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Graph-based method for extracting spatial information from semi-formal text to derive 3D bridge and damage models from legacy maintenance data

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ABSTRACT

Aging bridges require improved maintenance strategies; however, recent developments often rely on newly collected data to represent the bridge and its condition, hindering their large-scale adoption and thus significant improvements. This paper demonstrates how existing data from legacy bridge management systems (BMS) can be utilized to automatically create object-oriented knowledge graphs and three-dimensional models of bridge structures and their inspection data. It applies a relative spatial reference system to position and link components and damage, generating a bridge maintenance graph from BMS data that supports spatial queries using natural-language-based location terms. This enables the automatic localization of recorded damage through their textual location descriptions. The method successfully processed 90% of 2,348 damages from two use cases with a precision of 0.8 and a recall of 0.97. The approach bridges the gap between the needs of modern information models and legacy data structures, facilitating the widespread implementation of improved maintenance strategies.

1. Introduction

The increasing aging of existing bridges leads to deteriorating structural conditions, affecting the entire road infrastructure network, with direct economic and societal consequences. In the USA, 42% of 617,084 highway bridges are over 50 years old [1], and in Germany, 45% of all 52,563 federal highway bridge structures were built before 1980 [2]. Thus, an international interest is developing efficient maintenance strategies to counteract this development and ensure a sustainable working infrastructure.

Conventional processes like visual bridge inspections are part of a reactive maintenance strategy. This strategy focuses on observing the asset regularly, documenting damage, and recording its condition in a database-centered Bridge Management System (BMS) [3]. Based on the information collected, maintenance actions are planned, such as adjusted traffic regulations, repairs, replacement of components, or rebuilding of the bridge [4].

However, as stated by the American Society of Civil Engineers [1], this maintenance strategy is no longer sufficient to compensate for the increasing stock of bridges with deteriorating conditions, as it builds on time- and cost-intensive processes and reacts too late to changed conditions. Against this background, considerable research has already been carried out to support the information management, the inspection process, and the maintenance planning to enable a predictive maintenance strategy in the long term [5–7].

Much of this work focuses on how improved inspection processes and information management systems can be implemented in future using state-of-the-art methods such as automated spatial data acquisition methods [8], Structural Health Monitoring (SHM) [9], Building Information Modeling (BIM) [10–13] and Digital Twin (DT) frameworks [14–16].

A prerequisite for these approaches, such as BIM- or DT-supported maintenance, is an object-oriented, three-dimensional representation of the bridge construction and inspection data. Since these are often unavailable for existing structures, most research approaches either newly acquire the required data using modern reality capturing (RC) technologies or manually re-record existing information to fit the proposed data structures.

This workload was manageable as the approaches were often only tested on individual use cases or implemented as pilot projects. However, the developed methods must be widely adopted and implemented in practice to exploit their full potential and achieve significant improvements.

This paper introduces a method to reduce the dependency on extensive (manual) data collection or migration by leveraging existing BMS data sets. These data sets offer essential information regarding a bridge's construction, condition, and history. They are accessible for numerous bridges across various countries, have been compiled over

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many years, contain thousands of damage entries, and adhere to a consistent data structure established by regional or national guidelines [3,17]. For instance, roughly 52,000 bridge structures in Germany are recorded within the national BMS.

The proposed process automatically reads BMS data and transfers the recorded bridge inspection information into object-oriented knowledge graphs and three-dimensional representations. Consequently, it can facilitate the implementation of model-based maintenance by providing a knowledge graph and geometric model of the bridge and, more importantly, of all recorded damages.

Most information in a BMS is textual, particularly inspection reports and condition documentation, which rely on detailed textual descriptions. Damage to a specific component or bridge area is typically indicated using relative location information expressed in natural language, such as "damage is at the left, rear end of the beam". Thus, the core of the presented process is transferring the implicit damage documentation into explicit spatial links and geometrical representations.

The process is initiated by deriving a bridge model graph from the BMS data, which employs the same relative spatial referencing system as the documentation of existing damage entries. This compatibility subsequently enables querying the bridge graph with the documented relative location information of damages. Consequently, the damage can be automatically allocated to a specific component and, where applicable, to a designated component area.

This establishes an object-oriented information structure compatible with BIM methodologies, facilitating structured spatial queries of the BMS dataset. Such capabilities may assist in identifying areas of a bridge that have sustained significant damage, while also permitting a comprehensive spatial analysis of multiple BMS datasets, for instance, to discern patterns at the network level. Furthermore, since all historical damage documentation is readily accessible, the bridge's condition for each year can be represented to analyze the evolution of the bridge's condition and identify areas that have been particularly stressed over time.

Furthermore, the methodology derives geometric models from the knowledge graph, providing a spatial representation for textual damage records. In addition to the enhanced spatial overview and accessibility to inspection data, the method facilitates the spatial superimposition of other bridge-related information (e.g., plans, photographs, models), thus enabling the identification of spatial cross-references within the dataset pertaining to a particular bridge. This approach is explored in the 'SpaceLink' project, to which this work is affiliated. The project aims to produce an automatically interlinked, spatially accurate dataset of a bridge that can serve as a foundation for digital twin developments.

Nevertheless, the BMS database has been selected as the exclusive data source within the workflow in this paper due to its well-defined and structured data collection. This facilitates creating a broadly applicable and highly automated process that does not depend on secondary data sources or pre-processing steps, which may vary for different datasets. Since the BMS adheres to a national data model amenable to structured querying, rule-based transformations can be employed to encode expert knowledge within specialized algorithms. Consequently, this process can be directly applied to individual datasets in contrast to stochastic machine learning (ML) methods.

Due to the purely numerical and textual information in BMS, this decision implies that the method can primarily create rough representations of bridges with simple geometries. Therefore, it focuses on straight plate, girder, and frame highway bridges. Since these types account for 76% of bridges built in Germany [18], the method still has many application scenarios.

Thus, the method enables systematic access to existing BMS datasets and provides an improved structure and representation of collected inventory information that is compatible with state-of-the-art information models. The proposed approach can bridge the gap between the requirements of modern maintenance methods and legacy data structures, contributing to easier and faster implementation of enhanced maintenance strategies by avoiding an immense and unaffordable workload for (manual) data migration. Additionally, it integrates historical maintenance data into improved solutions and helps prevent potential information loss.

This work specifically investigates the following research questions within the framework of the proposed method:

Research Question 1 (*RQ* 1). *Can models of a bridge and its damage be generated automatically from BMS data sets? Is the information contained in the BMS sufficient for this?*

Research Question 2 (*RQ* 2). *How can relative, natural-language-based location data be processed to automatically derive the relationship of damage to a component and the location and size of the damage area?*

Research Question 3 (*RQ* 3). *How can spatial attributes and relationships be formally described to represent the geometry of bridges and damage correctly?*

Research Question 4 (*RQ* 4). *What accuracy can the method achieve? Are the results sufficient to implement model-based maintenance concepts?*

Research Question 5 (*RQ* 5). *To what extent can the entire process be automated? What information cannot be processed automatically?*

The methodology is demonstrated on the German BMS *SIB-Bauwerke* and two bridge datasets. In the following Section 2, state-of-the-art methods and related research approaches are reviewed. Section 3 outlines the method, beginning with background information about the German BMS and previous work. Next, we explain the creation of the bridge graph, the processing of damage descriptions, and the derivation of simple bounding box geometry models. We demonstrate the methodology using the bridge datasets and evaluate the outcomes in Sections 4 and 5. Finally, Sections 6 and 7 offer discussions and conclusions regarding the presented method and its findings.

2. State of the art in research and technology

This section provides an overview of current BMS systems and introduces recently developed digital methods that support bridge maintenance and documentation. Furthermore, we explore research projects focused on data collection and modeling of existing bridges, as well as methods for evaluating recorded inspection data. We conclude with a summary of current research gaps.

2.1. Digital bridge and damage representation

Bridge management systems (BMSs) are digital solutions to support infrastructure owners in managing and efficiently maintaining existing bridges. BMSs are usually database applications specifically developed or adjusted for country- or region-specific data models and guidelines. In general, they must fulfill the basic requirements of providing bridge construction data, recording and storing inspection data, enabling condition assessments, and planning maintenance actions [5,6,19].

Overviews of different BMSs used worldwide are given in the works from Hearn et al. [20], Helmerich et al. [5], Mirzaei et al. [17] and Brighenti et al. [3]. They include a selection of European (e.g., Denmark, Norway, Germany, Switzerland, Netherlands, UK, etc.), North American (USA and Canada), Asian (Japan, South Korea, Vietnam, Taiwan), African (South Africa, Namibia, Botswana), and Australian BMSs.

In summary, all reviewed BMSs use databases as a central component, populated through various user interfaces ranging from offline desktop applications to web-based mobile applications. In some cases, they are supplemented by a business logic layer. In most systems analyzed, the condition assessment relies on damage documentation and is subdivided by component types or groups. Therefore, damage is assigned to certain predefined component types. The Danish *DANBRO* system, for example, has 15 main components; the German *SIB-Bauwerke*, 14; and the BMS *STRUMAN*, mainly used in African countries, has 21 main element types.

As there are usually no models of existing bridges and most BMSs do not (yet) support model representations, damage locations are often (if at all) indicated by free text descriptions. In Germany, there are predefined fields for each direction in which the location descriptions are stored. In the Dutch BMS *DISK*, damage entries can be additionally linked to items on construction drawings, and in the BMS*STRUMAN*, damage can also be located on schematic plans by a linked picture.

In the USA, the condition assessment is performed for individual components instead of component groups. However, there is no separate damage documentation; it is part of the free-text description of the component's condition.

To improve information management, Building Information Modeling (BIM) for bridge maintenance is gaining increasing interest. BIM offers model-based, object-related data management and facilitates the exchange of information between different stakeholders [21]. In the maintenance context, the BIM model of a bridge can additionally support the inspection process by providing a better overview and easier localization of component and damage data, thanks to the three-dimensional representation [22,23].

With the extension of the Industry Foundation Class (IFC) schema to include infrastructure and bridge-specific definitions from version 4.2, the vendor-neutral representation and exchange of BIM bridge models is also made possible [24,25]. However, the IFC Bridge Extension focuses on the main components of a bridge; there are no dedicated classes for mapping maintenance data, such as damages.

