, the IFC standard is used as basis for the data model. Furthermore, the data model shall be visualized by available IFC software. Hence, testing and extending existing software is explained as well.

4.1 Object-oriented Implementation of the DIM based on IFC

Based on the model given in Figure 3.16, an implementation shall be done using an established AEC data model. As explained in Section 2.5, IFC has been chosen as a suitable data format. IFC already contains numerous classes to model building elements, materials, persons, processes, and more. Figure 4.1 shows an overview of the mappings between IFC entities and the classes in the object-oriented model. In the middle are the classes from the object-oriented model and on the outer left and right are the related IFC entities. The defect annotation may be represented by four different IFC entities. A proxy element is the most generic approach to represent a defect including a geometry independently from the damage type. However, proxy geometries are treated like a geometries of building

[1] This chapter contains republished work of a retracted article from ASCE [135]. The article has been retracted by the authors because of copy right issues [136]. All content, which was affected by the copy right issues, has been replaced, i.e., IFC code snippets in Figures 4.2, 4.4 to 4.6 and 4.9 have been revised, Figure 15 from the article has been replaced with Figure 4.10.

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elements, i.e., they are visualized as spatial elements, which could be counter-intuitive in case of cracks or spalling. Better would be that a crack or spalling is subtracted from the geometry of the building element.

Annotations allow to add information to a building element. Despite of the traditional thought of a defect is an annotation, this entity may be used in seldom cases only because it is limited to 2D geometry as stated by the formal proposals of the IFC standard [13]. 2D geometries are suitable for defects, like cracks, in the form of crack maps or abrasion as marked area on a surface. Similarly, surface features may also represent defects that mainly affect the surface of a component. However, to accommodate the BIM concept, it should be omitted to use annotations for defects because according to the IFC standard, 'An annotation is a graphical representation [...] that adds a note or meaning to the objects [...]' [13].

In case of damage types that include geometry subtractions of the affected component, a voiding feature is suited best because the dedicated relationship *IfcRelVoidsElement* implies that the geometry of the voiding feature is subtracted from the related building element. Some examples for these damage types are cracks, spalling, and voids. Summarizing, depending on the damage type, there are four IFC entities that may be used for a single defect and the best suitable has to be chosen. Nonetheless, none of these entities represent a defect semantically correct, hence, a distinctive defect element should be included in the IFC standard to properly include damage information. In contrast to the suggestion of Tanaka, Nakajima, Egusa, *et al.* - adding three additional entities - it would be enough to add a single entity to properly include defects [93].

4.1.1 IFC Classes for Semantic Data

Up to now, there are no specific defect entities implemented in the IFC. However, the IFC offers several alternatives: *IfcProxy*, *IfcAnnotation*, *IfcSurfaceFeature*, and *IfcVoidingFeature*. Table 4.1 presents a comparison of the advantages and disadvantages of these IFC entities. *IfcProxy* is a generic entity, but the IFC 4 lists the proxy as deprecated and recommend using *IfcBuildingElementProxy* instead. A look at newer versions of the IFC reveals that the proxy is marked deprecated no longer. The DIM should be usable in future

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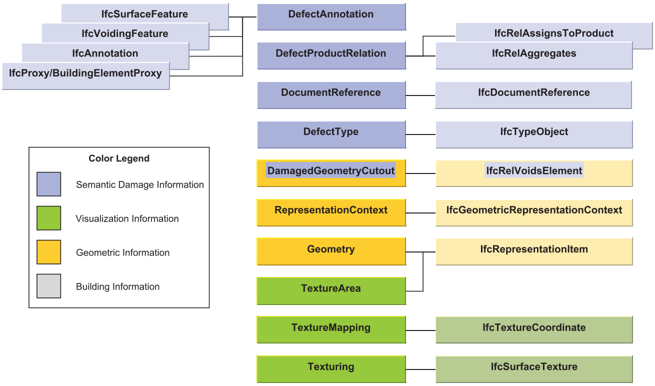

Figure 4.1: Mapping of the IFC entities onto the classes of the object-oriented Model.

standards, and hence, the proxy is taken as an option instead of *BuildingElementProxy*. A proxy is very flexible and thus suitable for every defect type. However, a proxy is treated as an individual element or building element, which conflicts with the nature of a defect. A defect cannot exist without the affected component. An *IfcAnnotation* may be used to add further annotations to a component. However, *IfcAnnotations* are only meant to have 0D, 1D, or 2D geometries. This circumstance limits their applicability to damages without or geometries or surface damages. *IfcSurfaceFeatures* and *IfcVoidingFeatures* are suitable for specific defects. Surface features are suitable for modeling corrosion or other defects, which only affect the surface of a component. Voiding features are suitable for defects like cracks or spalling, which add a void to a component. However, they are not suitable for modeling further damage types, e.g., material changes below the surface, divergences from specifications, or wash-outs. On the whole, depending on the defect, a suitable IFC entity has to be chosen. Corrosion or other surface changes claim for surface features. Cracks and spalling are represented by voiding features at best. Other defects could use either annotations or proxies.

In the next step, the analysis of suitable relationships from the IFC standard is presented. *IfcRel-Assigns* “is a generalization of 'link' relationships among instances of IfcObjects and its various 1st level subtypes” [144]. A specific identification of the relationship is

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Table 4.1: Overview of the possible IFC entities with advantages and disadvantages

	IfcProxy	IfcAnnotation	IfcSurfaceFeature	IfcVoidingFeature
+	interpretable by most applications	add (textual) information about defect to component	suitable for specific defects,	suitable for specific defects,
			geometry is not visualized like geometries of components	geometry is not visualized like geometries of components
-	generic container,	less supported by applications,	only designed for modifications at surface,	only designed to reduce volume of element,
	independent object in contrast to a dependent defect	limited representations,	less supported by applications,	less supported by applications,
		modeling defects as annotations conflicts with the original meaning of annotations	modeling defects as surface features may conflict with original meaning of surface feature	modeling defects as voiding features may conflict with original meaning of voiding feature

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Table 4.2: Overview of the possible IFC entities with advantages and disadvantages

	IfcRelAssignsToProduct	**IfcRelAggregates**	**IfcRelVoidsElement**
+	interpretable by most applications	interpretable by most applications	avoids additional data for geometry
-	not usable for defects, which are part of a component (cracks, spalling ...),	some defects are not part of a component (e.g. vegetation) parts	designed for voids only
		representation results from geometry of sub	less supported by applications

stored as the name of the relationship. In case of the *DefectProductRelation*, the name of *IfcRelAssignsToProdcut* would be "Defect product relation." However, a defect is part of a component and if the component is destroyed, the defect no longer exists. Hence, a composition is more precise. Strict compositions are modeled with *IfcRelAggregates*. Construction and design practice understands aggregations as a sum of different products. This would imply that a defect is a product if an aggregation is used, which is questionable. Altogether, aggregations seem to be the most precise relationship for physical defects. Both relationships the aggregation and the assignment may be used for other defects. In case of using *IfcVoidingFeature* to represent defects, the decomposition relationship *IfcRelVoidsElement* is suitable. "IfcRelVoidsElement is an objectified relationship between a building element and one opening element that creates a void in the element." [144]. As stated earlier, the voiding feature and the voids relationship are only applicable to cracks or spalling and not in case of material changes or other damage types. An example is depicted by Listing 4.2. *IfcRelAssignsToProdcut* may be used for effect-cause relations with the name "cause" or "reason." Additional information about the relation might be given by the description of the relationship. Table 4.2 provides an overview of the existing relationships and related advantages and disadvantages.

Figure 4.3 shows a schematic overview of one possible implementation of the DIM in IFC.

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```
/* Building element */
#244= IFCBEAM('2tso43_ekkqjB6caA5ViEg',#42,
      'Test Beam', $,$,#242,#233,$,.BEAM.);

/* Defect Spalling */
#9002= IFCVOIDINGFEATURE('0n1ZskSHuEqdlb4p0105hg',
       #42,'Spalling','Spalling at beam',
       'Defect - Spalling', #8556,$,$,.CUTOUT.);
#9004= IFCRELVOIDSELEMENT('2hSrdH4wY0ynUPT1SyLhxw',
       #42,$,$,#244,#9002);
```

Figure 4.2: Extract of an IFC file modeling a damaged beam (#244) as damaged building element. The defect is represented by a voiding feature (#9002) and the voids relationship (#9004) models the relationship to the beam.

The defect is implemented as voiding feature in the middle. Properties are used to include measurements and other alpha-numeric data related to the defect. Type objects are utilized to add classifications to defects, such as spalling or crack. Document associations are able to relate external documents to the defect, for example, photos, reports, or testing results. On top, the relationship *IfcRelVoidsElement* connects the defect to the affected bridge element.

Figure 4.4 shows an excerpt to illustrate the incorporation of classification, measurements, and external documents. Entity #9000 is once again the defect. This defect is classified as spalling by the type object #9011. This classification may be hierarchical, for instance a classification for defects and a sub-class for spalling. #9021 is a property set of measurements for the spalling containing a diameter (#9022) and depth (#9023) with a unit (#43). At the end of the excerpt, is a reference to an external report of an ultrasonic investigation (#9031). Such external documents could also be photos and included together together with the IFC step file into an IFC-zip file.

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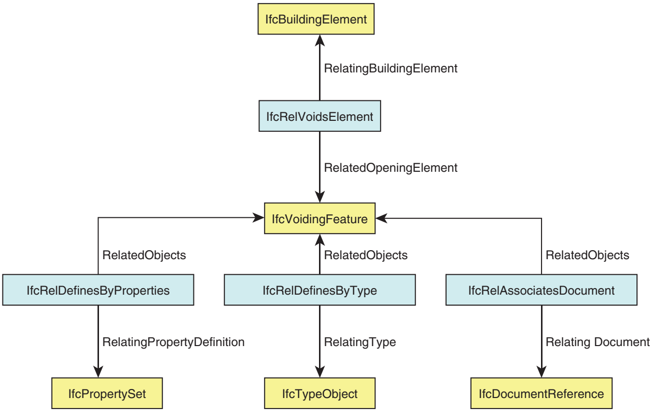

Figure 4.3: Block diagram of the resulting IFC structure. Yellow elements are instances and blue elements are relationships.

4.1.2 IFC Classes for Geometry Data

This subsection discusses the implementation of geometries of the DIM by using the IFC. Besides modeling the geometry of the damaged component, the method of modeling a defect geometry and the use of geometric representation contexts are illustrated.

Relationship-based geometry

This paragraph illustrates the implementation of the geometry model described in the Relationship-Based Geometry section and is related to Figure 3.14. Listing 4.5 shows an extract of an IFC file that contains an *IfcVoidingFeature* (#9002) as defect entity and a related component (#244). The *IfcRelVoidsElement* (#9004) represents the relationship between the defect and component and implies cutting the defect geometry out of the component geometry.

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```
/* Defect Spalling */
#9000= IFCPROXY('0igGRCoTwk6XcjC1hqayEA',#42,
        'Spalling',$,'Defect',#242,$,.NOTDEFINED.,$);

/* Damage type */
#9010= IFCRELDEFINESBYTYPE('1bIoUtPdkkqxQGAgf-5vpA',
        #42,'Damage type','Typification of a defect',(#9000),
        #9011);
#9011= IFCTYPEOBJECT('10gzfsrKgEihXsn84QV_hQ',#42,
        'Damage type Spalling',$,'IfcProxy/Defect',$);

/* Measurements */
#9020= IFCRELDEFINESBYPROPERTIES('1S7kZBQd3USDFsV8uKQvDA',#42,
        'Defect Measurements','Diameter and depth of the
        spalling',(#9000),#9021);
#9021= IFCPROPERTYSET('0zky6s7LQ0CXauZHIiqYTA',#42,
        'Diameter and Depth',$,(#9022,#9023));
#9022= IFCPROPERTYSINGLEVALUE('Diameter',$,IFCREAL(151.0),#43);
#9023= IFCPROPERTYSINGLEVALUE('depth',$,IFCREAL(12.0),#43);
#43= IFCSIUNIT(*,.LENGTHUNIT.,.MILLI.,.METRE.);

/* Document */
#9030= IFCRELASSOCIATESDOCUMENT('2Nv5qvEsoku-QzHBcSpXXA',
    #42,'Report of ultra sonic survey',$,(#9000),#9031);
#9031= IFCDOCUMENTREFERENCE('http://standards.buildingsmart.org/
        IFC/RELEASE/IFC4_1/FINAL/EXPRESS/IFC4x1.exp',
        'U_S_16092020-42','Ultra Sonic report 16092020-42 from
        the 16th September 2020',$);
```

Figure 4.4: Part of an IFC file modeling a proxy for the defect (#9000) and a type object (#9011) to define a damage type namely 'Damage type Spalling'. Additionally, some measurements (#9021) and a reference to an external document (#9031) are included.

