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[1] This chapter contains republished work of a retracted article from ASCE [135]. The article has been retracted by the authors because of copy right issues [136].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.

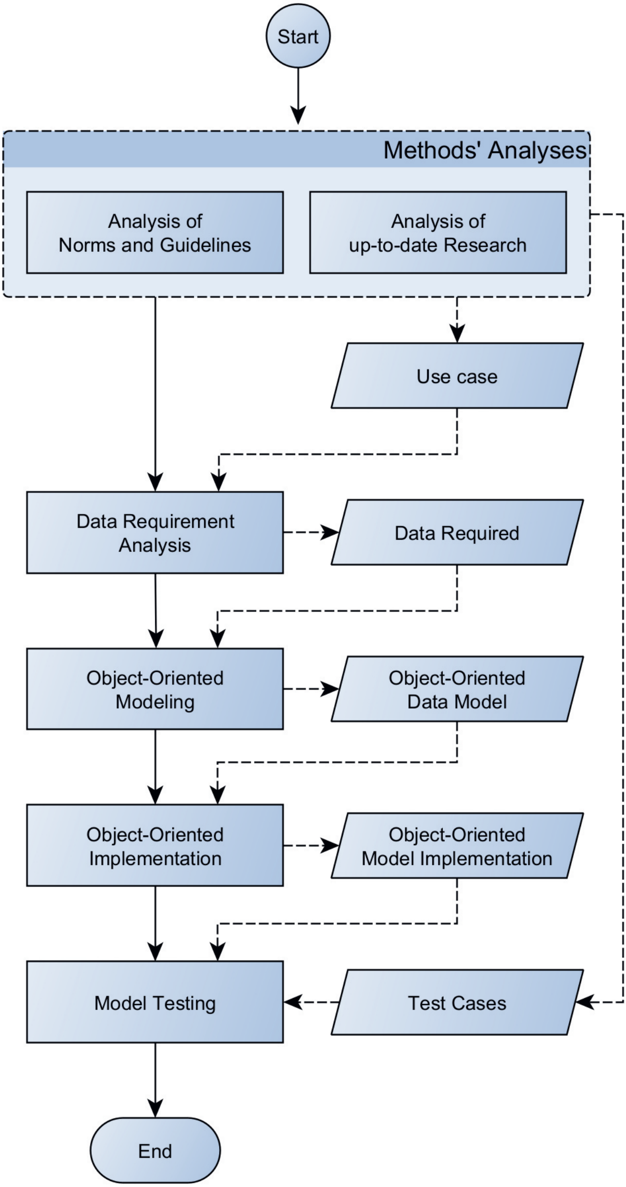

Figure 3.1: Process to define the final damage information model.

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

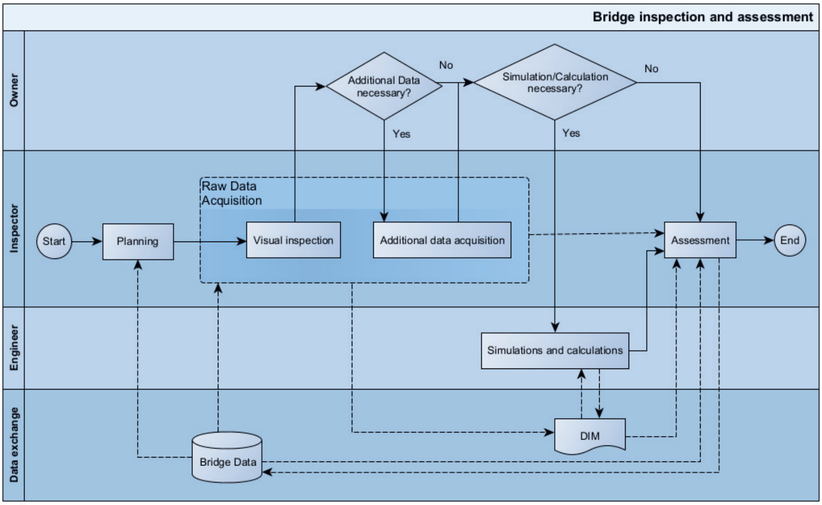

Figure 3.2: Entire workflow from inspection planning to condition rating. Dashed lines show data exchange. Consecutive processes are connected by solid lines [12].

