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.

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-

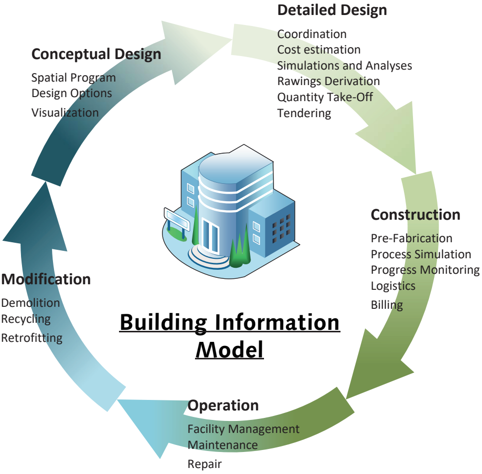
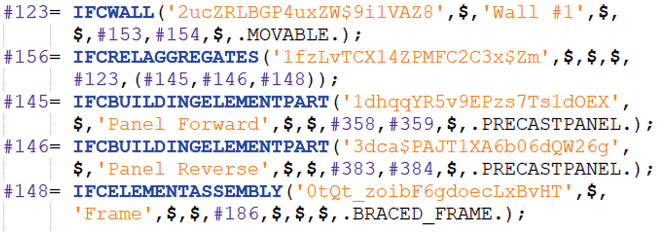


Figure 2.1: Building Information Model for the whole life cycle [12] (acc. [10]).