Since the operational phase of assets includes a lot of heterogeneous data Linked Data methods from Semantic Web technologies are being investigated. With the help of Web Ontologies for specific fields of application, data with a wide variety of formats and from different sources can be represented in the linked data format, a Resource Description Framework (RDF) graph [26,27]. Using the SPARQL query language [28], the interlinked data sets can be efficiently queried.

IfcOWL [29] can display any IFC model as an RDF graph. In addition, several bridge- and maintenance-specific ontologies have already been created, which follow either a monolithic or a modular approach.

Monolithic ontologies include all the classes and properties required to map a specific application context. A recent development in the USA aims to provide a national Data Dictionary (DD) for general bridge and infrastructure terms that should be transferred to an ontology [30]. The DD should promote the alignment between the terminologies of different states and include all necessary terms to store and exchange information about infrastructure-related tasks. An ontology to support the inspection process is developed by Zhang et al. [31]. The bridge inspection ontology (BIontology) contains general bridge element classes and structural and spatial relations between them. Other monolithic bridge-maintenance-focused ontologies are the BridgeOnto [32], the BrMontology [33], and the BRONTEX Ontology [34]. They were developed to evaluate bridge inspection data and provide basic classes to represent the bridge elements and detailed concepts to map deterioration knowledge, deficiency causes, hazard types, and materials.

Modular ontologies can be used flexibly and are easier to combine with other ontologies, making them more widely applicable. Hamdan and Scherer developed the modular Bridge Ontology (BROT) [35], which is derived from the Building Topology Ontology (BOT) [36]. The BROT Ontology provides classes of spatial zones and bridge components and can be extended by sub-ontologies with definitions for component details, construction specifications, building materials, and structural analysis. The authors also defined topological relationships to express the spatial and structural dependencies between components. The Damage Topology Ontology (DOT) [37] was developed to define damage to components and describe the topological relations between components, damage areas, damage patterns, and damage elements. The Area of Interest Ontology (AOI) [38] can be used in combination with the BROT and DOT Ontologies to define sub-areas of component surfaces that are damaged, such as the center or peripheral area, and top and bottom. However, the AOI Ontology does not offer direction-specific definitions.

2.2. Related research

Various research projects are investigating the application of the above-mentioned methods to improve the representation and management of bridge maintenance data.

Creating a three-dimensional representation of existing bridges is an inherent step in many approaches. The SeeBridge project presented by Sacks et al. [12] derives a BIM model from Point Cloud Data (PCD). The model follows a defined Information Delivery Manual (IDM) for BIM Bridge Inspections and a corresponding Model View Definition (MVD). Another PCD-based approach is followed by Mafipour et al. [39], where a parametric prototype model is fitted to the PCD. A combination of manual modeling based on construction plans and automatic geometry derivation from PCD is investigated in [40] to reach the most comprehensive representation of the bridge. The interpretation and spatial arrangement of existing construction plans for deriving a superstructure model is demonstrated by Faltin et al. [41]. They extract viewing markers in the construction plans to position the plans relative to each other and store their spatial relations to each other. Another approach for automatic model creation is shown in [42]. The approach works with existing bridge management data from railway bridges and template spatial alignments of main element axes to each other. The parametric template axis model is defined using Revit and Dynamo, filled with dimension values from the management data, and results in a bounding box model with different levels of detail. The model is then enriched with element information from the bridge management data and exported to IFC.

The representation of damage in 3D models is subject to different approaches. Artus [10] present an IFC-based approach where damage is represented using specific IFC entities, such as Voiding, Surface, or Annotation elements. In Tulke et al. [43], 3D pointers in a custom-made viewer highlight the position of damage in a 3D model. Both approaches rely on manual entry and localization of damage. In [8, 12,22], damage is automatically detected on geo-referenced image and point cloud data. In [12], the detected damage is integrated into an IFC model as element surface textures; in [22] the damage information is added as custom property to the IFC element, and in [8] damage is stored in an RDF graph and classified using Description Logic (DL).

Several approaches address the direct integration of current BMSs in their methods. Tulke et al. [43] built a framework where the German BMS *SIB-Bauwerke* is fully integrated via a bidirectional data exchange between a 3D model that is used for inspection and the BMS. This allows historical data to be accessed and the BMS to be provided with current data. However, the model is a non-object-oriented CAD model and only refers to component groups via different layers. The assignment of the BMS data to the model is a manual process. The integration of the German BMS with a BIM model is presented in [13]. Their approach uses an Information Container according to ISO 21597 to link IFC model elements to the BMS database, thus supporting a BIM-based inspection process compatible with the current BMS. However, they do not focus on representing past data in the IFC model. The SmartBRIDGE project presented in [44] developed a Digital Twin (DT) approach, where existing damage from the BMS is located in the model, and additional tabular damage information can be accessed. As it is a singular pilot project, the BMS data was manually integrated into the DT.

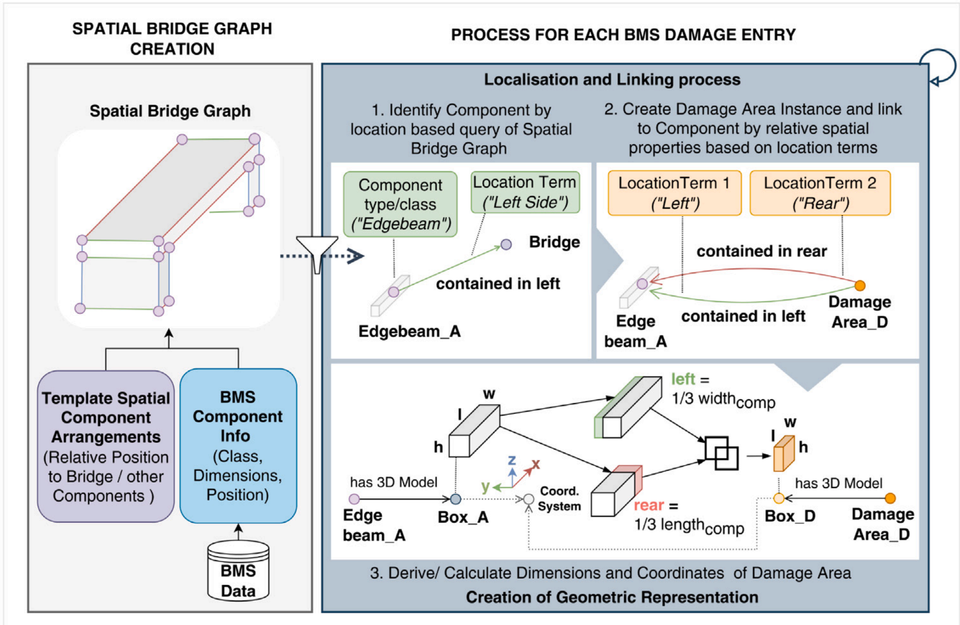


Fig. 1. Process overview.

The extraction of damage information from unstructured text documentation is presented in [32,45]. The authors present a Conditional Random Fields (CRF) based information extraction method from textual inspection reports that recognizes component, defect, size, quantity, and impact-related terms. The terms are defined in an ontology (BridgeOnto) that captures bridge maintenance and deterioration knowledge and thus supports the automatic interpretation and analysis of inspection reports.

Additionally, some approaches demonstrate the benefits of interlinked (bridge) maintenance data management. In [31], an ontology-based approach analyzes the documented damage entries and their spatial relations to suggest the next element to inspect at a current inspection to speed up the process. The spatial relations are manually added to the existing data and expressed with cardinal points. Singer et al. [46] employ asset data from the German BMS as a knowledge base for bridge design processes that can suggest possible construction types based on input parameters such as length, depth, and curvature. Another approach where documented knowledge is looped back for decision support is described in [47]. Here, defect data from construction projects is stored in an RDF graph, together with its context information from the BIM model, to build a knowledge base. The knowledge base can then be queried for correlations between component construction types, materials, or processes, and defects that occurred to these components during the construction or operation phase. As it was tested on buildings, the defect documentation did not follow any regulations and was taken with a custom-made sheet, which was then converted to RDF.

2.3. Research gaps

In summary, the automatic processing of existing data has not yet been sufficiently investigated. Approaches for automatically creating or deriving models or damaged areas often depend on newly recorded data (point clouds, images). This methodology is unsuitable for a large-scale application due to the required effort. In addition, these approaches did not take historical data into account. If historical data were integrated, it was a manual process for only small test use cases. The ontological approaches focus mainly on representing bridge elements or damage areas, but cannot describe their spatial attributes and relationships without referring to external data.

The methods that use existing data sets from the BMS or construction plans focus on creating a model but do not handle inspection data. When textual inspection data is examined, it is primarily a question of machine-supported interpretation of damage data to analyze its effects. A detailed consideration and processing of the spatial aspects of damage information is not undertaken. At most, the damage is assigned to components or component groups.

Thus, this approach can contribute to a structured access to existing BMS data by automatically generating 3D bridge models, including spatially localized historical inspection data. As it is not dependent on newly acquired data, the approach has potential for large-scale application. Moreover, resulting datasets can support Natural Language Processing (NLP) methods for understanding spatial relationships and dependencies in text data.

3. Method

The proposed method consists of three parts, illustrated in Fig. 1:

1. **Bridge Graph Creation**: Creating an object-oriented Spatial Bridge Graph (SBG) containing bridge components
2. **Damage Localization**: Adding the recorded damage to the SBG by spatially linking them to the affected components based on their relative location descriptions.
3. **Model Generation**: Calculating the dimensions and local coordinates of the component and damage objects for deriving a three-dimensional model representation.

The input data for the process is sourced from the BMS database, which contains documentation on the bridge type, dimensions, components, and inspection history. In Germany, the database is part of the closed proprietary software *SIB-Bauwerke*. Due to associated accessibility and querying limitations, a process was previously developed to convert the database contents of each bridge into an RDF graph.

To represent the spatial relations among the objects in the graph, the Relative Location Ontology (RELOC) was developed. It corresponds with the relative, natural language-based localization method of the BMS data and facilitates the expression of topological relationships.

The ontology is used to create the initial Spatial Bridge Graph (SBG), which includes the bridge components and their spatial relationships.