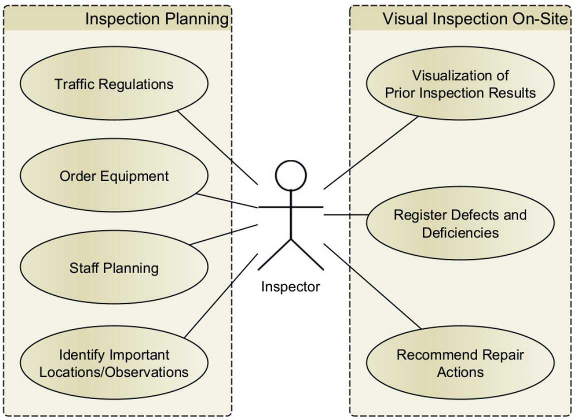

Figure 3.3: Use cases related to the inspector during inspection planning and execution.

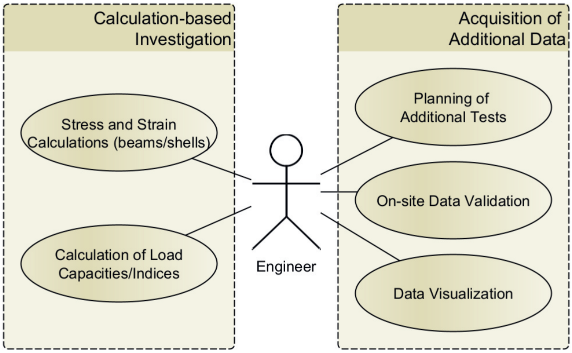

Figure 3.4: Use cases related to the engineer for in-depth analyses.

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 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].

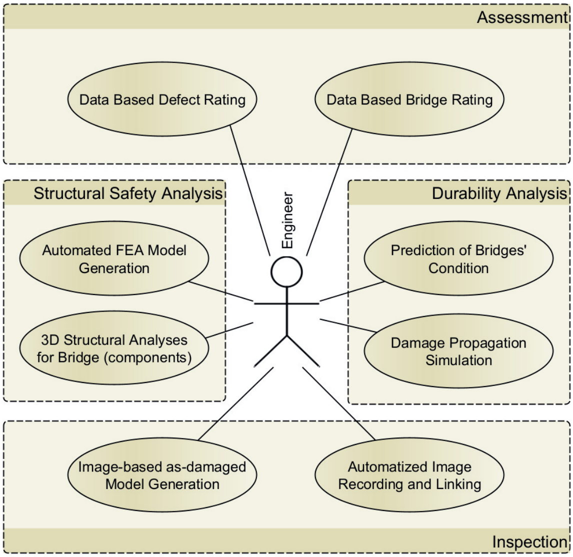

Figure 3.5: Use cases related to the engineer in recent literature.

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

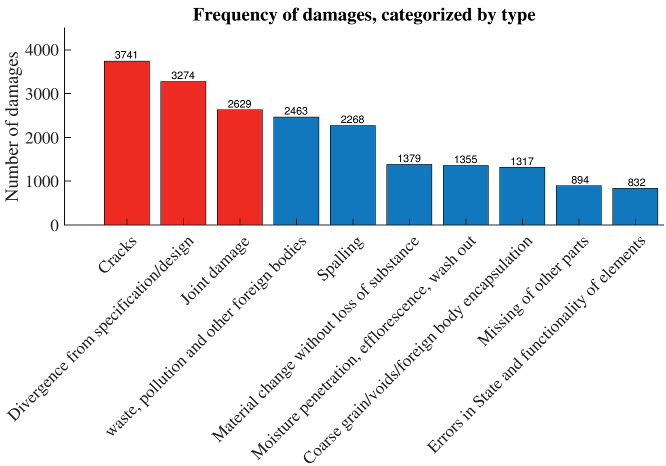

Figure 3.6: Top ten most frequent damage types in Thuringia. Top three in red [12].