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```
/* Building element */
#244= IFCBEAM('2tso43_ekkqjB6caA5ViEg',#42,
        'Test Beam',$,$,#242,#233,$,.BEAM.);
#233= IFCPRODUCTDEFINITIONSHAPE($,$,(#227,#231));
#231= IFCSHAPEREPRESENTATION(#103,'Axis','MappedRepresentation',
        (#229));

/* Defect Spalling */
#9002= IFCVOIDINGFEATURE('3-7hkhVEek2181I_ZN1Gzg',#42,
        'Spalling','Spalling at beam','Defect - Spalling',
        #8556,$,$,.CUTOUT.);
#9004= IFCRELVOIDSELEMENT('191hmq9RzkaK7Q650o6tKw',
        #42,$,$,#244,#9002);

        /* Defect Geometry */
#9003= IFCPRODUCTDEFINITIONSHAPE($,$,(#8548));
#8548= IFCSHAPEREPRESENTATION(#105,'Body',
        'MappedRepresentation',(#8546));
#8546= IFCMAPPEDITEM(#8542,#232);
#8542= IFCREPRESENTATIONMAP(#8541,#8539);
#8539= IFCSHAPEREPRESENTATION(#105,'Body','SweptSolid',(#8538));
#8538= IFCEXTRUDEDAREASOLID(#8534,#8537,#20,250.);
#8526= IFCCARTESIANPOINTLIST2D(((-125.,-30.),(125.,-30.),
        (125.,30.),(-125.,30.),(-125.,-30.)));
#8533= IFCINDEXEDPOLYCURVE(#8526,$,.F.);
#8534= IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,'Box',#8533);
```

Figure 4.5: Extract of an IFC file modeling a beam (#244) as damaged building element. The defect is represented by a voiding feature (#9002) and the voids relationship (#9004) represents the relationship between the beam and the defect.

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Independent relationship and geometry

This section illustrates the implementation of the geometry model described in the Independent Relationship and Geometry section and is related to Figure 3.15. In case of storing the geometry of the damaged component in the IFC, representation contexts are chosen to distinguish the geometries of intact and damaged components. A product might have multiple representations and every representation has a different representation context. Listing 4.6 illustrates the use of multiple geometries and representation contexts. The defect and the beam have their own geometries as shown by entities #9003 and #233. In this context, the damaged geometry of the beam, entity #9100, is a CSG geometry with a subtraction of the undamaged beam and the defect geometry. An example is depicted in Figure 4.7. The beam without any defects is shown on the left. In the middle is an exemplary cuboid defect and on the right is the beam with the cuboid damage geometry as cutout.

4.1.3 IFC Classes for Geometric-semantic Data

Geometric-semantic data may be stored as document references or as textures, which are depicted on a 3D surface. Document references have been discussed in the FC Classes for Semantic Data section. Coming to the implementation of textures, Figure 4.8 illustrates how to include a texture in an IFC file. To position an image, for example, a PNG-file, within the 3D model, a geometry is necessary. This geometry is represented by the *IfcRepresentationItem*. Such a geometry could be a plane, which carries the texture slightly above the related position of the affected component. A listing example can be found in the study by [89]. In addition to the texture itself, the mapping is necessary. The IFC offers the class *IfcTextureCoordinate* to add texture-mapping information and subclasses, such as *IfcTextureCoordinateGenerator* and *IfcIndexedTriangleTextureMap* to either define an algorithmic or point based texture mapping.

Texturing is a special method to include geometric-semantic data and needs a mapping algorithm to correctly depict the texture on the geometry. Figure 4.9 shows how to achieve that using IFC. Again, the defect is defined as proxy (#9000) with a simple cuboid geometry

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```
/* Building Element */
#244= IFCBEAM('2tso43_ekkqjB6caA5ViEg',#42,
        'Test Beam', $,$,#242,#233,$,.BEAM.);

/* Undamaged Geometry */
#105= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,
        *,*,#99,$,.MODEL_VIEW.,$);
#155= IFCEXTRUDEDAREASOLID(#149,#154,#20,12125.4);
#187= IFCREPRESENTATIONMAP(#186,#165);
#225= IFCMAPPEDITEM(#187,#224);
#227= IFCSHAPEREPRESENTATION(#105,'Body','MappedRepresentation',
        (#225));
#233= IFCPRODUCTDEFINITIONSHAPE($,$,(#227,#231,#9100));

/* Defect Spalling */
#9000= IFCPROXY('0igGRCoTwk6XcjC1hqayEA',#42,
        'Spalling',$,'Defect',#242,#9003,.NOTDEFINED.,$);

/* Defect Geometry */
#8526= IFCCARTESIANPOINTLIST2D(((-125.,-30.),(125.,-30.),
        (125.,30.),(-125.,30.),(-125.,-30.)));
#8533= IFCINDEXEDPOLYCURVE(#8526,$,.F.);
#8534= IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,'Box',#8533);
#8538= IFCEXTRUDEDAREASOLID(#8534,#8537,#20,250.);
#8539= IFCSHAPEREPRESENTATION(#9050,'Body','SweptSolid',(#8538));
#9003= IFCPRODUCTDEFINITIONSHAPE($,$,(#8539));
#9050= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Defect Geometry',
        'Defect Geometry',*,*,*,*,#9051,$,.MODEL_VIEW.,$);
#9051= IFCGEOMETRICREPRESENTATIONCONTEXT('Defect',
        'Model' ,3,0.01,#96,#97);

/* Damaged Component Geometry*/
#9100= IFCSHAPEREPRESENTATION(#9150,'Body','CSG',(#9101));
#9101= IFCCSGSOLID(#9102);
#9102= IFCBOOLEANRESULT(.DIFFERENCE.,#155,#8538);
#9150= IFCGEOMETRICREPRESENTATIONSUBCONTEXT('Damaged Components',
        'Damage Model',*,*,*,*,#9151,$,.MODEL_VIEW.,$);
#9151= IFCGEOMETRICREPRESENTATIONCONTEXT('Damaged-geometry',
        'Model',3,0.01,#96,#97);
```

Figure 4.6: Excerpt of an IFC file modeling a distinct geometry and relationship. An assignment (#9001) represents the relationship between the beam (#244) and the defect (#9000). The beam has two geometries: a damaged geometry (#9100) and an undamaged geometry (#227).

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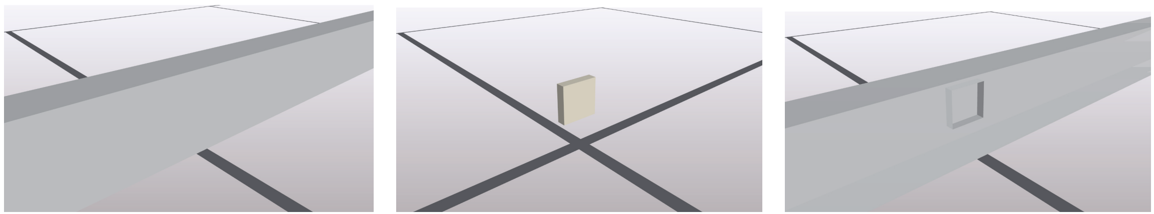

a) b) c)

Figure 4.7: A geometric damage representation by using CSG in the 3D view. a) shows the undamaged beam, b) the defect geometry, and c) the damaged beam.

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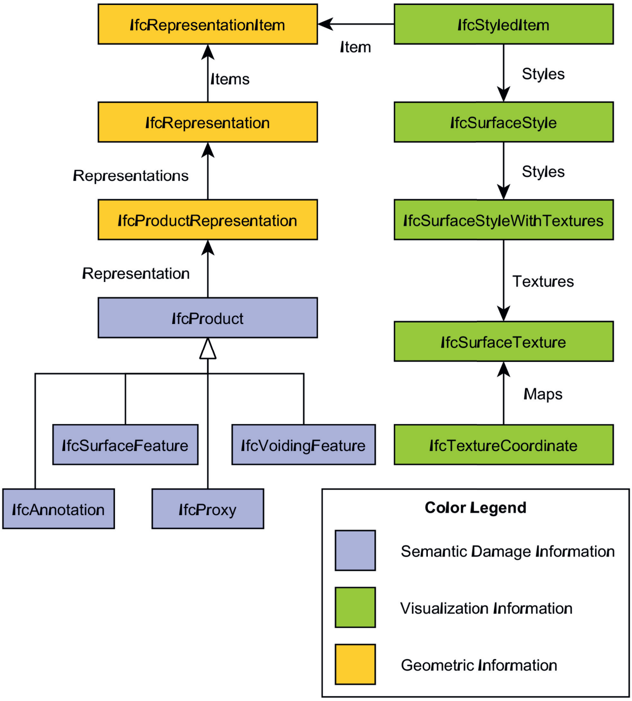

Figure 4.8: Damage model with texture using *IfcSurfaceFeature* and related elements. The defect is shown in orange. Multiple superclasses, subclasses and selects are omitted for simplicity. [89]

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Table 4.3: Overview of tested BIM authoring software and IFC viewers

Authoring software		**IFC viewers**	
Autodesk Revit 2019	[17]	apstex IFC viewer	[23]
		BIM Vision	[22]
		Desite BIM	[19]
		Solibri Model Viewer	[24]
		usBIM	[20]
		xBIM Xplorer	[21]

(#8538). In addition to that, a texture in form of a JPG-file shall be depicted on the geometry (#10000). To create a correct visualization, the spherical mapping algorithm shall be used for this texture (#10061). Further details about the modeling may be found in Chapter 3.

4.2 IFC Software Verification and Extension

As explained in Section 3.3 and Figure 3.10, a verification or testing of the model has to be done to eventually adopt the model and/or existing software. This has been done by using a broad variety of existing software. Table 4.3 gives an overview of all examined software applications. This study focused on modeling data and not on the usability of authoring software. Hence, only Revit was tested as representative of authoring tools. Future research should investigate editing possibilities as well.

4.2.1 Verification of Semantic Data

In the first step, the functionality of visualizing semantic data has been tested. All four IFC entities, i.e., *IfcAnnotation*, *IfcProxy*, *IfSurfaceFeature*, and *IfcVoidingFeature* were tested. The expectation is that the software provides a geometric view, a hierarchical tree view, and a view for the properties. Table 4.4 presents an overview of the test results. Revit, Desite BIM, and Solibri Model Viewer lack the hierarchical view of the model, and hence, the

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```
/* Defect Spalling */
#9000= IFCPROXY('0igGRCoTwk6XcjC1hqayEA',#42,'Spalling',
        'Spalling at beam','Defect -Spalling',#242,#9003,
        .NOTDEFINED.,$);
#9001= IFCRELAGGREGATES('3--Gt7_4p0qqpOGbNAh_sw',#42,
        'Damage to product','The related product is damaged',
        #244,(#9000));

        /* Defect Geometry */
#9003= IFCPRODUCTDEFINITIONSHAPE($,$,(#8539));
#8539= IFCSHAPEREPRESENTATION(#105,'Body','SweptSolid',(#8538));
#8538= IFCEXTRUDEDAREASOLID(#8534,#8537,#20,250.);
#8526= IFCCARTESIANPOINTLIST2D(((-125.,-30.),(125.,-30.),(125.,30.),
        (-125.,30.),(-125.,-30.)));
#8533= IFCINDEXEDPOLYCURVE(#8526,$,.F.);
#8534= IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,'Box',#8533);