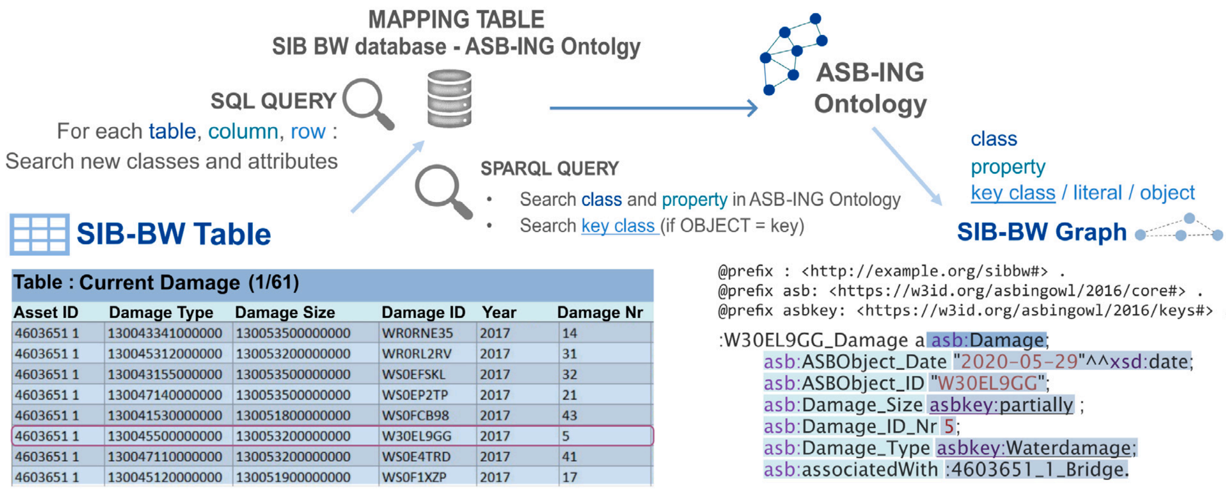


Fig. 2. Conversion process of the BMS database into RDF graph.

The information about the components is taken from the BMS data. The method focuses on the following conversion of the textual damage location information from the BMS data into formal, spatial relations between the damage and the (affected) bridge components, which also utilizes the RELOC ontology. The final SBG graph combines both the components and the damages. By using documented or derived components and damage dimensions, relative coordinates can then be calculated, completing the extraction of spatial information. These coordinates are subsequently used to create a simple bounding box model.

In the following Section 3.1, we briefly introduce the previous work steps and results, including the conversion process of BMS data into RDF graphs (Section 3.1.1) and the RELOC Ontology, in Section 3.2. Additionally, we present our prior approach for damage localization, based on an external geometric model, to facilitate a comparison between the two methods (Section 3.1.2). Next, we outline the process steps in Sections 3.2, 3.3, and 3.4, with their implementation on two use cases described in Section 4.

3.1. Background & previous work

This section provides background information on the data sources and models employed in the proposed method. It outlines the German BMS and national data models and summarizes the outcomes of earlier work phases. All German terms are translated into English in the remainder to enhance clarity.

3.1.1. Conversion of german bridge maintenance system data to RDF graphs

German bridge data is managed and stored in the proprietary, relational database system *SIB-Bauwerke* [48]. It contains textual information about administrative aspects and the bridge's construction and maintenance history. Additionally, 2D plans, pictures, and documents can be stored; however, the system does not support a 3D model representation of the asset.

The data types used to populate the database include variable text, numerical types, or predefined terms (enumerations). The enumeration values are defined in hierarchical key–value tables and encoded as 15-digit numbers.

The structure of the database and the key–value tables are defined by the national guideline *Instructions for the Road Information Database - Subsystem Structural Data (Anweisung Straßeninformationsbank - Teilsystem Bauwerksdaten) (ASB-ING)* [49]. The ASB-ING data model contains about 120 classes, more than 500 attributes, and 3000 enumeration values, related by restricted relations representing mandatory rules and standards.

SIB-Bauwerke uses a relative spatial reference system employing directional terms for localization. Therefore, the bridge direction is defined at the beginning of the documentation process using cardinal points or city references (e.g., *"from North to South"*, *"from Cologne to Munich"*) and references to the overarching road network.

To document the bridge construction, *SIB-Bauwerke* stores information about the bridge's type, direction, curvature, total length and width, and the number of spans. Each span is described with an ascending number, a width, a minimum and maximum height, and a link to a substructure component. The ordering of the bridge spans follows the bridge direction, starting with zero at the front. In addition, individual components (superstructure, substructure, cap, deck, etc.) are documented with a specific type designation (e.g., substructure: pier), a free textual location description (e.g., *"left side"*), and partly, with broad dimensions (e.g., superstructure: construction height: 1.5 m). For the superstructure and substructure, there is also an indication of the number of beams or columns in the transverse direction.

The maintenance documentation includes condition assessments, damage records, and recommended actions. The condition assessment is based on the assignment of damage to component groups. Using a simple calculation process, described in [50], each group gets a condition rate, contributing to the overall bridge condition.

Damage is recorded by specifying its type, the affected component group, the affected component type, its size, location, and impact factors. Additionally, a picture and an annotation can be attached. While component locations are stored as free text, the database provides four designated fields to store the damage location. These are filled by selecting from 206 different enumeration values, including longitudinal, transversal, and vertical location terms. However, sometimes, the annotation field is misused to specify the location.

These enumeration values are predefined, textual, natural-language-based descriptions of relative locations. Thus, directional terms such as *front abutment, at the end of the superstructure, xx. beam from the left, right side panel, 5 m behind the start of the 3rd span, bottom,* or *right*, describe the position of the affected component and its damaged area (see also Fig. 26 in Section 5).

To convert the contents of the *SIB-Bauwerke* database into graphs, the ASB-ING data model was transformed into a Web Ontology [51]. The ASB-ING Ontology[1] enables the representation of the BMS data as open and accessible RDF graphs while maintaining compatibility with the mandatory data structure.

[1] ASB-ING Ontology: https://w3id.org/asbingowl/core.

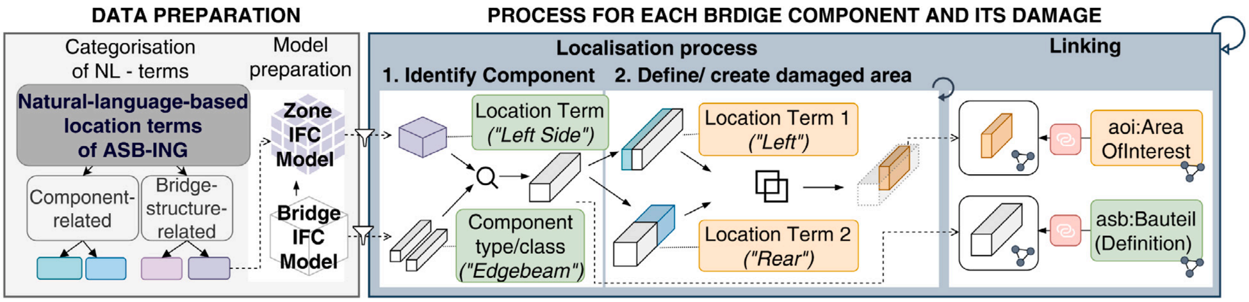


Fig. 3. IFC model-based process [53].

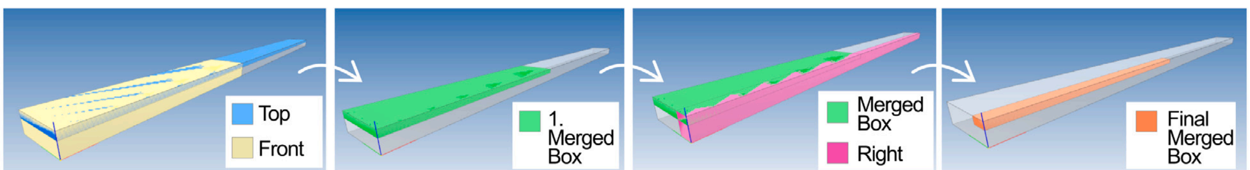


Fig. 4. Creation process of the damage area box [53].

Table 1
Example of a BMS damage entry converted into RDF.

prefix rdf: http://www.w3.org/1999/02/22-rdf-syntax-ns#
prefix asb: https://w3id.org/asbingowl/core#
prefix asbkey: https://w3id.org/asbingowl/keys#

Subject: DamageInstanceXY

	Predicate	Object
1	rdf:type	asb:Damage
2	asb:Assessment_InspectionYear	2017
3	asb:Damage_Damage_ID_Nr	5
4	asb:Damage_Type	asbkey:WaterDamage
5	asb:Component	asbkey:Abutment
6	asb:ComponentSupplement	asbkey:Concrete
7	asb:ComponentGroup	asbkey:ComponentGroup _Substructure
8	asb:Damage_Location	asbkey:AbutmentFront
9	asb:Damage_Location	asbkey:Bottom
10	asb:Damage_Location	asbkey:Left

To include the enumeration values in the RDF graphs, they were transformed into classes of a sub-ontology, the ASB-ING Key Ontology,[2] with their hierarchy represented by subclass relations.

Fig. 2 illustrates the conversion process of the BMS data to an RDF graph, described in [52]. As input for the process, database files (dbf) containing the information of a single bridge are needed, or direct access to the database is required.

In advance, the database tables and columns were mapped to their corresponding classes and properties of the ASB-ING Ontology. Using this mapping, each table row is transformed into an instance (RDF subject) of the respective class and linked to its attribute values via the respective ontological properties. Textual and numerical values are represented as RDF Literals. If the cell contains an enumeration value, its ontological representation (class) is searched by its identifier in the ASB-ING Key Ontology.

Table 1 shows an example of a damage entry converted into the RDF structure. The example also illustrates the spatial referencing method of the BMS, combining a component type indication and the description of the component and damage area position (see rows 5 and 8–10).

3.1.2. Geometric representation of BMS data using external models

In Göbels et al. [53], an approach was developed that uses an externally created IFC bridge model to enhance the BMS data with geometrical representation. It achieved an improved overview and access to the data and an unambiguous, explicit localization of damage. The IFC model was created based on 2D documentation and segmented point clouds as part of the TwinGen research project, which developed methods to (semi) automatically generate Digital Twins for the operation and maintenance of existing bridges [16].

Fig. 3 shows the rule-based process that links the components and damages of the BMS data graph to (an RDF representation of) the IFC model and creates simple geometrical representations of the damaged areas.