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

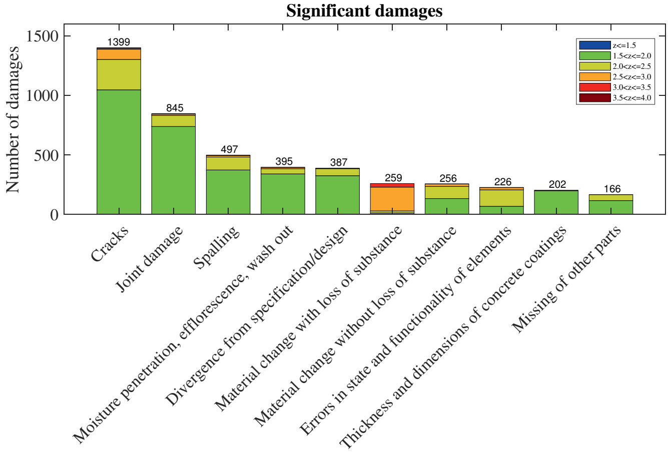

Figure 3.7: Top ten most severe defects at bridges in Thuringia, Germany, considering the severity. The colors display the Z-rating between one and four [12].

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.

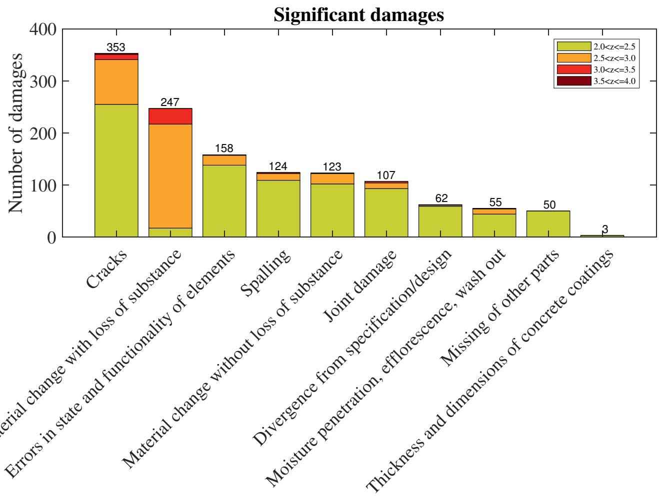

Figure 3.8: Top ten most severe defects with a rating greater or equal 2.0 at bridges in Thuringia [12].

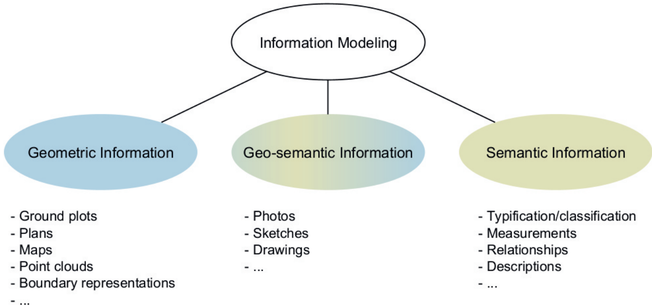

Figure 3.9: Conceptual illustration of the 3 subcategories of information modeling.

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.

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

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

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.

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.

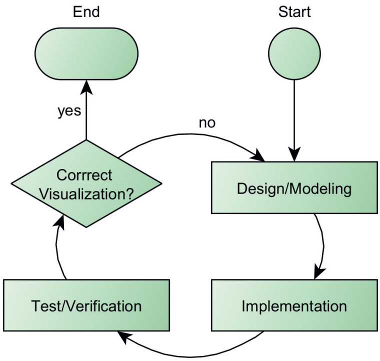

Figure 3.10: Iterative cycle for data modeling.

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.

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.