        /* Texture */
#10000= IFCSTYLEDITEM(#8538,(#10010),$);
#10010= IFCSURFACESTYLE('Damage Texture',.BOTH.,(#10020));
#10020= IFCSURFACESTYLEWITHTEXTURES((#10030));
#10030= IFCIMAGETEXTURE(.T.,.T.,'TEXTURE',#10040,$,'./Texture.JPG');
#10040= IFCCARTESIANTRANSFORMATIONOPERATOR2D(#10050,$,#10060,1.0);
#10050= IFCDIRECTION((1.,0.));
#10060= IFCCARTESIANPOINT((0.0,0.0));
#10061= IFCTEXTURECOORDINATEGENERATOR((#10030),'SPHERE',$);
```

Figure 4.9: Part of an IFC file modeling a proxy for the defect (#9000) and add an image as texture (#10030) to the entire defect geometry (#10000). The texture mapping is defined as spherical mapping (#10061).

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Table 4.4: Shows which software has visualized the defect information in a hierarchical or properties view.

Defect types	**Autodesk Revit**	**Apstex IFC Viewer**	**BIM Vision**	**Desite BIM**	**Solibri Model Viewer**	**usBIM**	**xBIM Xplorer**
Annotation		x	(x)			x	x
Proxy		x	x			x	x
Surface Feature		x	x			x	x
Voiding Feature		x	x			x	x

defects without geometries could not be selected. Furthermore, none of the three includes a hierarchical view of the model. All other software visualizes the test files properly.

Next, the visualization of the relationships was tested. For this purpose, typification, external references, and defect relationships were added. Classification could be visualized via a property view or by using the correct product type. Table 4.5 summarizes the test results. IFC viewers do not access product catalogs, and hence, the type is shown as property in the view. Revit uses its internal type catalog to select the corresponding type of an entity. However, this is only possible if the typification is stored with correct Revit family names. The same problem arises with measurements or properties in Revit. External references should be shown at least in the property view with their URI. The Apstex IFC viewer and xBIM show external references in such a way. None of the other software tools showed the external document references. Last, defect relationships, i.e., aggregation, association or voids element, should be shown in the hierarchical view or as properties. xBIM and Apstex show aggregations in the hierarchical view and associations as properties. BIM Vision was able to show aggregations but not the associations.

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Table 4.5: Performance of the software regarding relationships.

Defect Information	Autodesk Revit	Apstex IFC Viewer	BIM Vision	Desite MD	Solibri Model Viewer	usBIM	xBIM Xplorer
Classification	(x)	x				x	x
External References		x					x
Measurements	(x)	x					x
Defect Relationship		x	(x)				x

4.2.2 Verification Texture Implementation

Textures are the second requirement in the data model. To test texturing, an image has been attached to an additional plane, which is at the defect position. Other geometries may be used instead of a plane. As depicted by the last row in Table 4.6, none of the available software was able to properly visualize the texture. Most of them ignored the texture parameter. usBIM only shows the plane where the texture should be depicted.

4.2.3 Verification of Geometry Data

Geometric representations are very common in the AEC sector. However, the software programs support the geometric representations in different quality, which is evidenced in Table 4.6. The visualization of CSG geometries was done properly by all IFC viewers except Desite BIM and the Solibri Model Viewer. None of the viewers that are available by the software vendors offers a selection of representation context. This requirement was

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achieved only by Revit. Revit includes 2D plans and 3D views for its building models; however, multiple 3D geometries are not possible in Revit.

The next step tested the visualization of an *IfcVoidingFeature* with an *IfcRelVoidsElement* relationship in accordance with the relationship-based cut-out. The voiding feature is correctly supported by apstex's IFC Viewer and xBIM Xplorer. Other programs do not respect an *IfcVoidingFeature* with an *IfcRelVoidsElement* relationship. Many viewers are able to handle an opening in conjunction with an *IfcRelVoidsElement*. However, defining a defect as an opening is semantically wrong. Figure 4.10 shows the visualization of an *IfcVoidingFeature* with an *IfcRelVoidsElement* relationship in the original xBIM Xplorer. 4.10 a) shows a beam with typical spalling. Figure 4.10 b) depicts a close-up screenshot of the cut-out of the defect in the beam. Lastly, in Figure 4.10 c) one can see the blue highlighted defect geometry of the spalling. A similar result is achieved with the Apstex IFC Viewer.

4.2.4 Extension of xBIM Xplorer

Although, IFC is an established standard and implemented in many software applications, several of them show limitations regarding geometry and texture visualization. Furthermore, only Revit supports different views. Hence, manual extensions have to be made to an existing application. Three possibilities exist to extend existing software: (1) developing a plugin or extension, (2) using an Application Programming Interface (API) to add code within the software, or (3) the software itself is open source. In the given software pool, only Revit provides an API. However, Revit shows errors already on the IFC import. Hence, a completely new importer would be necessary that would mean a huge effort. None of the software has a fully developed plugin system. xBIM has a plugin system, however, it is under development. Two of the viewers are (partly) open source: xBIM and apstex. apstex offer only their core IFC parser and model as open source. xBIM offer their complete software including the viewer as open source. So, xBIM was chosen for further extensions. During the development, xBIM has been extended with

1. making links to external references clickable
2. saving and restoring camera positions

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Table 4.6: Performance of the software regarding different geometric representations and texture.

Geometry data		Autodesk Revit	Apstex IFC Viewer	BIM Vision	Desite BIM	Solibri Model Viewer	usBIM	xBIM Xplorer [original]	xBIM Xplorer [extended]
CSG + contexts	Context selectable	x							x
	Show different representations								x
	Show defect geometry		x	x			x	x	x
Voiding feature	Subtract geometry		x	x			x	x	x
	Show defect geometry		x	x			x	x	x
Texture									
Visualize Texture									x

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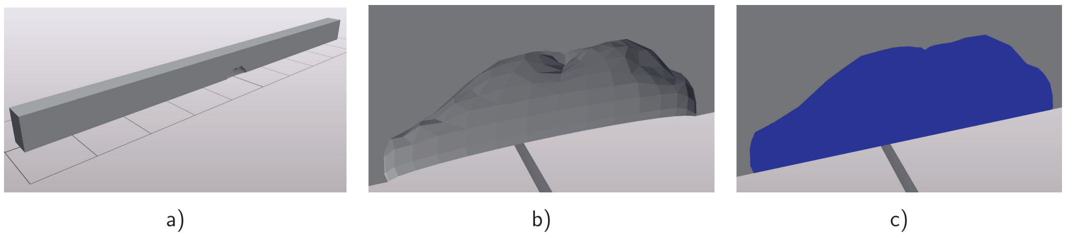

Figure 4.10: The visualization in xBIM Xplorer of a beam with spalling modeled by using a voiding feature a) and a close view at the spalling at the beam b). c) shows the typical spalling geometry. The transparency has been risen to improve the visibility of the cutout.

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3. export selected elements to wavefront obj files
4. select a visualization context
5. manual triangular texture mapping
6. and spherical texture mapping

Point 1 was done to getting in touch with the software structure of xBIM and try a first implementation. External references including a path may be included in a document reference. At that time, the path was shown as a normal string. With some minor changes in the *IfcMetaDataControl*, a clickable link was created that automatically opens the given file in the default application, e.g., the browser.

Writing articles, conference papers and documentation required several screenshots of models, defects, and components. However, if the same view shall be used for different models or a another screenshot has to be taken after some model changes, it comes in handy to save and restore camera positions. This leads to the implementation of an export and import of camera view parameters. This function can be found in the top menu under camera/camera position. After saving the properties via save as, a text file is generated as shown in Figure 4.11. Three 3D vectors define the view: the camera position, look and upwards direction. The x, y, and z components of these parameters each are stored in one line. Hence, the first three lines define the x, y, and z component of the position. Followed by the look and upwards direction in the same way.