Therefore, the model's orientation was aligned with the direction of the bridge stored in the BMS data. Then, bounding boxes were created in the IFC model representing relative location zones, like *front*, *end*, *right side*, *left side*, *first field*, etc. Additionally, the relevant IFC classes and ASB-ING component types were mapped.

To link a BMS component to its IFC model representation, the IFC model was filtered for elements of the respective class based on the mapping. Next, the component location description was analyzed for location terms represented by a zone (e.g., *left side*). Then, the spatial intersection of the filtered IFC elements with the respective zone was checked, and the intersecting or contained element was linked to the BMS component.

The damage area representation was created by subdividing the found IFC element by the location terms used to position the damage. Fig. 4 illustrates this process for a beam with the damage area location terms *front*, *top*, and *right*. The resulting bounding box is then linked to the damage entry in the BMS graph. A sub-part of a component for a specific axis (e.g., the front part) is considered a third of the respective extent since each direction can be separated into three areas (e.g., front, center, rear) in natural language.

When the method was applied to a use case example with 33 components and 40 damages, 72% of these elements could automatically be identified respectively located in the model based on their textual location description.

The main limiting factor of the approach is the completeness and structure of the IFC model. Many finishing elements and equipment objects were not modeled, and some components were modeled with a focus on construction and not inspection, e.g., the main girder was modeled as one compound object and not as a group of individual sub- and cross-girders. Thus, damage at a specific cross-girder could not be located. In total, missing or incorrectly modeled elements caused 68% of the localization failures. The remaining 24% was due to missing or insufficient location information of the BMS data.

[2] ASB-ING Key Ontologies: https://w3id.org/asbingowl/keys.

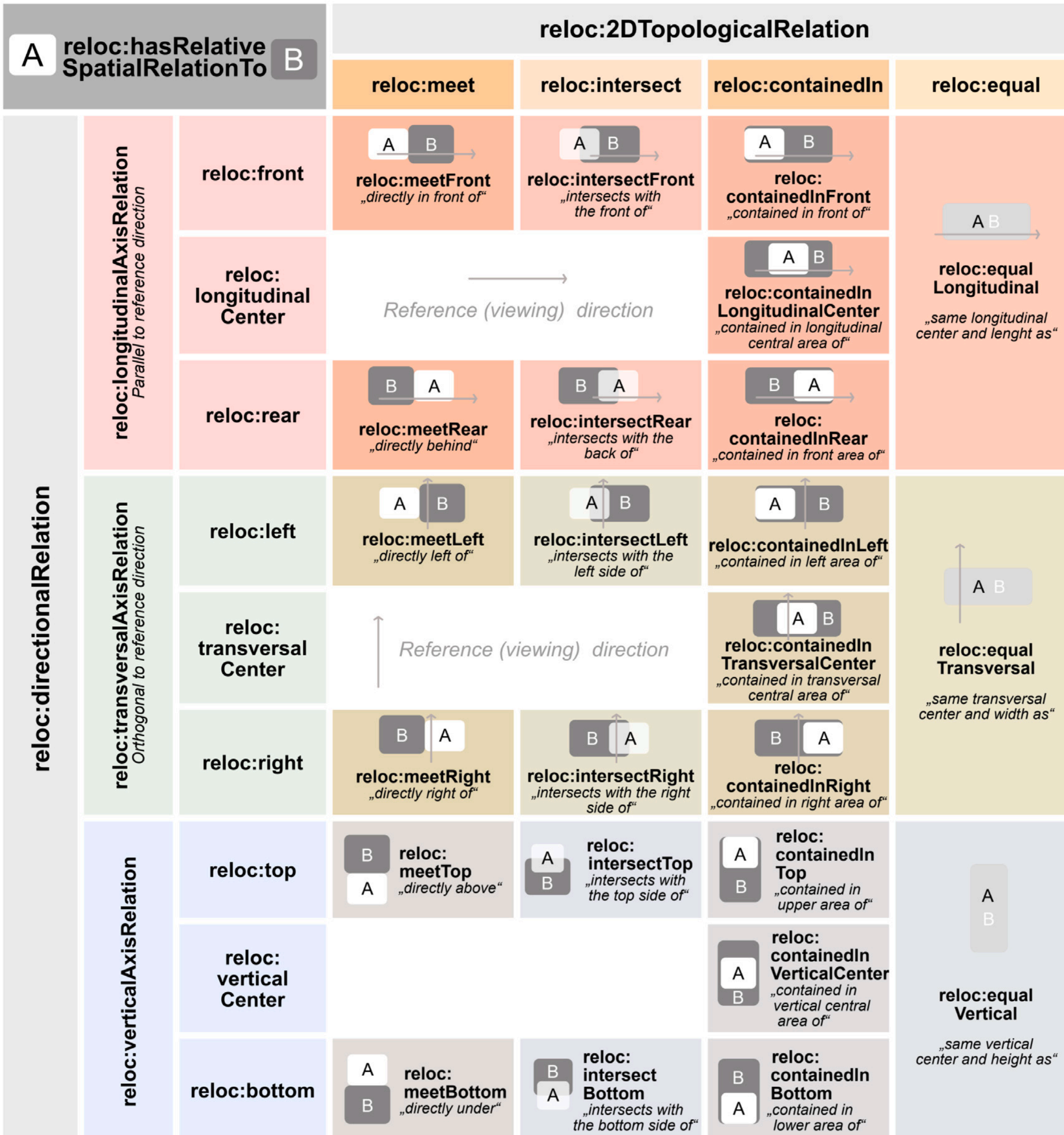


Fig. 5. Overview of the RELOC Ontology properties [54].

Hence, to be independent of the existence, completeness, and correctness of an externally modeled 3D model, the approach presented in this paper aims to be purely based on the BMS data.

3.2. Spatial bridge graph creation

The first step of the methodology is to create the initial SBG. The graph's content and structure requirements arise from its intended use for processing the relative location references of the BMS damage entries. Thus, it must support a relative, directional localization approach and include all spatial reference objects used for damage location references, such as individual components and abstract zones. The SBG emphasizes the spatial attributes of the objects. All further information about the objects is retained in the BMS graph, to which object-specific links are implemented during the process.

The creation process uses construction information from the BMS graph combined with general knowledge about the spatial constraints of bridge structures. These constraints are represented by template spatial relationships among specific component types. To ensure compatibility with the relative spatial reference system used for damage location descriptions, these template spatial relationships are expressed using the Relative Location Ontology (RELOC).

The Relative Location Ontology (RELOC) enables the expression of spatial relationships between two entities using directional-topological terms. The ontology is compatible with natural-language-based relative location terms and allows the conversion of these into structured spatial relationships.

The ontology provides directional properties for each axis, such as *front*, *center*, *rear*, and topological properties such as *meet*, *contained in*, and *intersect*. The core of the ontology consists of combined concepts of those categories, e.g., *containedInFront*, which can ontologically represent the spatial information in the statement: "The damage is *at the beginning of* the bridge deck". Fig. 5 shows an overview of all RELOC properties and a simple visualization of their spatial meaning. Detailed documentation can be found in Göbels and Beetz [54] and on the ontology website.[3]

[3] RELOC Ontology: https://w3id.org/reloc/.

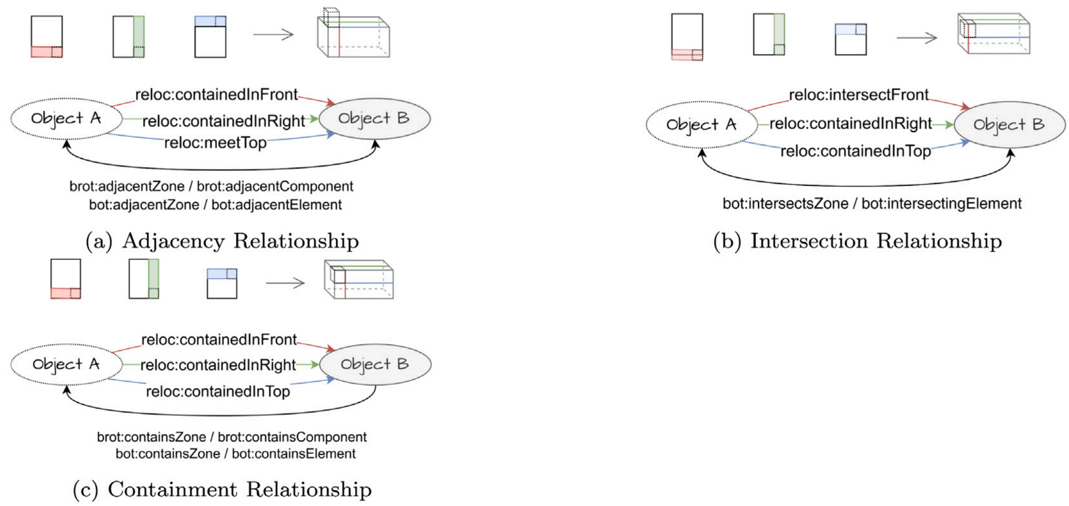


Fig. 6. Application examples of the RELOC Ontology to express three-dimensional relationships [54].

A property of the RELOC Ontology describes the spatial relation of an entity **A** to its reference entity **B**. The relation is expressed individually for each axis (longitudinal, transversal, vertical); thus, there can be multiple spatial relations between two entities that express their exact positioning in three-dimensional space. Fig. 6 shows three examples of spatial arrangements that can be described using the ontology. Additionally, it shows the alignment to other domain ontologies, such as the BOT [36] and BROT [35] ontologies.

Using the directional-topological expression of the RELOC Ontology, the template spatial relationships of bridge components are defined. The inherent functionality of a bridge to carry a traffic route over an obstacle (crossing paths, rivers, valleys, etc.) [55] leads to the typical directed structure, with one main axis aligned with the route's curvature, one to many spans, a substructure with vertical, load-bearing elements and a horizontal superstructure that spans the obstacle.

Depending on the construction type (e.g., plate bridge, girder bridge, truss bridge, suspension bridge, or arch bridge), the sub- and superstructure have typical designs and elements. The function of the bridge (pedestrian, highway, railway, etc.) determines the features of the superstructure, including a roadway, railway tracks or pavements, and specific safety equipment such as lightning, traffic barriers, and railings.

Within these categories (construction type and function), simplified directional spatial relations between specific bridge components can be stated, e.g., *"the girder is on top of the substructure components"* or *"the railings are on the right and left side of the bridge"*. Moreover, specific spatial arrangements can be described, such as *"the front abutment is intersecting with the first field"*.