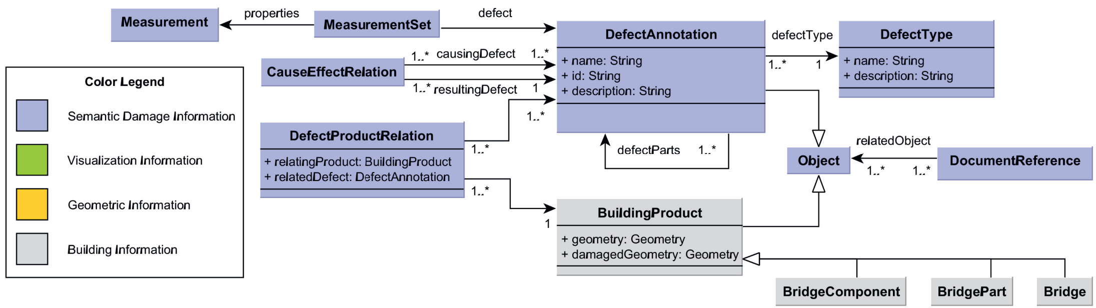

Figure 3.11: UML class diagram for the model of semantic data.

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.

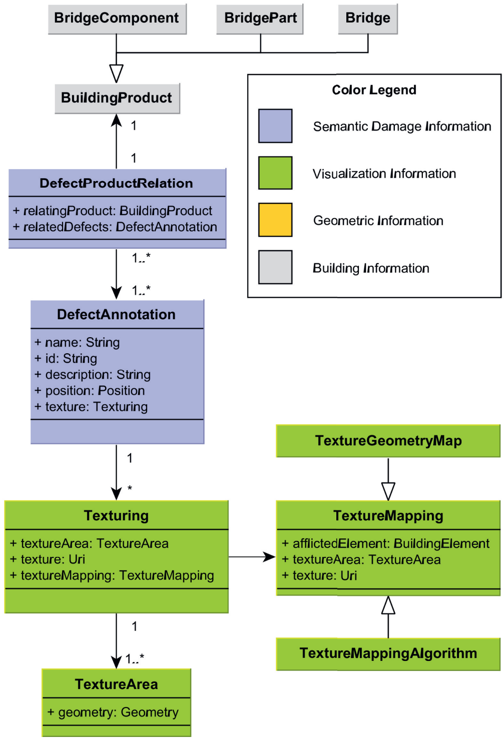

Figure 3.12: UML class diagram of the information model with additional textures.

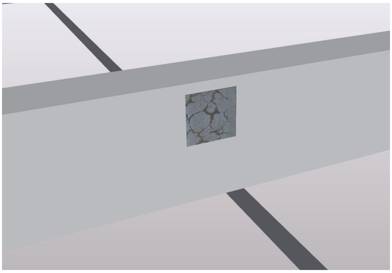

Figure 3.13: Visualization of an image applied as texture to a rectangular area.

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.

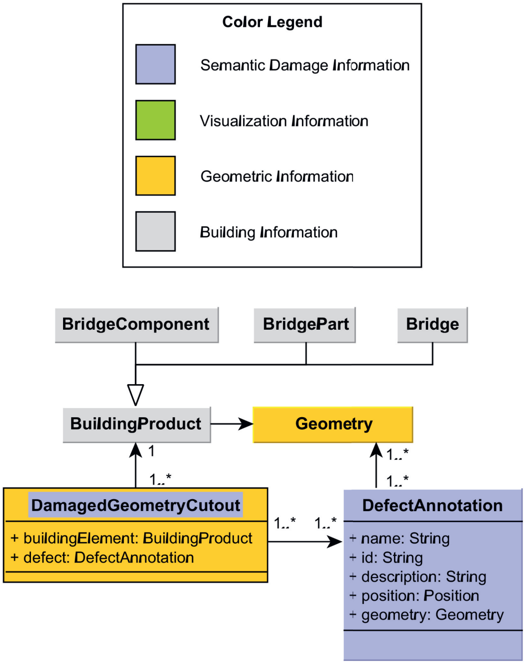

Figure 3.14: Class diagram for modeling the damaged component geometry with the component geometry and the defect geometry. The relationship *DamagedGeometryCutout* influences the geometry, hence, it is colored in blue and yellow.

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.