```
37.7465246782768
-2.11495031082126
2.48377096998818
-2.15067950496985
3.96105889744229
-1.33312049451982
-0.0374374448485882
0.068951195969613
0.996917333733132
```

Figure 4.11: Exemplary camera position file containing three lines each for position, look and upwards direction.

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Subsequent processes, for instance structural analyses with Ansys, required the geometry only. However, Ansys does not have a built in IFC import that meant another format was necessary. Wavefront files with the ending .obj come in handy in this case. IfcConvert is a usable tool for such tasks because it enables the transformation of IFC files into many other file types [25]. To enable also the selection of a specific representation context, the code has changed in that way that a representation context may be selected via its name [145]. So, the geometries of the selected context(s) are transformed only.

Unfortunately, IfcOpenShell is a command line tool and, hence, a bit cumbersome. After using IfcConvert several times, a graphical user interface found be much more practical. Therefore, the xBIM Xplorer has been extended with a small export function that allows to export selected geometries as wavefront files. Together with the selection of the representation context (4), any geometry may be exported in a more intuitive way.

Figure 4.12 shows the selection of different visualization contexts based on a model with undamaged (a) and damaged component geometries (c) as well as the damage geometry itself (b) in the extended xBIM Xplorer. The top line shows the selected representation context, the line below presents an overview of the model and the bottom line depicts a close-up view of the damaged section. If the defect geometry and the geometry of the damaged component are activated simultaneously, the used defect element, which is a proxy in this case, is shown as filling in the damaged beam. This is disadvantageous because the defect geometry should not be a filling. If the relationship-based cut out is used, i.e., *IfcVoidingFeature* with *IfcRelVoidsElement*, only the damaged component geometry is visible, but not the damage geometry solely. This is comprehensible because openings or voids are normally only visible as subtraction in another element and not as individual element.

Texture related information is represented by green boxes in the diagram. Besides the information, which image shall be used as texture, a texture area and texture mapping is required. Texture maps describe mathematically how to map photos as textures onto a given geometry. Such a texture map may be defined implicitly or explicitly. Multiple texture mapping algorithms exist. Two methods are implemented in the xBIM Xplorer to demonstrate the use of textures for DIM. First, a manual and a spherical texture mapping. Within the IFC file manual texture maps may be provided via the *IfcIndexedTriangleTex-*

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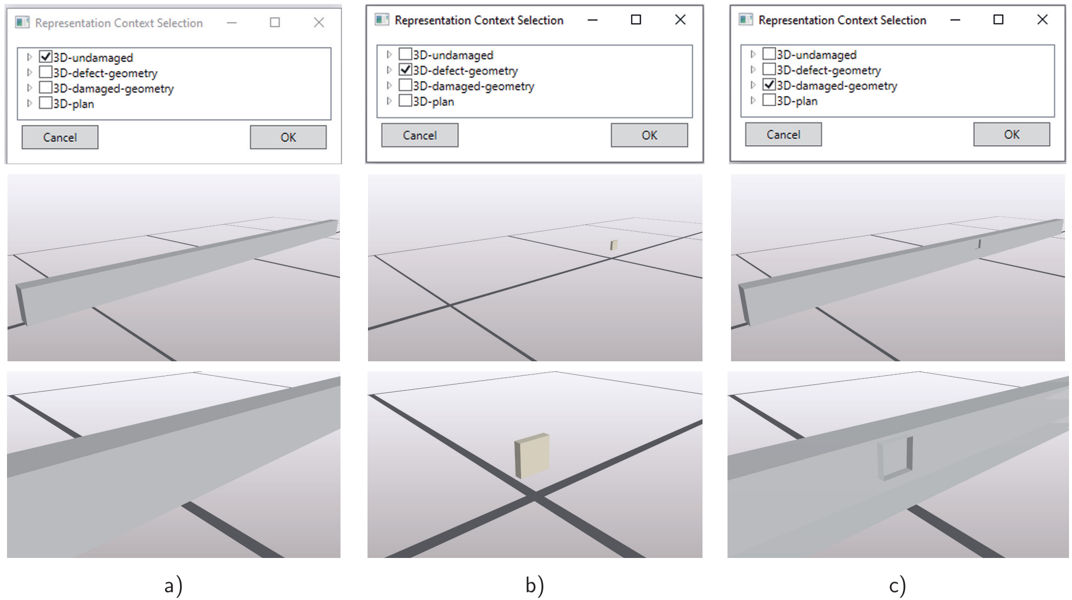

Figure 4.12: Model of a defect by using CSG and different visualization contexts in the 3D view. a) shows the undamaged beam, b) the defect geometry, and c) the damaged beam.

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tureMap. It contains a mapping between triangles of the shape and related coordinates in the texture, i.e., a vertex has one or more related u-v-coordinates [13]. So, the creator of the IFC file has the full control about the mapping.

Second, in case of a texture on a sphere, spherical texture mapping may be used. This maps the spherical coordinates of the mesh vertices onto the u-v coordinates of the texture. By identifying the midpoint v_0 of the volume, vectors between the midpoint and all vertices v_n of the 3D model are calculated. Subsequently, the spherical coordinates of these vectors, consisting of r, ϕ, and θ, are calculated. Figure 4.13 shows a sketch of the polar coordinates with ϕ. Analog to ϕ, θ is calculated using the z and y axes. Last, the spherical angles θ and ϕ as radians between 0 and 2π are mapped onto the two texture coordinates u and v between 0 and 1 with

$$u = \frac{\theta}{2\pi}$$

$$v = \frac{\phi}{2\pi}$$

Figure 4.14 shows the Nassi-Shneiderman of the resulting algorithm for spherical mapping. *midPoint* is calculated based on the min and max values of the vertices shown in Figure 4.15. *midPoint* is equally to v_0. Based on that midpoint a vector *direction* as well as the related angles ϕ and θ are calculated. As aforementioned, the algorithms are implemented in C# within xBIM Xplorer. C# allows to parallelize operations by using the *Parallel* class within the System.Threading.Tasks namespace as depicted in Figure 4.16 [146].

In order to provide an extensible object-oriented implementation, a interface based structure has been used for the implementation depicted in Figure 4.17. Generally spoken, each texture mapping algorithm aims to provide a texture map based on the vertices, normals, and triangles. Hence, this can be abstracted into an interface, which is called *ITextureMapping*. Besides the texture map itself, this interface also forces the implementations to provide an information about their algorithm as an enumeration *TextureMapGenerationMethod* via the *GetTexturingMethod* Possible states are defined in the IfcTextureCoordinateGenerator of the IFC 4 standard [13].

The described interface is implemented by two classes: *ManualTriangularTextureMapping* and *SphericalTextureMap*. To create the correct instance, the static class *TextureMappingFactory* takes an *IfcTextureCoordinate* object as argument and returns the related

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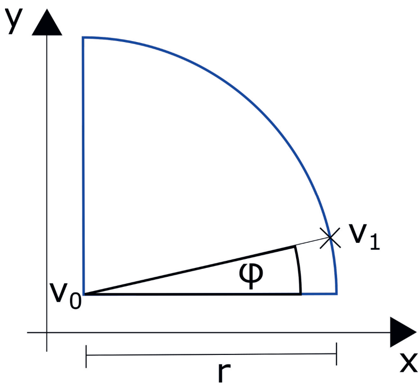

Figure 4.13: Exemplary sketch for calculation of φ for spherical mapping.

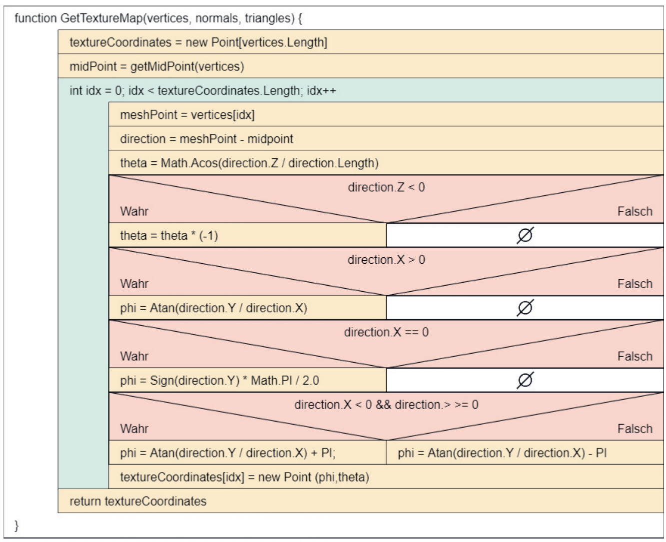

Figure 4.14: Nassi-Shneiderman diagram of the algorithm to create a spherical texture map.

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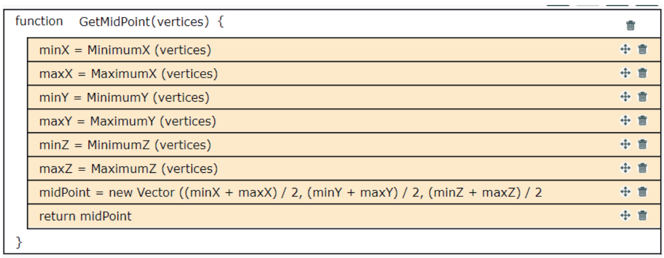

Figure 4.15: Nassi-Shneiderman diagram for the calculation of the midpoint.

implementation of *ITextureMapping*. Hence, if the provided texture coordinate generator has the mode sphere, a *SphericalTextureMap* is returned.

4.2.5 Comparing Test Results to Requirements

Altogether, with the use of IFC and an extension of the xBIM Xplorer, it was possible to address all requirements stated in the Requirement Analysis section. Table 4.7 shows an overview of the requirements and finally used entities of the standardized IFC 4. All implementations could be verified by using an extended version of the xBIM Xplorer.

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```
public IEnumerable<Point> GetTextureMap(
IEnumerable<Point3D> vertices,
IEnumerable<Vector3D> normals, IEnumerable<int> triangles)
{
        Point[] textureCoordinates = new Point[vertices.Count()];
        Vector3D midPoint = this.GetMidPoint(vertices);

        Parallel.For(0, textureCoordinates.Length, (verticeIndex) =>
        {
                Point3D meshPoint = vertices.ElementAt(verticeIndex);
                Vector3D direction =
                (Vector3D)(meshPoint - midPoint);
                double theta = Math.Acos(direction.Z
                / direction.Length);
                if (direction.Z < 0)
                {
                        theta *= -1;
                }
                double phi;
                if (direction.X > 0)
                {
                        phi = Math.Atan(direction.Y / direction.X);
                }
                else if (direction.X == 0)
                {
                        phi = Math.Sign(direction.Y)
                        * Math.PI / 2.0;
                }
                else if (direction.X < 0 && direction.Y >= 0)
                {
                        phi = Math.Atan(direction.Y / direction.X)
                        + Math.PI;
                }
                else
                {
                        phi = Math.Atan(direction.Y / direction.X)
                        - Math.PI;
                }
                double u = phi;
                double v = theta;

                textureCoordinates[verticeIndex] = new Point(u, v);
        });
        return textureCoordinates;
}
```

Figure 4.16: Calculation of the spherical texture map in C# using the Parallel library to provide a faster computation.

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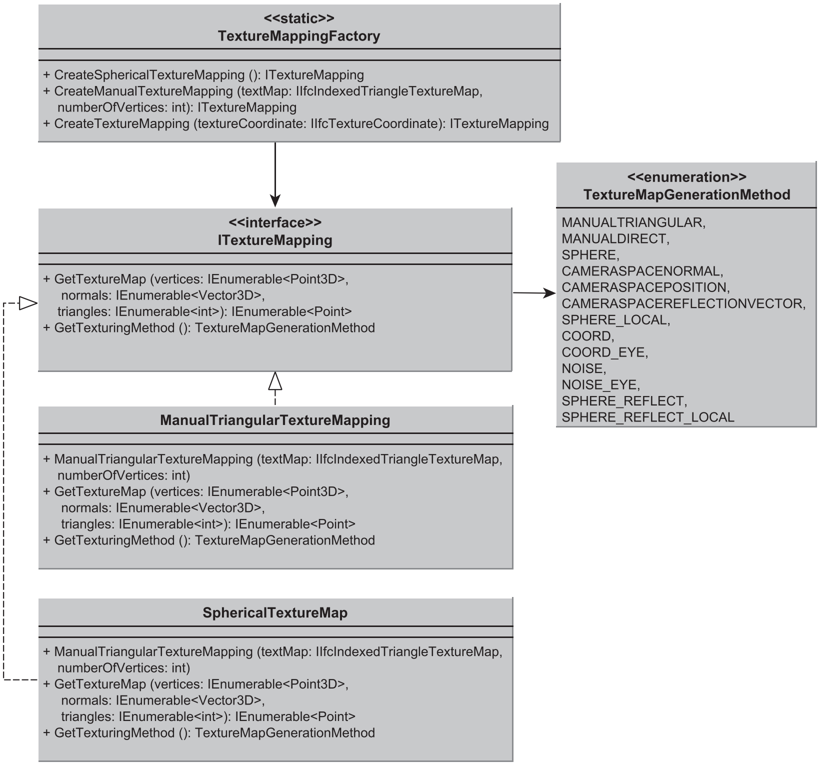

Figure 4.17: UML diagram of the structure for texture maps.

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Table 4.7: Summary of test requirements and test results.

Requirement	Successfully tested solutions
Defect entity	IfcAnnotation, IfcProxy, IfcVoidingFeature, IfcSurfaceFeature
Relationship for damaged components	IfcRelAssociatesProduct, IfcRelAggregates, IfcRelVoidsElement
Relationship for defect groups	IfcRelAggregates
Relationship for cause and effect	IfcRelAssociates
Relationship for related documents	IfcRelAssociatesDocument
Classification	IfcTypeObject and IfcRelDefinesByType
Defect properties	IfcPropertySet and IfcProperty
Multiple photos, images, or videos	See relationships for documents
Textures	IfcImageTexture and IfcTextureCoordinate
1D, 2D, and 3D defect geometry	IfcProductDefinitionShape and subclasses
Multiple geometries and selection	IfcGeometricRepresentationContext

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5 Experimental Results[1]

BIM aims to support the entire life-cycle of buildings and structures. Damage information is mandatory during bridges' operation phase because every national guideline for inspection and assessment relies on defect information. Hence, beside generating accurate as-built models of existing buildings or structures, it is mandatory to enhance BIM with damage information in order to make it usable for the operation phase. Numerous studies focus on BIM in the context of design. The operation phase has so far been considered only sparsely. Sacks, Kedar, Borrmann, *et al.* have come to a similar conclusion as they emphasized that a damage representation is currently missing [39]. This dissertation addresses the lack of such a damage representation. Whereby, the majority of the publications propose closed frameworks for inspection automation, for example, automatizing damage registration [57], [58], [60], [75], [78], [89], [147], and less effort is invested in developing a data model to ease collaborative work of different stakeholders during the operating phase. Existing approaches either lack implementations and testing or flexibility in supporting different stakeholders [91], [100]. By considering multiple use cases, such as inspection, structural analysis, and assessment, a comprehensive information model for the operating phase has been provided.

BIM defines a digital information model to reduce costs and information loss during constructions' life-cycle. To address companies' internal processes and allow developing new processes, buildingSMART International provides documentation about how to develop new IDMs and MVDs [14], [148]. By following these guideline, it was possible to develop a DIM based on the existing BIM concept containing also a damage-specific MVD.

[1] This chapter contains republished work of a retracted article from ASCE [135]. The article has been retracted by the authors because of copy right issues [136]. All content, which was affected by the copy right issues, has been replaced, i.e., Figure 23 from the article has been replaced with Figure 5.14.

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BIM is a concept that has been designed to be highly flexible because it shall be used by numerous stakeholders. This led to an extendible approach for modeling building information. An IDM for inspection purposes has already been provided by Sacks, Kedar, Borrmann, *et al.* [119]. Though, this IDM does not include geometric and geo-semantic information data, it has been extended with further information, for example, images. Based on the methodical approach of object-oriented analysis and design [137], a data model for damage information with respect to BIM has been designed. Thus, by providing DIM for bridges, BIM is capable supporting the operation phase.

Structural engineers and inspectors, among others, are involved in the operation phase of bridges. The data model designed is capable to incorporate and deliver necessary information for the operation phase to multiple stakeholders, such as structural engineers, inspectors, or owners. Hence, without manual transfers, inspectors may register damage information digitally and share it with other actors. Flexible approaches, like property sets and objectified relationships, allow to further extend this data model if required.

5.1 Data Analysis

Numerous damage types are known to nationalities [44], [46], [47], [149], [150]. Some are widespread others depend on regional climate, and hence, occur only in particular nations. Several damage types are related to specific bridge types. Germany provides an extensive catalog of defects affecting civil engineering structures [40]. An analysis of this catalog revealed numerous damage types. These types have been designed in a general way to make them applicable to other nations as well. Common damage types are corrosion, spalling, and cracks. Additional types have been defined based on the German damage catalog [40].