The presented approach focuses on straight plate, girder, and frame highway bridges as they represent the majority (76%) of bridge types built in Germany [18]. Thus, the spatial relationships between bridge components of these types are defined.

Fig. 7 displays a set of defined relations for the main components of a bridge, including the directional-topological relations of a *front substructure* to the *first span* (see left of Fig. 7(a)), or the positioning of safety equipment relative to a cap (see Fig. 7(c)).

The defined relationships mainly encompass the primary components of a bridge, including the superstructure and substructure. Additionally, secondary components with known information in the BMS are included, such as caps, railings, roadway, curbs, and road transition structures. However, elements like drainage pipes or inspection equipment are excluded, as no general spatial statements can be made about them.

Specifically, template spatial relationships are defined for the following bridge components and zones. A graphical illustration of all defined template relationships can be found in the Appendix.

1. Spans (see Fig. A.27)
2. Substructure elements (abutments, piers) positioned at different locations (see Figs. 7(a), A.29, A.30, A.31, A.38)
3. Foundations (see Fig. A.28)
4. Sub-components of the superstructure (longitudinal beams, deck plates; see Figs. 7(a), A.32)
5. Cross-girders of the superstructure (see Fig. A.33)
6. Roadways and roadway transition constructions (see Figs. A.34, A.35)
7. Caps (see Figs. 7(b), A.36)
8. Safety equipment (railings, traffic barriers, safety curbs; see Figs. 7(c), A.37)
9. Interior zones of components (for hollow constructions; see Fig. A.39).

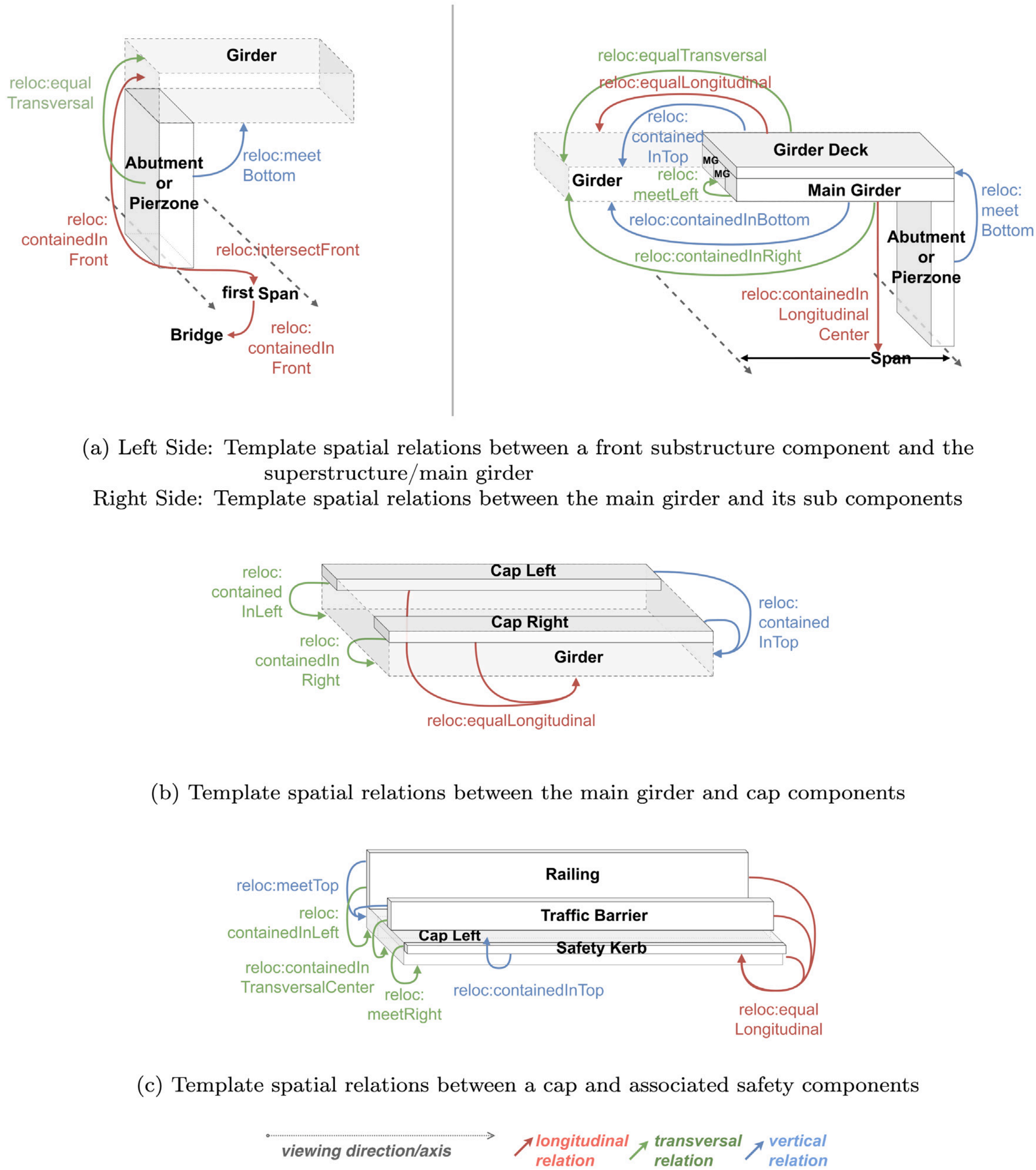
It is important to note that the defined spatial relationships are intended to support relative spatial referencing and facilitate the generation of a simple model. They do not represent any exact geometries or load-bearing relationships and do not claim to be comprehensive or entirely accurate.

Using these definitions, the components and zones, along with their respective template spatial relationships, can be combined to form a complete spatial bridge graph based on an individual bridge's data stored in the BMS.

As the original data model of the German BMS, the ASB-ING (Ontology), is a purely German standard with complex class structures, we decided to create the SBG using the generic Bridge Ontology (BROT) [35], which allows a more straightforward representation of bridge components. Therefore, we prepared a mapping of the ASB-ING Ontology component classes to the BROT classes (e.g., asb:Pier_Column = brcomp:Pier).

Fig. 8 shows the creation process of the SBG. The component types are selected based on the criteria outlined previously. The minimum individual information requirements for a BMS dataset include specifying a bridge type to verify the overall method's suitability, along with the bridge width, the number, order, and length of spans, and the height of the substructure. The BMS also provides additional dimensional information, such as the height of the superstructure or the height of the railings. However, these details are not required and, if missing from the current dataset, can be approximated using broader assumptions (see also Section 3.4).

Spatial dependencies determine the sequence of the process, which is divided into steps that create components occurring only once at the bridge, at each span, on both sides, and at the beginning and end of the bridge:



(a) Left Side: Template spatial relations between a front substructure component and the superstructure/main girder
Right Side: Template spatial relations between the main girder and its sub components

(b) Template spatial relations between the main girder and cap components

(c) Template spatial relations between a cap and associated safety components

Fig. 7. Template directional-topological bridge component relations.

1. Superordinate bridge object: It is created first and serves as the reference object for the girder and spans of the bridge. At the end of the process, it is linked to the components that indicate the maximal extent of the bridge for the specific axis: the first and last span for front and back, the caps for right and left, and the railing and foundation for top and bottom.
2. Superstructure (main girder): It encompasses the entire length and width of the bridge and serves as the primary reference point for the longitudinal and transversal positioning of other components.
3. Spans: They serve as longitudinal reference objects for the subsequent creation of the substructure elements (3.2–3.4) and the superstructure's sub girders (3.5). The number of spans and their order (ID number) are retrieved from the BMS, and the process step is repeated for each span. Each span is spatially linked to its neighboring spans, while the first and last span are spatially connected to the front and rear of the bridge, respectively.
4. Caps on each side: They are the direct references for the associated safety equipment (4.2).
5. Road transition constructions (5.1) and the roadway (coating) (5.2).

Fig. 9 illustrates the steps required to create an individual component and demonstrates the exemplary creation of a front substructure component. The steps in the component creation process are:

1. Retrieving component information from the BMS graph and obtaining the corresponding BROT class. Since the BMS graph structure is known, specific SPARQL queries for each component type are utilized to retrieve the respective input data.
2. Instantiating the component as an instance of the BROT class. The BROT class is chosen based on the mapping between the ASB-ING and BROT Ontology. Each component receives a unique name and is linked to its corresponding object in the BMS graph.

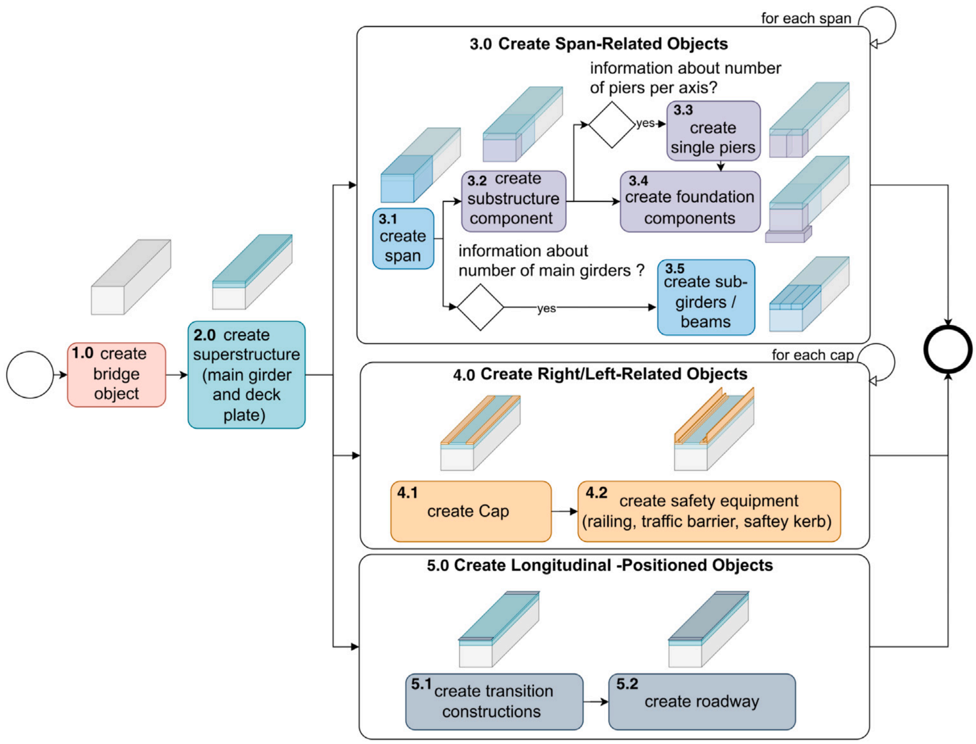


Fig. 8. Creation process of SBG.