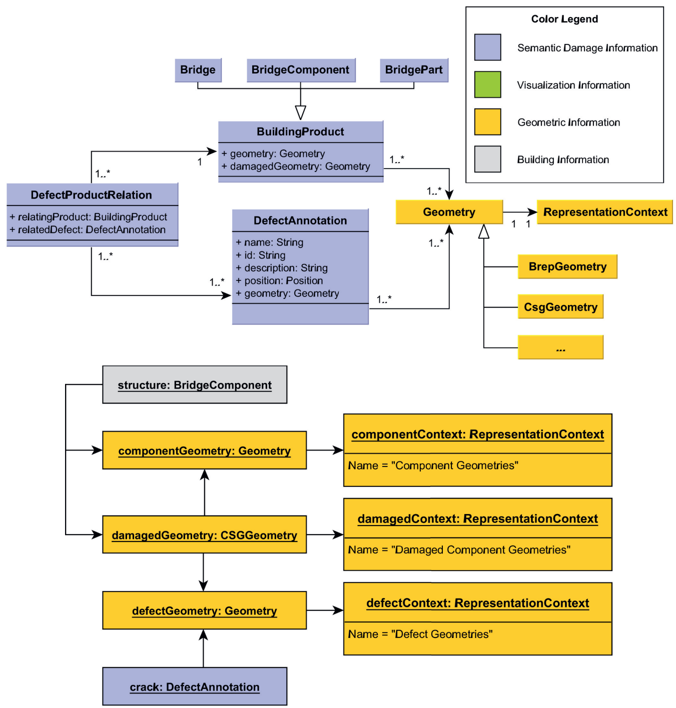

Figure 3.15: Top: UML class diagram for modeling the threefold geometry: intact component geometry, defect geometry, and damaged component geometry. bottom: object diagram for the threefold geometry model.

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.

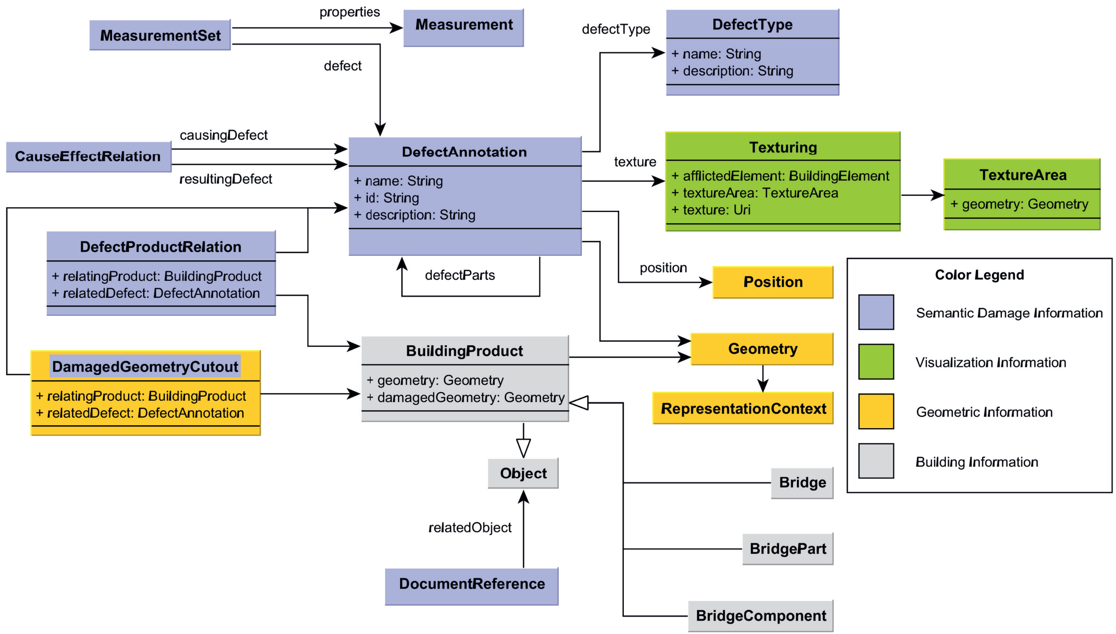

Figure 3.16: UML model including both variants A and B with the relationship-based geometry and the distinct geometry and relationship.