A statistical analysis of data retrieved from the Thuringian administration has revealed frequency and severity of defects. Cracks are most frequent in the analyzed data. Under the consideration that the analyzed data is limited to prestressed concrete and reinforced concrete, this result was expected because concrete is a brittle material. If the data set would have focused on steel or wooden bridges other damage types would have been dominant.

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Divergences from specification and design occur second most frequently. One reason for this could be the age of numerous bridges - more than 30 years [151]. These 30 or more years old bridges maybe not fulfill the criteria of updated norms and guidelines. Another source of this damage type are errors during the construction process. Independently of reasons, modeling divergences from specification and design may allow a better tracking of violated norms or guidelines.

Joints or expansion joints have gotten less attention until now, hence it was not expected that joint defects play such an important role for assessing bridges' condition. However, the data analysis has shown that joint defects occur frequently with medium impact on bridges' condition.

Waste and other pollution occurs very frequently but with less impact on condition. Only if the state or functionality of bridge elements is affected, these defects become more severe. Moisture penetration may lead to depassivation and corrosion, which leads to high impacts on durability. The following list summarizes eleven damage types that have been selected for modeling after the statistical analysis.

- crack
- spalling
- material changes without material loss
- material changes with material loss
- joint defects
- missing parts
- divergences from specification and design
- foreign elements, e.g., waste or vegetation
- moisture penetration
- insufficient quality of concrete, e.g., low thickness, coarse grain, or voids
- errors in state or functionality, e.g., fixed bearing or clogged drainage

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Most studies focus on cracks, spalling and corrosion [12], [39], [60], [78], [80], [89], [91]; however, these damage types do not cover all possible defects and deficiencies. Material changes are partly considered by the sector of HBIM and the given classification of defects is unique in its extent. However, most of the work in the HBIM sector focuses on brick walls and/or wood constructions [96], [98]; concrete is out of scope. The approach provided by this thesis is focused on defects at concrete bridges with respect to more damage types.

Material changes have high impacts on bridge condition states and include multiple damage sub-types from corrosion up to carbonation and alkali-silica reaction. Some of these sub-types would benefit from geometric information, such as the extend of carbonation within a concrete building element. Present studies consider primarily corrosion [39], [73], [89]. Only Kubota and Mikami has mentioned alkali-silica reactions but did not provide a comprehensible data model [128]. Due to the possibility including multiple geometries for a single defect or damaged element, as well as adding material parameters as property sets, the model proposed may also include information about material changes for subsequent structural analysis.

Furthermore, BIM extensions have been published to incorporate climate aspects or natural hazards [116]. However, impacts and defects from natural hazards and climate changes are different from common inspection defects. Natural hazards and climate change often lead to broken elements or a high degree of destruction of buildings. Normal abrasion during the operation phase leads to smaller changes in geometries and semantics of buildings. The present model focuses on defects resulting from abrasion and deterioration. Broken or missing elements were not in the focus of this work.

Joint defects may be represented via semantic information and geo-semantic information. However, joints are usually not part of building models because of their huge quantity. Belsky, Sacks, and Brilakis showed a method to automatically infer joints from given models and represent them by relationships [152]. Unfortunately, a relationship is not a product, which may be affected by a defect. A joint is a (virtual) building element and not only a relationship. If this would be included in the concept of BIM and changed in the definition of the IFC modeling joint defects could be modeled more precisely.

Moisture penetration is not directly a defect, moreover, it is an indicator or reason for other defects, e.g., missing/damaged joints or corrosion respectively. NDT methods, such

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as ground penetrating radar, are able to identify the extent of moisture penetration [61]. If moisture penetration including their extent could be represented by the building model, induced depassivation and corrosion may be better observable and predictable for engineers. This additional information would enable engineers to estimate the durability of structures more precisely. So far, no study that the author is aware of has considered modeling moisture penetration, although, it has high importance for durability. The DIM presented allows to include information about geometry of moisture penetration. Additionally to that, a quantitative statement about moisture may be included via property sets.

Divergences from specification or design primarily come from outdated construction practices, obsolete guidelines, or construction errors. Especially construction errors, such as missing joints, induce subsequent errors, e.g., moisture penetration. Divergences rely on semantic and geo-semantic information, e.g., related guidelines or photos. Both information elements can be stored in the model proposed in this thesis.

Related to divergences are concrete quality issues, for example, concrete graining or thickness of the concrete cover. Material parameters, for instance granularity of concrete or concrete grade, may lead to subsequent defects, such as spalling, and hence, are important for the durability assessment. This information could be stored semantically as description in the proposed DIM model. Furthermore, if such quality issues are available as 3-dimensional information, this geometric information can be added as well.

Movable parts are affected by impairments of their functionality. This could be unmovable bearings because of corrosion or dirt as well as clogged drainage. Although, these defects may lead to severe subsequent defects and have high impacts on the durability rating, they were not respected in existing data modeling concepts. Using semantic or geo-semantic information from the data model provided here, e.g., property sets or photos, allow to include such information in the bridge model.

The last damage type are missing objects or elements. These occur in case of rivets, screws, screw-nuts etc. Contrary to the intuitive assumption that this defect has no or little effect, the analysis of the German damage catalog shows that strong negative effects are to be expected here with regard to durability. Notwithstanding this fact, this damage type has not been considered for DIM in literature yet. Although it would be possible to include this defect via property sets, it would not be sufficient because such a property would need

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additional interpretation for visualization. Further research has to address how to visualize missing elements and how to model it properly.

Concluding, based on statistical analyses, eleven damage types have been identified to be covered by a DIM. In a prior study, twelve damage types have been used [12]. Two of those types, "Coarse grain/voids/foreign body encapsulation" and "Thickness and dimensions of concrete coatings" have been merged into concrete quality to reduce the number of types. These results helped to define an adequate DIM. The state of the art shows a rag rug of isolated applications and partly developed data models for damage information. Inspections and assessments during the operation phase of bridges have to consider several different damage types. However, most literature only cares about cracks and maybe spalling.

5.2 Information Modeling

The primary point is to add an entity for defects, which acts as a container for all related damage information, and a relationship to link defects to damaged building elements. The relationship to the damaged building element links the damage and building information. Further damage information may be added to these two elements. These central objects allow to semantically group damage information, which is inspired by the human understanding of a defect. Other literature followed a similar design [39], [60], [90], [93]. A decentralized approach would be better in case of some types of analysis methods, e.g., structural health monitoring, because they are not necessarily connected to a defect. However, traditional inspection focuses on defects. Inspectors combine several information about a structure's state to defects, for instance a lack of material and exposed reinforcement is summarized as spalling.

Borrmann, König, Koch, *et al.* have defined semantic and geometric data for buildings [10]. As far as bridge inspection and assessment highly rely on photos, sketches, or videos, and this information does neither fit into geometric nor semantic information, a new category of geo-semantic information has been added to the BIM concept. The term geo-semantic information has been chosen because images or photos consist of geometric information as the locations of pixels and semantic information as the color of them.

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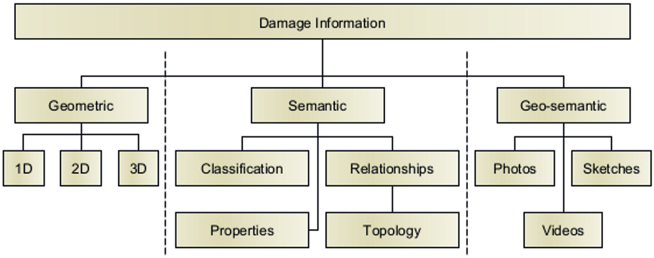

Figure 5.1: Overview of the data categories of defects. Extended categorization of [10]

Figure 5.1 shows an overview of the entirety of the data. Geometric data is used to describe 1D, 2D, or 3D geometries of damage information. Whereby, a 1D geometry information could, for example, be a point or line of a component. 2D geometries are mostly related to plans and 3D geometries contain spatial representations.

Semantic information consists of classifications, relationships and properties. Classifications of defects are, for instance spalling or crack; examples for properties are names, descriptions, and relationships. Several studies have considered that inspection photos have to be included in the data models [39], [70], [89], however, none of them has considered geo-semantic information in their model. With the data model provided, this gap has been bridged by the proposed work.

Damage's topological information are very important for engineers, for example, a crack in the superstructure over the bearing has another meaning and importance as in the middle between two bearings. Topological information contain damage positions in relation to other damages or building elements. This may be reflected via relationships as well.

Figure 5.2 shows an overview of the entire damage model, which highlights if elements have been synthesized from other studies, adjusted, or newly added. The defect annotation as central container similar to other publications [10], [39], [60], [89], [90] and has been adjusted by adding a texture and cause-effect relations. Specific measurements or additional descriptions may be added via a measurement sets that are related to the defect annotation, which is a result of including the work of Hamdan and Scherer into the model [90]. Another

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result of including the work of Hamdan and Scherer and [93] is to add referred documents. This allows the inclusion of inspection photos or analysis and evaluation reports [90], [93].

Some other studies showed that damage classification is required [39], [128]. The present concepts extend this approach in order to allow classifications in general. Instead of providing a fixed amount of damage types, a classification object that will be related to the defect entity is provided. With this class, the model has a higher flexibility and future damage types may be included without model adjustments. Disadvantageous is, that the semantic information of how to name damage types is missing and has to be defined. Terminology and standardized nomenclature have already been discussed in the concept of BIM in Section 2.1. In short, the bsDD may be used to define common names for required classifications.

The proposed model includes relationships between building elements and defects as well as between defects and defects. The former allows to mark elements as damaged and the latter allows to include causing and resulting defects. Both is required to allow a proper assessment process. Several studies have incorporated damaged elements [39], [93], [120], [128]. Hamdan, Bonduel, and Scherer as well as Tanaka, Nakajima, Egusa, *et al.* included to split defects into spatial part defects [93], [100], but no prior study respected the semantic relationship of a defect causing another defect.

To keep the model flexible and allow adding further damage types, the typification itself has been done via a typification object. This object consists of at least a name and description. So, without changing the entire information model, additional damage types may be included. Respecting that each damage type requires different parameters, all parameters are added as measurement sets. Again, detailed definitions of required measurement sets and nomenclature has to be defined in future.

Besides the semantic information, geometric information has been included. Dependent on the view, different geometries are possible similar to the geometries of buildings. 1D geometries could be, for instance the location of a crack on a building element. Plans or crack maps represent 2D information of buildings or cracks respectively. 3D information of defects represent volumetric geometries and are interesting in case of material changes or spalling. Several studies focused on registering defects in photos and generating the related geometry [58], [60], [153]. 3D Geometries could be used for FEAs [58], [79]. Furthermore,

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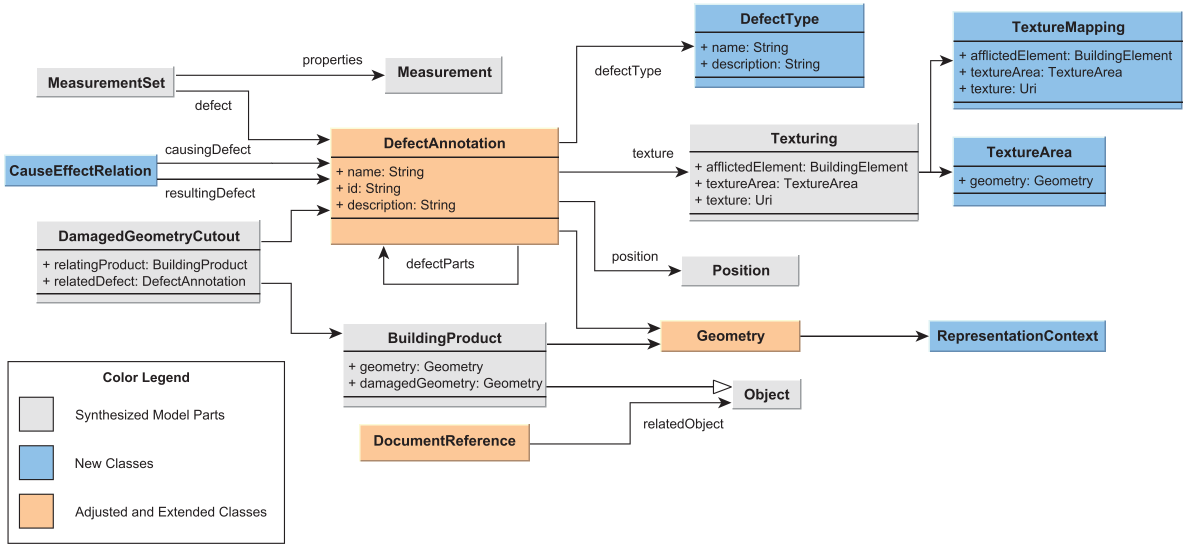

Figure 5.2: UML model of the overall DIM. Grey elements have been included and synthesized from other studies. Blue classes have been added and orange classes have been basically included from existing studies and adjusted.