3. Enriching the component with documented dimensions, if they are available in the BMS.
4. Spatially linking the component to the other bridge objects based on the defined template spatial relationships for the component and its position within the bridge. The target objects of the relationships, such as *"the first span"*, are queried by their spatial relationships to the bridge first.

If this process is conducted for all elements illustrated in Fig. 8, the initial SBG is complete. The SBG meets the criteria for processing damage information by utilizing RELOC properties to spatially connect the components. As a result, the graph can now be queried for specific elements based on the relative locations specified in the damage documentation.

3.3. Damage localization process

The damage localization process creates an object-assigned and explicitly located damage area object based on the existing implicit damage location information.

To initiate the process, the damage location information is queried from the BMS graph. The query returns the affected component type and up to four location terms (see top of Fig. 10). The location terms can include longitudinal, transversal, and vertical references. A term can be purely textual (e.g., *"asbkey:Bottom"*) or refer to numerical data, e.g., to indicate a specific field or an absolute, measured distance (e.g., *"asbkey:XXmFromFieldStart"*). Using this information, the affected component is first identified, then its damaged area is defined and localized by implementing spatial relationships.

The process of identifying the component involves querying the spatial bridge graph for components of the specified type and, optionally, comparing their positions with the damage location information (see Fig. 10).

The specific steps depend on the respective component type. Three criteria for each type are decisive for the process, reflecting general bridge knowledge and addressing potential misinformation:

1. Is the component type valid for this bridge type?
2. How often does a component of this type occur per bridge construction?
3. Which axis (axes) defines the position of the component?

This first criterion defines the outcome when no component of the type is found in the SBG. Since it initially includes only the defined set of components, cross beams or wing walls, for example, are not part of it. However, they are valid component types for the bridge type. Therefore, they can be created and added to the SBG using the information provided in the damage description: type and, optionally, position. Nevertheless, it is also possible for a component type to be incorrectly specified, such as a stay cable at a slab bridge. In this case, the information cannot be processed further.

The second criterion determines whether a component's position requires analysis. If a component can occur only once (e.g., the main girder), it has already been identified. If a component can occur multiple times, the locations of the identified component(s) and the description of the damage's position must be compared.

The third criterion determines which location data must be compared with each other in this case. The damage description and the component can have spatial references for each axis. However, only specific axes are relevant for identifying a specific object of a component type. For instance, the longitudinal axis position is pertinent for distinguishing between the front and rear abutment, while the transversal axis position differentiates the right and left cap. For columns or beams, both axes are necessary to ascertain the exact position.

Knowing the relevant axis, the comparison process outlined in Fig. 10 can be conducted. A SPARQL query compares the component's spatial relationships (RELOC properties) with the damage location information for the specified axis.

For textual damage location expressions, the label of the component's RELOC property is compared with the damage's location term using a regular expression filter. To achieve a high match rate, care was taken while creating the RELOC ontology to include labels for various languages and alternative expressions, such as *"beginning"* and *"start"* in addition to*"front"*.

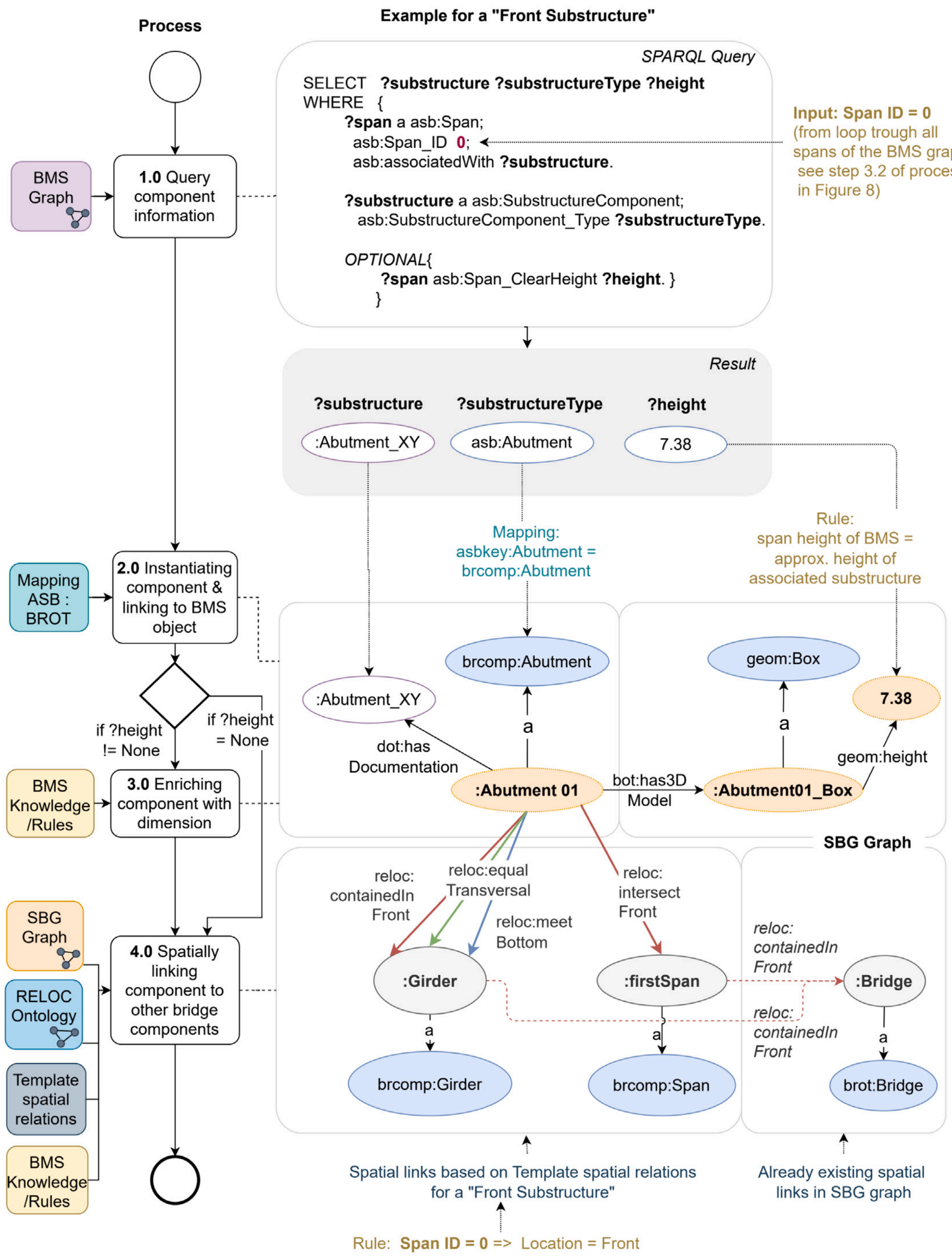


Fig. 9. Component creation process example for a front substructure.

If the location is expressed with a span number, that span is identified by this number, and the component linked to it is selected. When a complex location description is present, such as *"the third component from the left"* and *"second field"*, several queries are combined.

If the comparison fails but the component type is valid for the bridge, a new component is created that matches the type and location details of the damage description. In this way, the SBG becomes increasingly detailed and includes all the necessary components to accurately represent the damage, even if these were not originally documented. However, damage to secondary elements excluded from the beginning (e.g., drainage and inspection devices) is still filtered out.

If the individual component is identified, the damage area localization process starts with instantiating the area as an individual of the Damage Area Class of the DOT Ontology [37]. Next, the component is semantically linked to the damage area using the DOT property *"hasDamageArea"* (see bottom of Fig. 10). Additionally, the damage area is linked to the damage entry of the BMS data graph, which provides all inspection-related information.

The localization of the damage area is established by spatial relationships from the damage area to a reference object. Generally, the identified object from the previous step serves as the reference object unless stated otherwise. However, the reference object can vary for each axis. There are predefined location terms such as *"at the center of field X"*, *"at the beginning of the bridge"*, or *"in the area of the first pier"*. If the location terms reference anything other than the damaged