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



```
#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.

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]

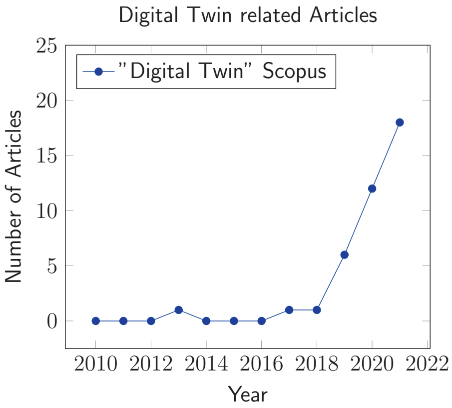


Figure 2.3: Number of articles per year having Digital Twin, bridge, and inspection in the title or abstract, as indexed by scopus. Articles have been checked manually to be also related to the AEC sector (April 2022).

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 observation 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

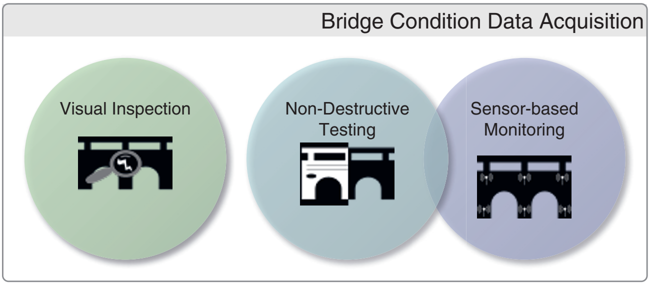


Figure 2.4: Methods used to acquire raw bridge condition data.

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

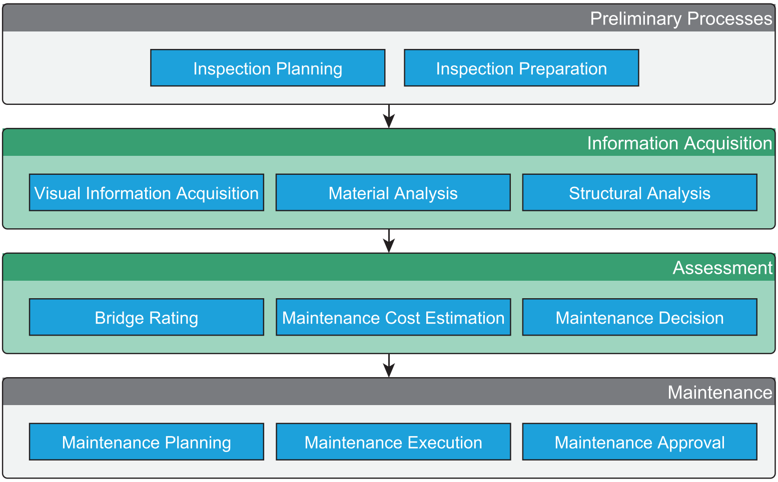


Figure 2.5: Overview of the process for bridge inspection and maintenance (acc. [12]).

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.

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

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 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.

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 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 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 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

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 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

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		

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, 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].

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]	

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.

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

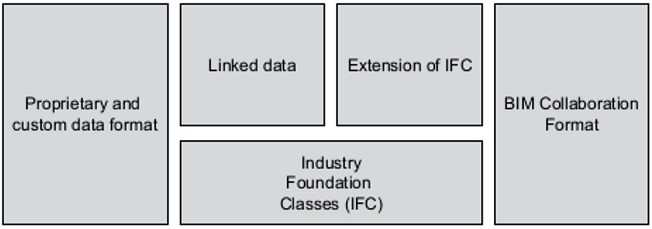


Figure 2.6: Possible approaches to model damage information.

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

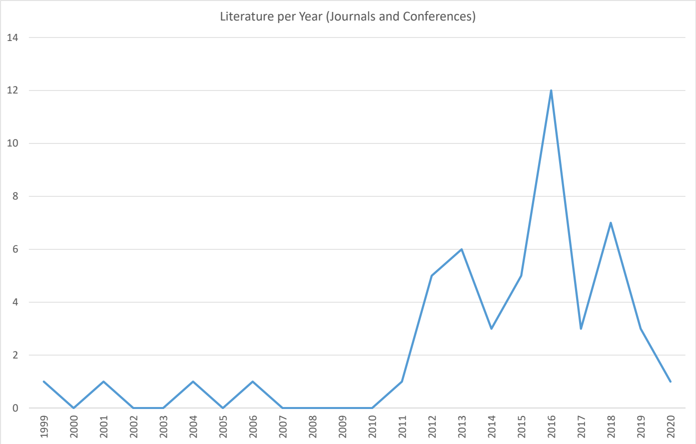


Figure 2.7: Year of publication of all literature [12].

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.

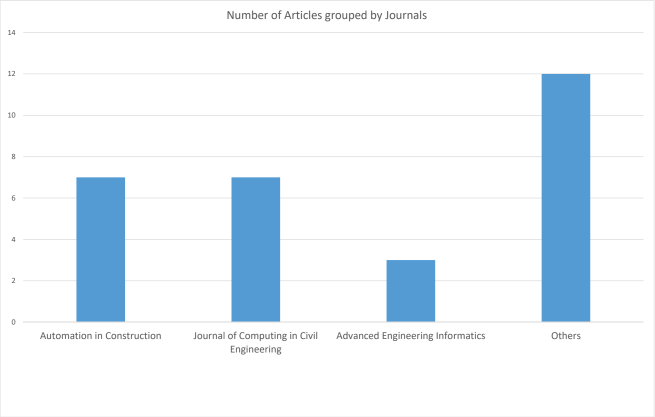
Those can be split up and grouped by the related conferences and journals as shown in Figure 2.8 [12]. 14 journal articles have been published in Automation in Construction or in the Journal of Computing in Civil Engineering. Far the most conference papers have been presented at the International Conference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



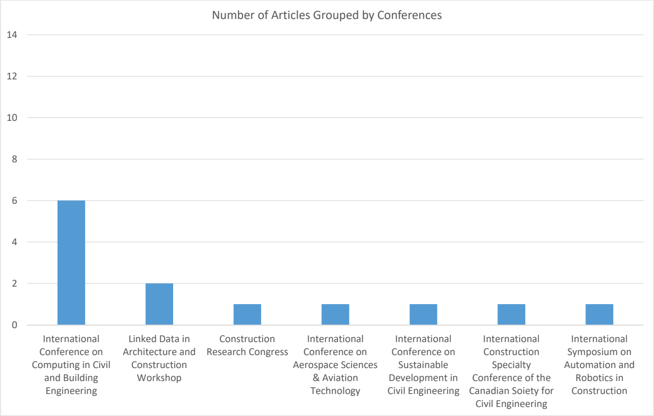


Figure 2.8: Number of journal articles (top) and conference papers (bottom) [12]

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?