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defect coordinates maybe used for planning aspects or durability analyses. Planning of repair actions benefit from 2D and 3D representations in order to identify locations, plan work orders, and material quantity. All three geometry types are respected by the proposed model, which is novel compared to existing information models.

Depending on the subsequent use case, multiple geometries for the same object may be required. For example, the assessment process needs a plan of the defects to visualize defect distances depending on building element faces. In parallel, a 3D visualization is necessary to improve the spatial perception of the defect. Based on the representation context selected, the geometric representation has to be visualized. The representation context allows to add semantic context information to geometries, which helps the user choosing the appropriate context.

Multiple geometries for a single object allow to include multiple views in the same model. However, the software has to interpret that correctly, which also depends on the use case; for example, if a plan and 3D view exist, all elements that do not have a plan view should be hidden if the plan view is selected. Another usability of this concept is to include different representations depending on inspections, i.e., having one representation context for each inspection. A conceptual sketch of this is shown by Figure 5.3. Defect 1 was detected first during inspection A in 2019 and updated in 2022. Defect 2 was registered first in 2019 and not updated later. If a defect geometry does not vary between two defects, the representation should stay the same. So, the last available representation should be visualized if there is no representation in the context of the current inspection. Regarding the example in Figure 5.3, the geometry of defect 1 from inspection B has to be shown as well as the geometry from 2019 of defect 2 both as the last geometry of the respected defect. Deciding about the correct representation context requires further information or assumptions. The proposed model is capable to store this information; further definitions would be necessary to declare available contexts.

The proposed data model introduces two approaches for modeling the geometry of a damaged component:

1. either the relationship between a defect and the affected element implies geometry effects

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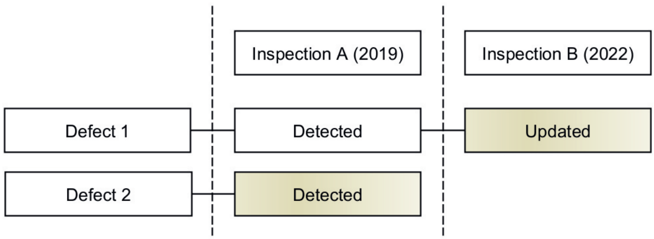

Figure 5.3: Multiple defect states over time. The yellow representation are the last ones and chosen for visualization.

2. or the relationship between a defect and the affected building element do not have consequences for the geometry and geometric aspects of the defect are modeled independently.

Approach (1) is applicable for physical damage types, such as spalling or cracks, and reduces the required information elements. Isailović, Stojanovic, Trapp, *et al.* also used the approach that a relationship implies geometric effects [60]. However, this leads to the circumstance that every defect geometry would be subtracted from a component. As aforementioned, a defect may change over time and can have different geometries. If all of those geometries are included in the same storage and related to the affected building component, several subtractions are performed, which could induce a erroneous geometry of the damaged building element. Approach (2) is beneficial for defects with geometries that should not be handled as subtraction. For this, additional objects and a conscientious modeling and management of the defect, its geometries, and resulting damaged building element geometries are necessary. None of the existing studies considered that both methods are important depending on the damage type, which has been addressed by the DIMproposed here. Although, the second approach requires more entities and management effort, it offers a better flexibility and a more specific defect definition.

Geo-semantic information information as part of DIM has been respected by prior studies

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already [70], [89], [98], [100]. Hüthwohl, Brilakis, Borrmann, *et al.* showed an example with a photo as texture [89]. Inspections often produce several photos of a single defect and not all of them may be used as texture. In contrast to the data model from Hüthwohl, Brilakis, Borrmann, *et al.*, the data model in this dissertation is able to include textures, and additionally, include photos via external references. Although, Hüthwohl, Brilakis, Borrmann, *et al.* provided some information how to include an image as texture, several important information were missing. To use a photo as texture three requirements have to be fulfilled:

1. the photo should be rectified
2. and as the defect is only at a part of the building element, an extra geometry for the defect texture is required to depict it at the correct position
3. a texturing algorithm is necessary to apply the texture correctly on the chosen geometry,

Rectified photos (1) are addressed in terms of image processing, which is not part of this dissertation. The model proposed in this work allows to add geometries for (2) texture placement. Also, different (3) texture mapping algorithms are supported. Besides this, multiple photos for a defect can be included, as well. Using textures and additional photos, engineers are provided with a 3D textured visualization of the model and further photos may be helpful for in-depth investigation.

5.3 Implementation and Testing

An object-oriented model is only the conceptual description, which has to be implemented for verification. The implementation of this model has to address two problems: (1) the data model needs to be transferred into a proper formal language, either a data modeling language, for instance EXPRESS, or a programming language, such as C#; and (2) software applications that operate on the data model have to be developed.

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5.3.1 Implementation using IFC

For the first problem, instead of implementing the data model from scratch in a programming language, the IFC standard, which is based on EXPRESS, has been used. Thus, IFC entities, relationships and properties have been identified to be used for damage information. IFC has been developed to provide entities for the entire AEC sector and possibilities for additional data that may have not been respected yet. A typical example are the proxies within IFC, which allow to integrate objects independently from their semantic context, for instance, bridge models have been created based on the IFC 4 standard even though there were no bearings or other required entities for bridges defined in IFC 4. It is even possible to create models of AEC foreign domains with the help of IFC, like the model of a car; although no one has done it yet. This is possible because IFC includes semantic and geometric information; the parts of the car may be modeled as proxies with additional type objects for classification. Proxies may have a geometry for representation and materials may be assigned as well. This leads to the advantage that existing IFCviewers can be used for visualizing the developed and implemented DIM.

Apart from IFC other possibilities to implement the data model are proprietary data formats, for example, Revit files [69]. Proprietary data formats have the advantage that there is professional software available for editing and visualizing the data. However, existing Bridge Management Systems (BMSs) rely on their own proprietary not BIM conform data formats, and hence, would require to write several data conversion applications to exchange data between stakeholders. Furthermore, also industrial BIM authoring software has not been developed for the operation phase. So, special workarounds are necessary to add damage information.

Different from that are open standards, like IFC, which are supported by current and future applications because the interface is open to everyone. Despite IFC 4 is not designed for damage information, several entities are generic enough to include damage information and several concepts are general enough to use them also for new processes. Existing software in the AEC sector are assumed to be able importing, visualizing, and editing IFC files that are conform to the standard. Disadvantageous is that some semantics or entities are missing, for example a dedicated defect class similar to other objects. Other studies have also utilized the IFC 4 standard for damage information modeling [60], [106], [122]. Because of

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the missing entities, some researchers decided to extend the IFC standard with additional entities [93]. Additional efforts for developing and implementing a software that supports this extended standard are the primary disadvantage. The present study shows that with existing IFC entities and concepts damage information can be included in building models; allowing to use resulting models in available IFC software, and therefore, lowers the efforts for later software implementation.

Three possible relationships are available within the IFC standard to model the circumstance that a building element is damaged: an assignment, aggregation, and *IfcRelVoidsElement*. An assignment simply provides the information that a defect is related to a building element. A stronger relationship is the aggregation, that implies the defect is part of the building element, which is normally the case. An *IfcRelVoidsElement* is also a decomposition and is used only in combination with openings or voiding features. A voids element relationship includes the subtracting the defect geometry from the building element geometry. Adding a specialized relationship for damaged building elements, would improve the modeling possibilities regarding semantic damage information. Tanaka, Nakajima, Egusa, *et al.* suggested to add two relationships to the IFC standard [93]. After analyzing the requirements, the conclusion may be drawn that one additional relationship with a typification enumeration could be enough. Currently, the IFC standard is already complex; hence, to ease the decision for the correct relationship for a damaged component, as less entities as possible should be added. Existing associations may be used for cause-effect relations.

Hüthwohl, Brilakis, Borrmann, *et al.* have shown how to use textures for visualizing damaged components [89]. The proposed approach added the dedicated texture geometry and texture mapping algorithms to properly depict textures. For this purpose, IFC offers the possibility to apply a texture to a representation item and add mappings via texture coordinates. With these two entities, depicting textures needs fewer assumptions for correct visualization.

5.3.2 Implementation of Software

Using the IFC standard for the implementation of the model, allows utilizing and extending available IFC viewers for damage information visualization. However, two challenges occurred in parallel: (1) a software that provides the best support of the developed concepts

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had to be identified and (2) the implementation of the data model had to be tested. This combination led to some uncertainties because some of the IFC viewers showed different interpretation of IFC entities, especially in case of voiding features and Constructive Solid Geometry (CSG) geometries. So, if the visualization of the defect was insufficient, it could be either a problem of the software, the IFC file, or both. A viable method to check the correctness of the structure and formal propositions of an IFC file is using an IFC validation tool, like the *IfcCheckingTool* of the Karlsruher Institut für Technologie [154]. If an IFC file passes this checking and the visualization is insufficient, an error in the software was assumed most probable.

Beyond doubt, the IFC standard is an established comprehensive and open interface for sharing building information. This standard has been developed with regards to numerous different stakeholders. It covers manifold geometric design concepts, materials, structural information, and many more; indeed, software vendors are not aware of all possibilities of the IFC standard. There are several potential reasons for that. First, the standard is very complex with its numerous classes, sub-classes, attributes and property sets. To limit the scope and make this complexity manageable, most vendors focus only on their subject. However, for a proper implementation, software vendors need to be aware of other disciplines as well to implement IFC functionalities correctly.

Second, software vendors, such as Autodesk, sell structural analysis or managing software besides their authoring tool, which leads to the interest selling multiple of their products to customers. So, all products can rely on a shared proprietary data format. Primarily relying on a proprietary data format has two advantages for them: (1) developing a single data format for all applications instead of translating data over an open standard saves development time and costs. (2) all applications interact seamlessly with the proprietary data format, which yields to a better user experience.

Third, the documentation of the IFC is primarily limited to the description of instances and some formal propositions. Examples provided by buildingSMART International Ltd. cover only basic problems and concepts [155]. Domain specific example files are rarely provided. Furthermore, a well written guideline for proper implementation of the IFC standard is missing. This could be also an effect of the high complexity of the standard that does not allow one implementation only.

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All test files have been edited manually by using a text editor. In order to reduce the time for manual editing of IFC files, all concepts have been individually tested with small files first. These files consist of a single damaged beam with different characteristics of defects, such as textures or geometry subtraction. This prototyping allowed a fast and distinctive testing of the software and concepts. Subsequently, an entire bridge has been set up for a case study, which includes all defects and visualization options.

Although, manual editing of IFC files is a cumbersome and error prone process it was inevitable because none of the existing BIM authoring tools support to add defects and custom building element families do not allow to subtract a geometry from another element in the building project. One possibility would have been to define damaged instances of existing building elements. However, defect geometries may vary, and hence, one family for each damaged component would be required, e.g., a cracked wall with multiple crack widths and paths, which is not representing the designed DIM, and moreover, is an even bigger effort because numerous variants of defects are possible.

In case of changing geometry information in the IFC test files, many parameters and correlations have to be respected; hence, changing the geometry of a defect manually in the IFC file, has taken many iterations of editing and viewing. To simplify this work, as often as possible geometric primitives have been used for conceptual tests. If these tests were successful, geometries have been changed to more complex variants. Furthermore, some text editors allow to define custom syntax highlighting. This eased reading blank IFC files in the text editor. Despite all of these simplifications, methods and tools, a comprehensive damage editing tool is necessary for future research.

Numerous IFC viewers and other BIM software are available. To decide about a software suitable for model verification, multiple software applications have been identified and tested with the prepared IFC files. Table 5.1 shows an overview of all tested software. Only one authoring tool, Revit, has been tested and six IFC viewers. All software application are either extensible via APIs or completely open source except for usBIM. This shows the awareness of software vendors offering options for automatizing workflows or customizing applications in the AEC sector.