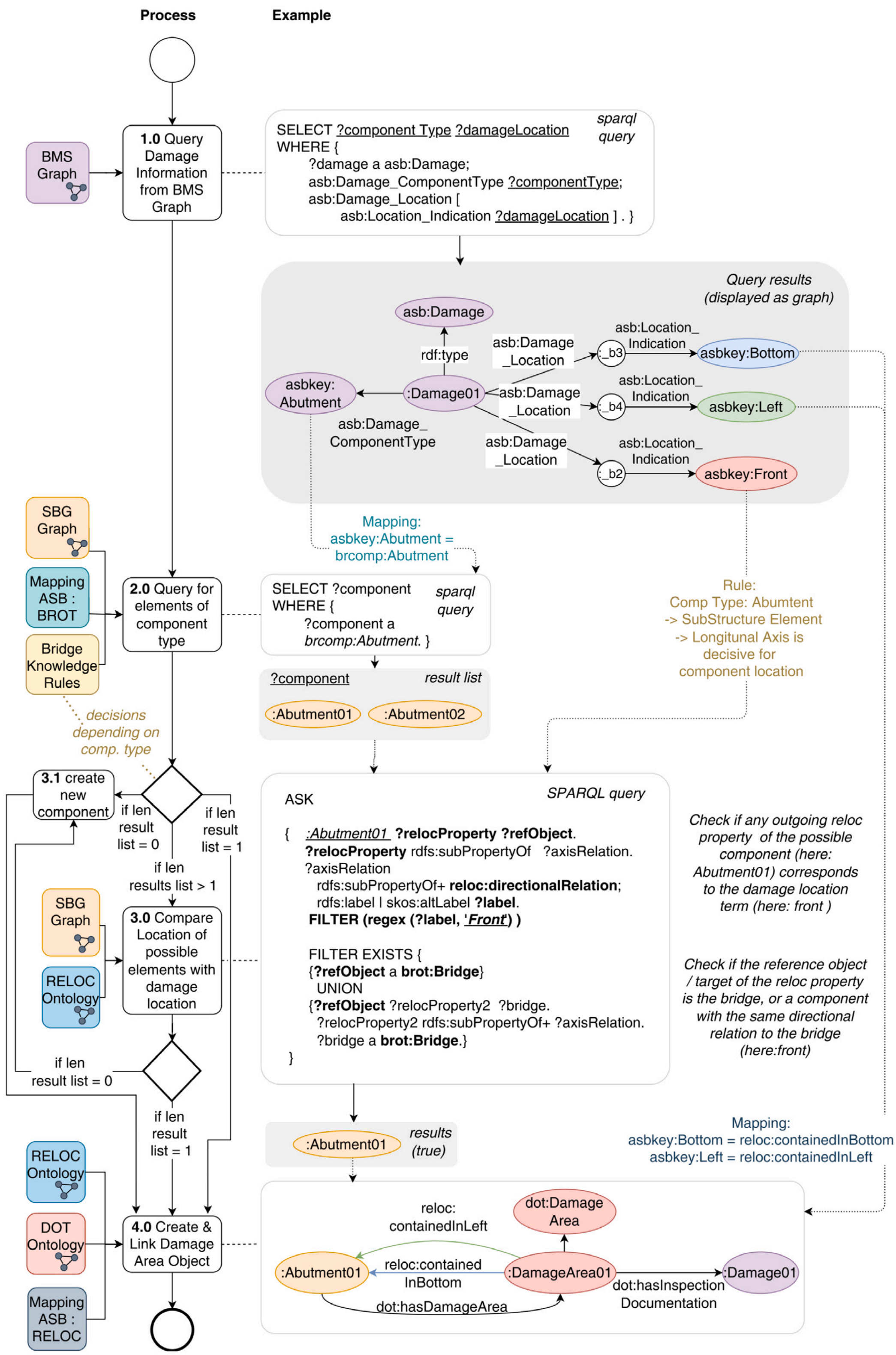


Fig. 10. Process outline of the damage localization.

component, this is identified following the steps described previously and used as the target object for the spatial relationship.

The spatial relationships used to express the location of the damage are directly derived from the given location terms. Since these terms originate from a relatively small set of enumeration values, we have manually mapped them to RELOC properties. In the example, the terms *"asbkey:Bottom"* and *"asbkey:Left"* are given, which are mapped to *"reloc:containedInBottom"* and *"reloc:containedInLeft"*.

Typically, the location descriptions for each axis are pertinent; however, the term designating the axis, used to identify the component, is

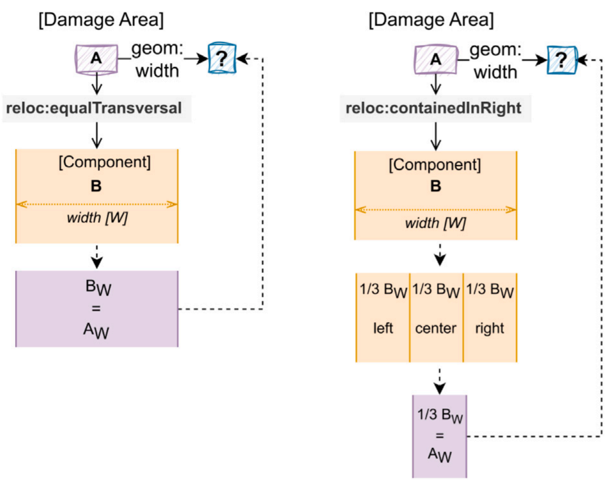


Fig. 11. Derivation of Extents based on *"reloc:equal"* and *"reloc:containedIn"* relations.

omitted in this step. This guideline addresses the ambiguity in the BMS data, as it remains unclear whether the documenting person intends *"front"* to refer to the front abutment or the front surface of that abutment. We chose to define areas or zones that are potentially too large rather than too small, to accommodate various interpretations.

Additionally, the process aims to identify the specific surface of the damaged component to create more detailed representations. Therefore, location terms and indications of component types are analyzed for words (parts) such as 'side,' 'surface,' 'ceiling,' 'floor,' etc. Rules based on component types can then derive the affected surface by combining this information with the relevant directional information. For example, if the component type indication of the BMS is *"asbkey:SideSurfaceOfBeam"* and a transversal direction is given, e.g., *"asbkey:Right",* it can be inferred that the right surface of the beam is damaged. This information is stored and used in the model creation process to develop two-dimensional damage areas on the specific surface of the component.

Finally, the damaged area is supplemented with detailed size information, if available. This information is either explicitly recorded in the BMS data (e.g., crack length: 0.5 m) or can be inferred from the damage classification (e.g., crack, transverse, 0.2–0.4 mm width). Fig. 25 shows a detailed representation of the resulting documentation of the damage area in the graph.

3.4. Calculation of relative coordinates & model generation

Calculating the coordinates for each component and damage area object in the SBG requires specific dimensions for every item. Depending on the type of object, the extents in one, two, or three directions are necessary. While spans only need a length specification, damage areas require both length and width, and components need all three dimensions.

The size information for components can come from various sources or processes:

1. Absolute dimensions, recorded in the BMS
2. Template sizes based on standards or typical dimensions
3. Parametric calculation
4. Derivation of dimensions based on spatial relationships

The BMS data records the basic dimensions of the entire bridge structure, including the length, width, and height of the superstructure, as well as the height of each span. These were already added to the corresponding SBG objects upon creation. Template dimensions can be applied in certain cases for dimensions that are not documented in the BMS. For instance, for curbs or cap constructions, these dimensions can be derived from the official reference drawings [57].

Given the basic dimensions of the BMS, broad sizes of subcomponents can be derived through simple parametric calculations. For instance, the individual widths of the longitudinal beams in the superstructure are determined by dividing the total width of the superstructure by the number of beams. Additionally, the established spatial relationships can be leveraged to derive dimensions of components related by *"reloc:equal"* relationships for one axis.

For damage areas, the size information is either precisely documented in the BMS data or must be derived from the affected component. Following the damage documentation guidelines [58], the width of damage always refers to the transversal bridge axis. In contrast, the length refers to the longitudinal bridge axis for horizontal damage and to the vertical bridge axis for vertical damage.

A recorded damage size can only be utilized for coordinate calculations if the damage is precisely located in the same direction. For instance, consider a longitudinal crack measuring 0.5 m in length situated 2 m behind the start of the bridge. If this condition is not met, although the exact size of the damage is known, its specific location within the defined area (e.g., *"the front left corner of the road deck"*) remains ambiguous. Thus, we differentiate between the size of the damage area, which refers to the described location, and the actual documented damage size.

The derivation of dimensions can be conducted for *"reloc:equal"* and *"reloc:containedIn"* relationships. Damage areas related by *"reloc:equal"* to the reference object can inherit the corresponding dimension from it (see left of Fig. 11). For *"reloc:containedIn"* relationships, we define that one-third of the respective extent of the reference object represents the corresponding extent of the damage area (see right of Fig. 11). The division into thirds is based on the premise that no more than three zones per area can be defined using single, natural-language words.

Since a damage area is a two-dimensional plane on a three-dimensional component, the spatial relationship for one specific axis determines the position of the damaged surface, while the relationships for the remaining axes define the location of the damage area on that surface. These relationships are also utilized to calculate the extent of the damaged area if no size is provided (see Fig. 14). The relevant axis for surface positioning is identified during the damage localization step by analyzing the location terms for indicative words.

Once each object has the required dimension, its local coordinates can be calculated. Therefore, their spatial relationships (RELOC properties) are interpreted as geometrical alignments. The topological level of each property determines the alignment type between the object and its reference object, and the directional property defines the edge(s) of the reference object on which the alignment is performed (see Fig. 12).

For the properties *"reloc:meet"* and *"reloc:containedIn"*, the outer edges of the objects are aligned, while for the *"reloc:intersect"* property, the center of the referencing object aligns with an outer edge of the reference object. The*"reloc:equal"* property specifies that both edges of the objects in the respective direction must be aligned. However, it should be noted that these definitions represent only one possible, highly simplified interpretation of the properties' semantic meaning to derive continuous geometry.

Combining the dimensions and alignments of each object for every direction enables the calculation of its coordinates, which define a rectangular bounding box representation. The coordinates pertain to a local coordinate system defined by an origin and orientation. The origin must be clearly documented relative to the bridge (e.g., *"upper, front, left corner of the main girder"*). The orientation must align with the documented bridge direction from the BMS and is defined by specifying the directions in which the axes point (e.g., the longitudinal axis vector points to "rear").

The coordinates of each object define the minimum and maximum points of its geometry. Fig. 13 illustrates the calculation of the transversal coordinates of object **A** based on the coordinates of its

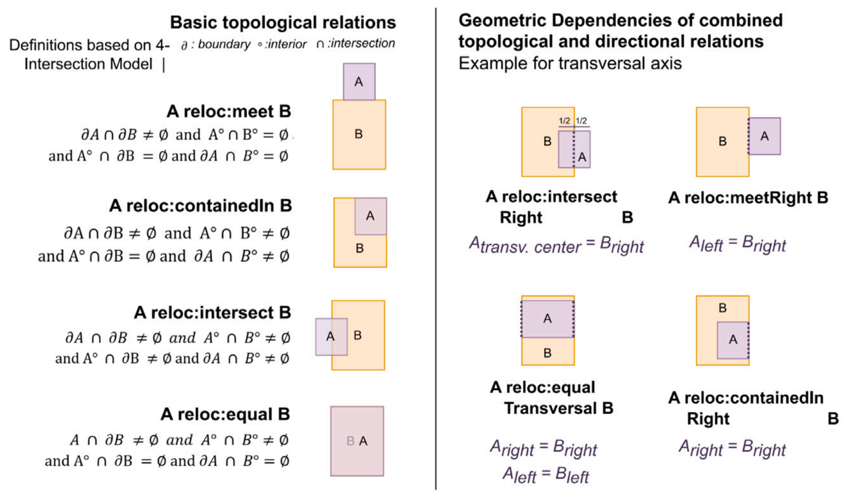


Fig. 12. Defined geometrical dependencies of the RELOC properties.