None of the tested software was able to cope with all used concepts of the IFC 4 standard; independently if those software is commercial or open-source. In fact, open source programs

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Table 5.1: Overview of tested BIM authoring software and IFC viewers

Software type	Name		Extension Options
Authoring software	Autodesk Revit 2019	[17]	C# API, Python API
IFC viewer	apstex IFC viewer	[23]	Open source
IFC viewer	BIM Vision	[22]	C++ and C# API
IFC viewer	Desite BIM	[19]	Javascript API
IFC viewer	Solibri Model Viewer	[24]	Java API
IFC viewer	usBIM	[20]	none
IFC viewer	xBIM Xplorer	[21]	Open Source

tend to support the IFC standard better than commercial software applications. This may also worsen the acceptance of IFC in the industrial environment because commercial authoring tools are primarily used in industry. In case of an erroneous software, the user is not able to separate whether occurring errors result from the standard or from the implementation; therefore, the standard is perceived as wrong or incomplete. Improving and/or ease the implementation of the IFC standard could raise the acceptance in industry.

Less problems occurred visualizing semantic information, which is mainly reflected via tabular or hierarchical views. This requirement also occurs during the design and planning phases, hence, it is a common requirement for BIM software to visualize data like that properly.

Although, the approach of subtracting a voiding feature from another building element is similar to modeling an opening, e.g., the opening for a window in a wall, only a few software applications interpret voiding features correctly. A possible cause of this could be missing knowledge regarding the IFC standard. Voiding features are uncommon in the AEC sector, so the related concept of voiding features is respected less frequently. Relating an opening to an element could also be used modeling a spalling or crack. However, this would be semantically wrong, which led to the decision to use a voiding feature from the IFC standard.

On the one hand, the lack of visualizing images as textures shows that images are of less interest during the design, planning, and construction phase; hence, software vendors were

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not instructed with implementing such cases or features. On the other hand, as BIM aims to support the entire life-cycle, new contexts and requirements have to be considered also by software vendors, which includes a correct interpretation of textures.

After all tests, the xBIM Xplorer and the Apstex IFC Viewer showed similar and most promising results. Using the xBIM Xplorer for further implementations resulted from the author's experience of several years with C#. Based on the development state of December 2020, custom extensions and adjustments have been added. To keep the code manageable and maintainable, the xBIM team has split the code into three packages for parsing IFC files, generating the geometry, and the final IFC viewer xBIM Xplorer - XbimEssentials, XbimGeometry, and XbimWindowsUI respectively. Numerous interfaces within the parser are necessary to keep the code compatible with IFC 2x3 and 4 as well as implementing concepts like selects from the EXPRESS language. For simplicity, all changes necessary for testing purposes were done in the xBIMWindowsUI package only [156]. This included mainly the possibility to select the visualization context and visualize textures via two texture mapping methods: the spherical texture mapping and explicit texture mapping, both are explained in Chapter 3.

Summarizing, the implementation effort could be limited by analyzing and extending existing software. Several IFC software lacks proper and comprehensive implementation. To support proper implementation, the IFC documentation needs further improvements in the form of examples, precise implementation guidelines, and maybe more strict certification. The open-source applications tended to have a better implementation of the IFC standard. Extending this software is possible due to the code availability. Furthermore, proper and fast support by the software vendors helped implementing missing features. All changes made to the xBIM Xplorer have been fed back to the software vendors and all except the texture visualization have been accepted. This acceptance reflects the importance and value of the developed extensions.

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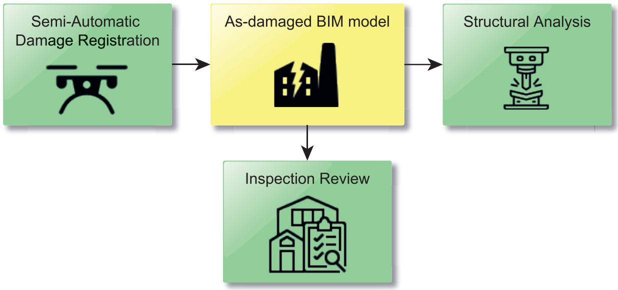

Figure 5.4: Overview of the cases for the proof of concept. Pictograms taken from icons8 [157]–[160].

5.4 Proof of Concept

The resulting as-damaged model may be utilized and processed in the context of different use cases. To provide a verification of the model, three cases have been covered as shown in Figure 5.4: an automatic damage recognition, an inspection discussion, and a structural analysis. Defects found during the automatic damage registration may be used for the inspection review and the structural analysis.

5.4.1 Semi-Automatic Damage Registration

A semi-automatic damage registration may be used to add damage information to the as-built BIM. Generally spoken, several photos of defects at the provided bridge are taken on-site and processed to segment defects and generate the defect geometry that are added to the as-built model [5], [60]. Next, this model is enriched with semantic data, such as further photos, measurements, and documents, which leads to the final as-damaged model. Figure 5.5 shows a schematic overview of this workflow. Such an as-damaged model may be used for subsequent visualization, planning, analysis or assessment.

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Figure 5.5 shows an exemplary framework from Artus, Alabassy, and Koch [5]. In this framework, photos are used to generate the point cloud of the bridge, identify defects and generate damage geometries. This data is added to the as-built model. Later, further semantic data is added.

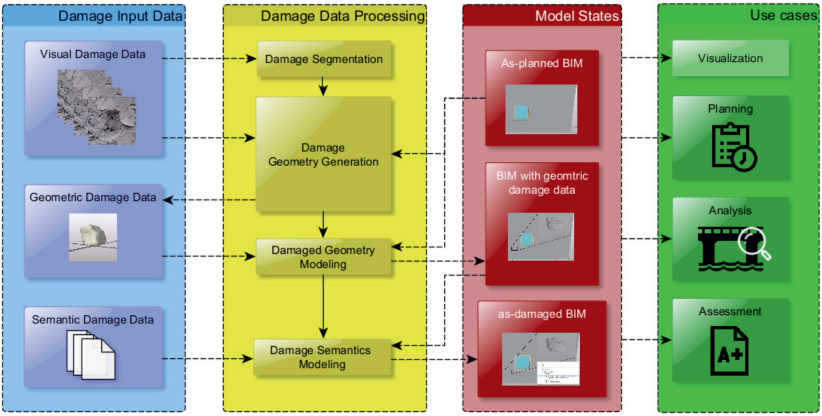

Figure 5.5: Overview of the framework with the damage input data, damage data processing, model states, and possible use cases. Originally published by Artus, Alabassy, and Koch [5]. Pictograms have been taken from icons8 [161]–[164].

Several ML methods are capable to recognize defects [5], [60], [165], [166]. These approaches may be used to identify defects in photos. Furthermore, Structure from Motion (SfM) methods offer possibilities to generate spatial geometries from photos [153]. By orchestrating these methods, a semi-automatic generation of geometric as-damaged models is possible and semantic data is added manually or automatically to the model.

Figure 5.6 shows the bridge that has been used for this case study. The photo has been provided by the "Thüringer Landesamt für Bau und Verkehr". A 3D model has been created via Revit, exported as IFC file and extended with the automatically generated damage geometry and semantics [5]. The bridge is approximately 14 m long. Because this is a short bridge, modeling was done manually. Further tests and evaluation may require long span bridges.

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Figure 5.6: Photo of the bridge for case study. The photo has been provided by the "Thüringer Landesamt für Bau und Verkehr".

Figure 5.7 shows the resulting damaged bridge model. a) is a close-up view of the damaged bridge. The exposed reinforcement can be clearly seen in the form of steel stirrups. c) shows the view of section A-A that again is shown in b). A manual generation of such a geometry would be time consuming and error prone because shape consist of numerous vertices and the position may be positioned wrongly. However, a detailed geometry may be not necessary for an assessment, but can be beneficial for later structural analysis, maintenance and test planning.

Depending on the approach for including defect geometries and subsequent utilization, different geometry representations had to be tested because not every software is capable of all geometry types, e.g., xBIM can handle advanced BRep but not faceted BRep.

Elaborating on this process showed that it is possible to use the DIM model for inspections of structures in general. Another result of the process ware highly detailed geometric models of defects; however, the IFC viewers faced problems during the rendering process of geometries with huge amounts of triangles. If not necessary, the complexity of the geometries should be limited to what is effectively necessary. The number of triangles depends on the subsequent utilization of the (geometry) model.

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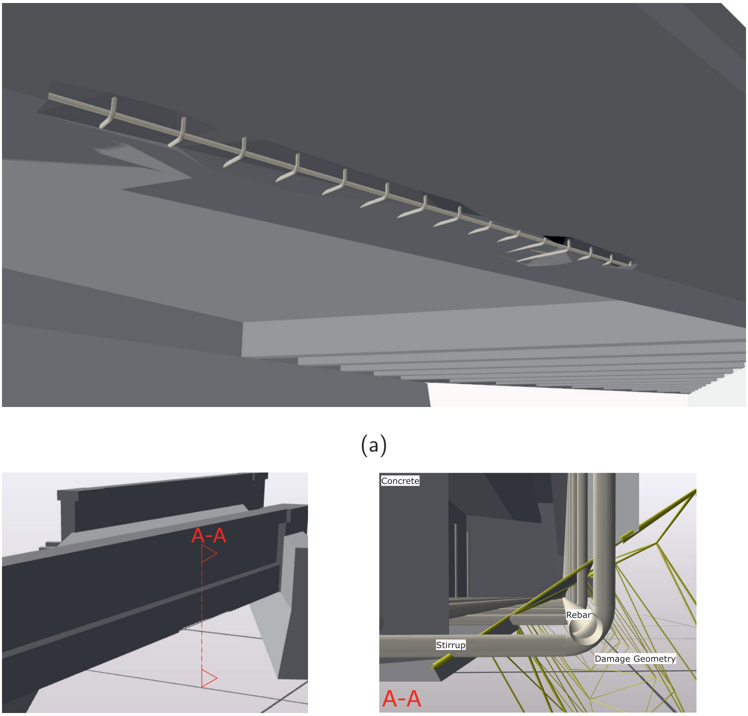

(a)

(b) (c)

Figure 5.7: Close-up view of the modeled defect. (a) close-up view of the bridge beam with spalling subtraction and exposed reinforcement (b) bridge overview with marked section A-A (c) section A-A with the subtraction as wireframe. [5]

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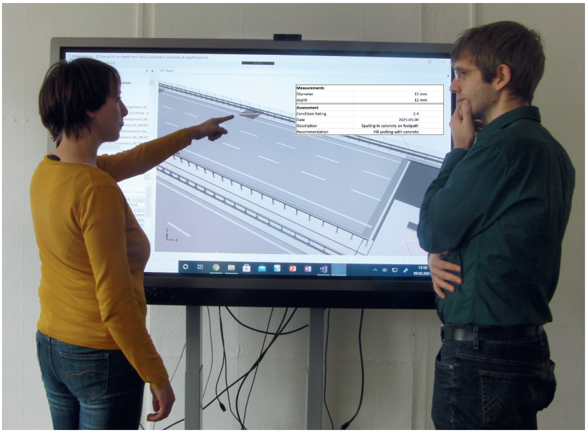

Figure 5.8: Scenario of a Model based inspection review including the discussion of detailed defect geometries.

5.4.2 Inspection Review

On the basis of the damaged bridge model, an inspection review may be performed. Figure 5.8 shows a scenario of discussing defects using the as-damaged bridge model. All defects, their properties, and related documents may be reviewed by a team of engineers. Instead of using drawings and textual descriptions only, a 3D model can be examined by moving around, selecting images, showing related data, discussing defect geometries and their impact on the condition assessment.

For illustration purposes, another bridge model made available by IFC Infra was used [167]. This model has been transformed from IFC 4.2 to IFC 4. Furthermore, damage geometries, measurements, references, and textures have been added. Figure 5.9 depicts the bridge with red markers at the positions of the defects. Starting from the left, there are two test drills at the abutment. The defect at the mid-top represents some cracks in the pavement. Third, the railing in the lower-mid is corroded. Last, there is a spalling on the lower-right at the abutment wall.

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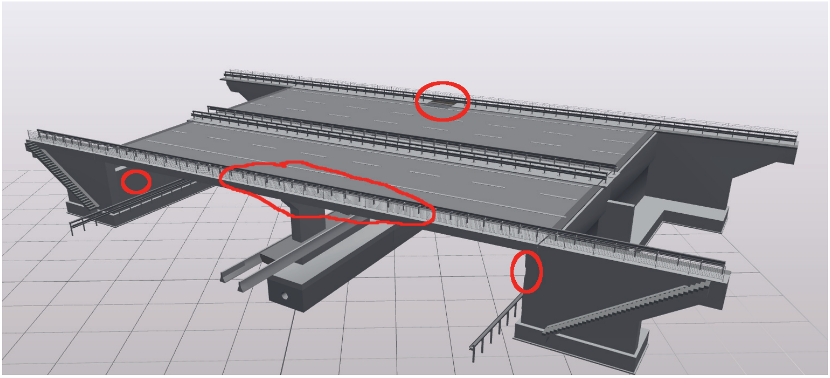

Figure 5.9: Bridge with four defects. The red markers show the places of the defects.

Corrosion

Figure 5.10 shows a photo of a corroded railing at the top-left position. Right next to this photo is the selected railing in the model. The bottom screenshot shows the properties of the railing in the model. Taking adequate photos to represent the corrosion of the entire railing is cumbersome and time consuming. Therefore, a simple property is used to represent this defect. The railing has only a body geometry, and hence, if the damaged component geometric representation context is selected, the railing is not shown anymore in the 3D view. This defect revealed that it is not fully sufficient to use geometric representation contexts for selection. Specialized views are necessary, such as a view with highlighted components or damage textures.

Cracks

Figure 5.11 shows some cracks on the pavement of the bridge. Furthermore, there is a bump in the pavement and the side walk. Only by using this photo as a texture, the inspector or engineer can get a quick impression of the defect. Aligning the texture to the 3D model can help the user gather additional information about related or near elements faster compared to studying 2D plans. However, this defect shows the problem of image

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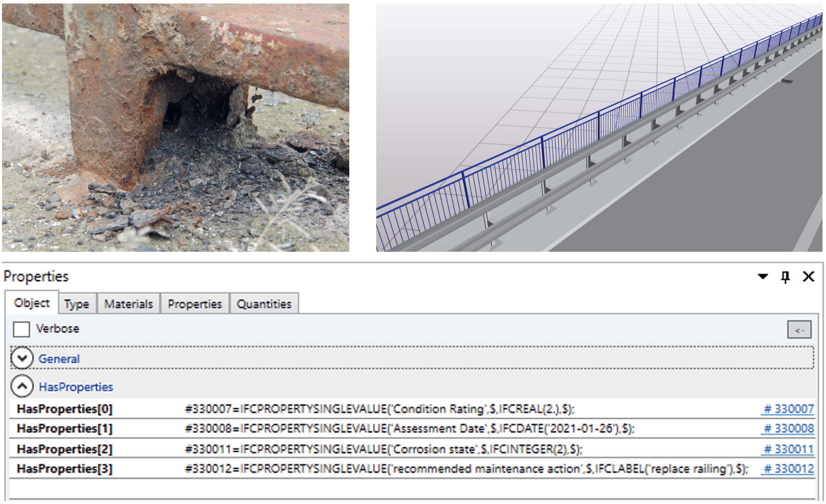

Figure 5.10: On the top left a photo of the corroded railing on-site. The selected railing is right next to the photo in the model visualized by xBIM Xplorer. On the bottom, the figure shows the related property set with a condition rating, an assessment date and further information.

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Figure 5.11: Representation of some cracks at the pavement as a texture depicted on a plane.

rectification for textures. The image, which has been used for the texture, has not been rectified. Hence, the texture shows the slope of the bridge at the position of the sidewalk, which could be misunderstood.

Spalling

Figure 5.12 shows an example of a geometric representation of a defect. The left side of Figure 19 shows a photo of the spalling, and the right side shows the defect in the final model. The geometry of the spalling was generated manually within the IFC file. This leads to the visual inaccuracies, such as the different paths of the lower part of the spalling. By using SfM, damage geometries can be modeled with higher accuracy [60]. However, the example shows that the principal concept provides geometry information of a defect.

Holes from Drilling Samples

Figure 5.13 shows the representation of two holes from drilling samples in the abutment. Figures 5.13 b) and 5.13 c) show the model after selecting the context of damaged components only. Hence, the abutment with the drill holes is shown without near components. Figure 5.13 b) shows the abutment with a texture at the position of the drill holes. Figure 5.13 c) depicts the visualization of the drill holes by cut-outs. The user can switch between

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Figure 5.12: Representation of a spalling at the abutment.

these visualizations by selecting the representation context. Those multiple visualization approaches would provide information about color changes or geometrical information by using the defect photos context respectively the damaged geometry context.

5.4.3 Structural Analysis

After the overall review of the bridge, some components may need further investigation. For this step, a geometry-based structural analysis, e.g., FEA is applicable to determine the impact of the defect on internal forces and stresses. Figure 5.14 illustrates an FEA in ANSYS with an individual beam. As an example, the equivalent von-Mises stresses were calculated. The top of Figure 5.14 presents the 3D model views of the beam and the spalling. The bottom part shows the colored beam in ANSYS and a close look at the beam. The color legend is shown in the lower left screenshot. For the FEA, the IFC file that contains the beam, is converted into a step file by using IfcConvert [25]. The engineer can add load conditions, bearings, and simulation parameters. With this workflow, the geometry of the beam can be imported directly instead of redrawing it. Subsequent to that, the FEA can be performed. This FE model is used as an example, not to perform an in-depth analysis but to show the capability of the information model.

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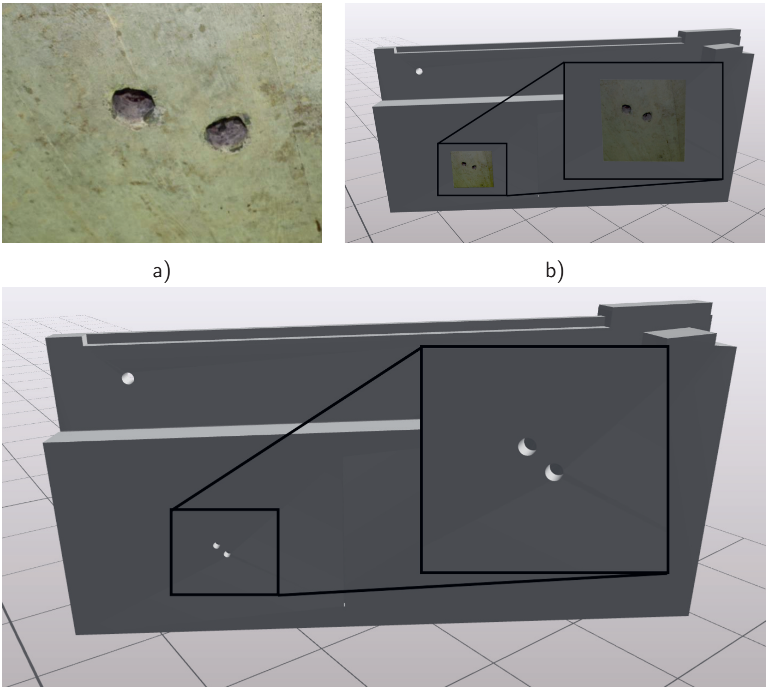

a) b) c)

Figure 5.13: a) photo of some test drills in the abutment. b) photo as texture on the position of the test drills in the model c) geometry of the defect in the building model.

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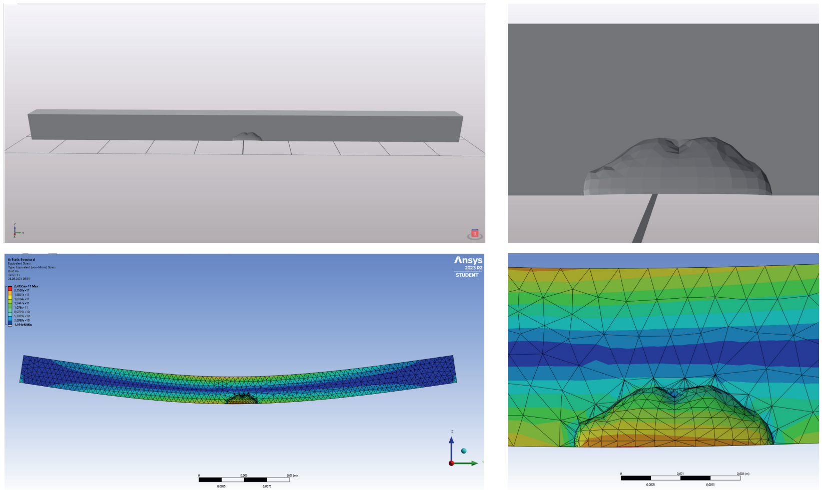

Figure 5.14: Top: BIM model of the damaged beam. Bottom: FEA model in ANSYS Mechanical showing the equivalent von-Mises stress.

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To see the potential effect on the principal stress of the defect, Figure 5.15 shows the maximum principal stress of the undamaged (left) and damaged (right) beam. The cut plane for this illustration is approximately at 1m from the left side and illustrated in Figure 5.15 top. The Figure shows that there is a bigger strain in the bottom part especially near the defect. However, this example is to illustrate the use of such geometric models for structural analysis. Problems could be the different meshes of both geometries as evident from the screenshots. Furthermore, the beam has to be modeled with respect to the entire structural system of bridge, which would influence bearings, loads and so on. Advantageous is the usability of existing geometric models to analyze building components in detail. Several of such models for important bridge components may be analyzed in parallel and would provide detailed information to, e.g., predict components vulnerable to defects.

Although, automatic methods for generating FEA models on the basis of BIM models exist [79], there is still research in progress to improve this transformation. Although, the damage geometry may be included automatically by the provided DIM model, experienced structural engineers have to decide about the final assessment. The model designed provides damage information in conjunction with building information which eases the creation of structural models. This helps accelerating the model generation and lowers costs.

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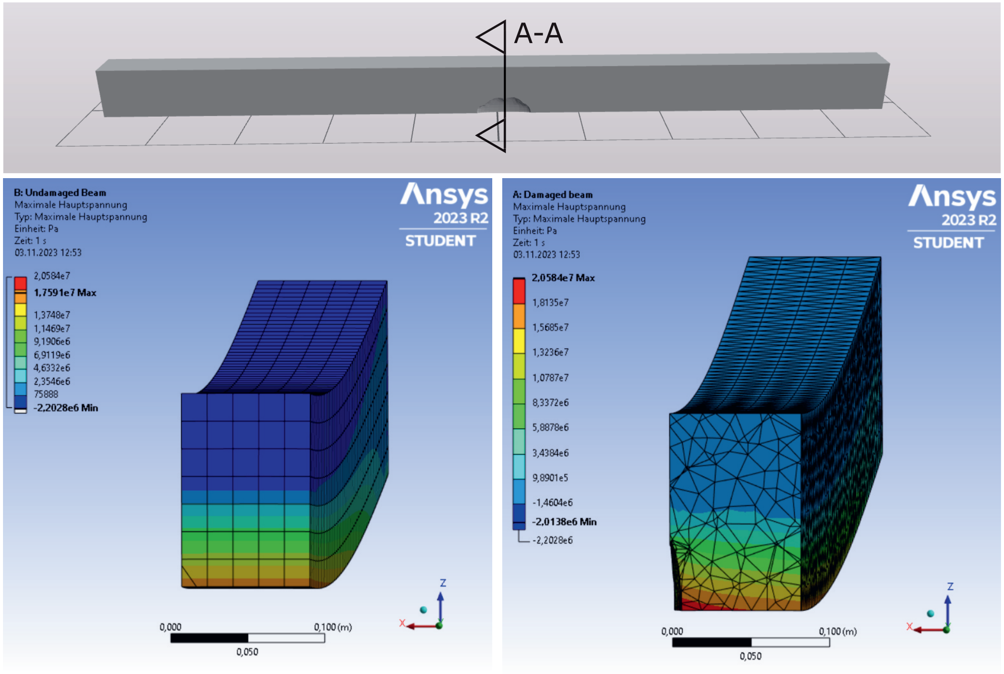

Figure 5.15: Top: cut plane. Bottom: cut view from ANSYS for the undamaged and damaged beam.

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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

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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.

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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.

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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.

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