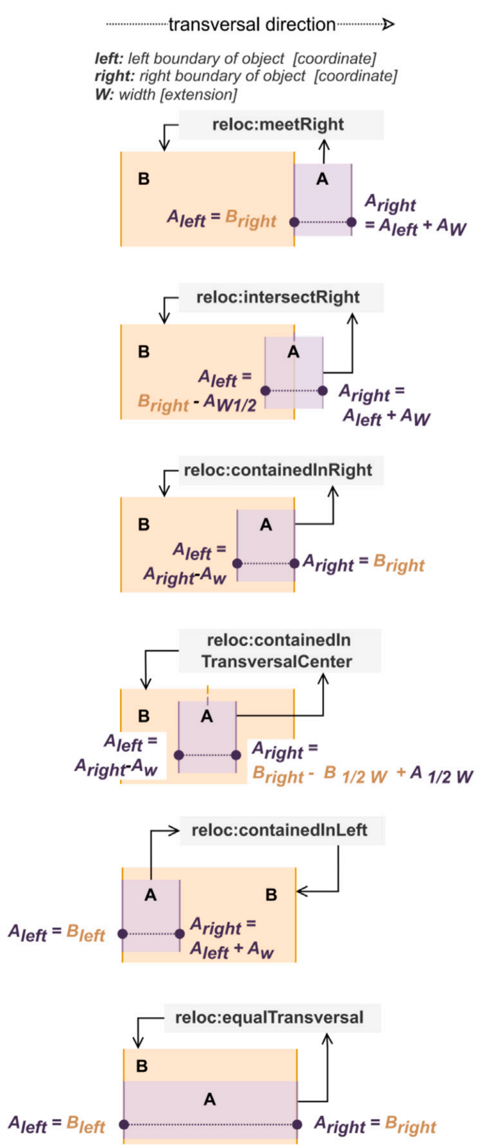


Fig. 13. Calculation of coordinates based on RELOC properties and object dimensions.

reference object **B** for different RELOC relationship types. This process is performed for each RELOC property of an object, ultimately leading to the specification of minimum and maximum points of the object in all relevant directions (see Fig. 14).

To initiate the overall calculation process, one component's minimum and maximum coordinates are defined in relation to the origin of the coordinate system. Since the main girder serves as a central reference element for other components, it is appropriate to use it as the starting component and the reference object for the origin. Based on that, a recursive process can calculate the coordinates of all objects.

4. Use case implementation

The presented method was tested on two use cases. Use Case (UC) One (Nibelungen Bridge) is a girder bridge crossing the Rhine that was built in 1949 (see Fig. 15). The bridge has four spans, a total length of 351 m, and a total width of 14 m. The superstructure is designed as a doubled-webbed girder, with haunched box-girders of 2 m width. The BMS data contains 2261 damage entries.

Use Case Two (Highway Bridge) is a multi-span girder bridge from 2002 with two spans, a total length of 57 m, and a total width of 12 m (see Fig. 16). The superstructure consists of a four-webbed plate girder. The BMS lists 87 damage entries.

The process was implemented using Python. The spatial rules and domain knowledge are encoded directly into dedicated algorithms or stored in carefully curated mapping tables. The input is the RDF graph of the BMS data, created with the approach presented in Section 3.1.1. The output of the process is the spatial bridge graph (SBG), which includes the bridge components and damage areas with their spatial relationships, local coordinates, and links to the BMS graph. The coordinates were used to create a basic bounding box model.

5. Results

The evaluation process includes a quantitative analysis of the results from the combined dataset of both use cases, as well as a qualitative assessment of the method and its outcomes, considering the precision and recall values based on a sample from this dataset. Finally, an evaluation of the individual bridge and damage models created for the use cases is performed.

For the quantitative evaluation, we examined the number of bridge components of the BMS that were successfully augmented with spatial representations and the number of damage entries that were effectively assigned, localized, and geometrically represented.

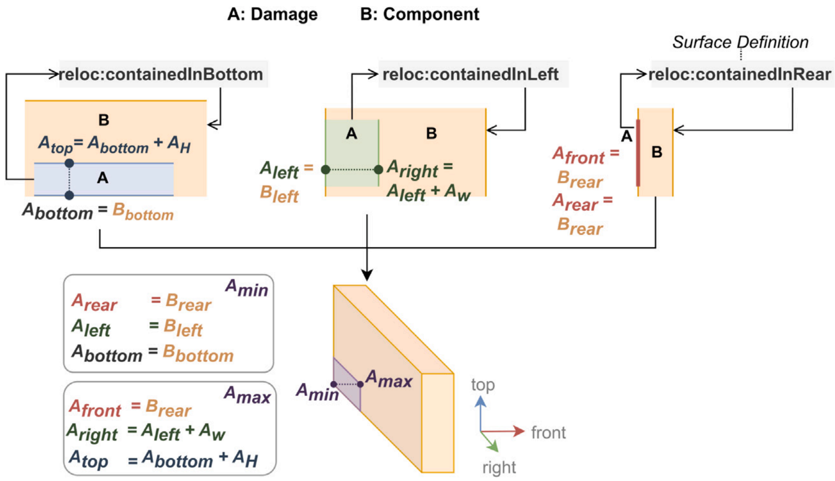
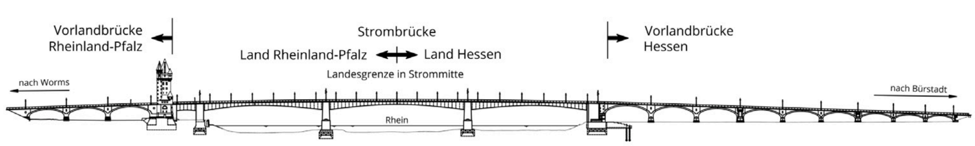


Fig. 14. Calculation of minimum and maximum points of a damage area.

(a) Overview Picture of the Nibelungen Bridge (front one). (Originally presented in Kang et al. [58])



(b) Side View Plan (The UC Bridge is the "Strombrücke") (Originally presented in Kang et al. [58])

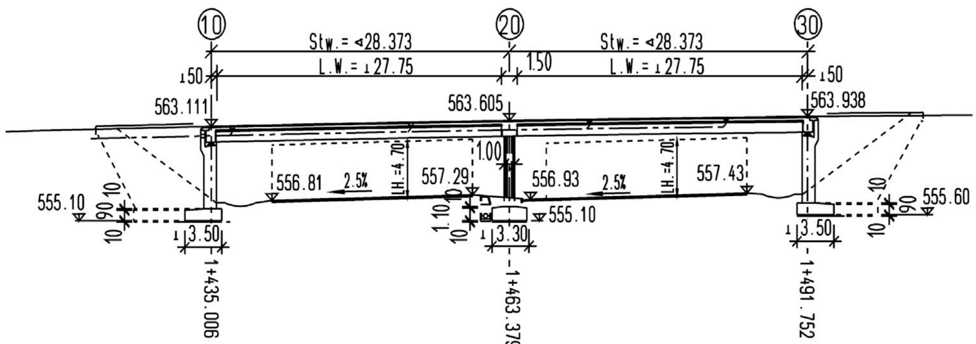
Fig. 15. UC1: Nibelungen Bridge, Germany (see [56]).

Fig. 17 illustrates that 30% of 90 documented bridge components have representation in the SBG and, thus, are also represented by the bounding box model. The fact that 70% of the components are not present in the spatial graph is primarily due to 73% of these components being excluded from the current process. These are mainly secondary equipment components, such as drainage, lighting, and inspection devices (ladders, flaps), or interior elements like pre-stressing cables. Since these component types are designed and arranged individually on each bridge, the cost of rule-based processing was considered too high, given the number of damages located there (143 out of 2348). Seventeen components could not be represented spatially because their locations referred to construction plan axes or unique points of interest on the bridge.

However, regarding the number of the located damage presented in Fig. 18, 30% of successfully processed components are sufficient to locate 90% of the damages, as these components represent the main elements of a bridge. For 10% of the 2348 damages, a damage could not be assigned to a component because the documented component type is excluded from the process or due to insufficient location information. As shown in the bottom right diagram of Fig. 18, the exclusion of drainage elements and inspection devices, in particular, has led to the majority of unassigned damages. In cases where damages have a valid component type but lack specific details, it is most common that damages at sub-girders cannot be identified. This typically occurs due to the absence of transverse positional data (e.g., *"left"* or *"3rd component from right"*).

Fig. 19 illustrates the number of successfully processed damages per component type, indicating that damage to the sub-girders accounts for nearly half of the total. The second most frequent damages are attributed to piers, followed by girder decks. Since the selected use case bridges (particularly UC 1) have numerous beams and columns, these numbers do not suggest that the process is best suited for addressing damage to beams; instead, they demonstrate that damage to beams occurred most frequently in the existing data. This factor should be considered in the subsequent evaluations.

(a) Side View Picture (Source: Autobahn GmbH Südbayern)



(b) Longitudinal section (Source: Autobahn GmbH Südbayern)

Fig. 16. UC2: Highway Bridge.

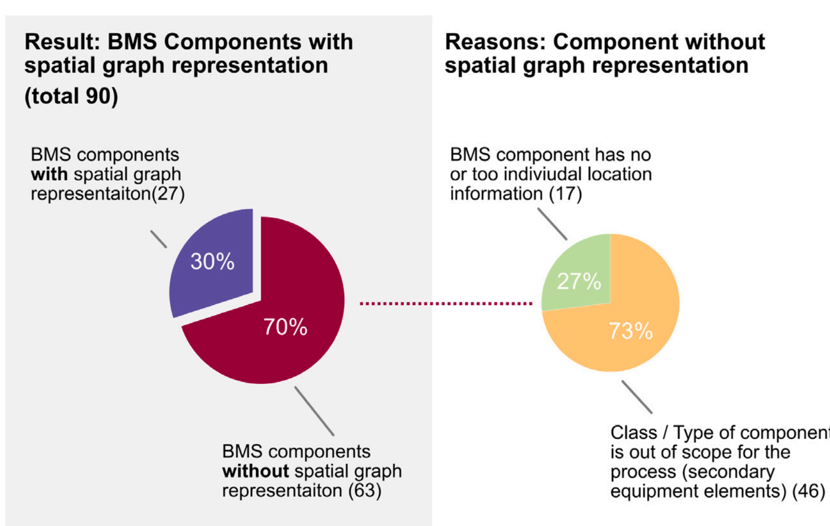


Fig. 17. Success rate of creating spatial graph representations of bridge components documented in the BMS.

In addition to the quantitative evaluation, the precision and recall values of the method were assessed to evaluate the correctness, completeness, and ultimately the reliability of the results. We used the manual readout of the BMS damage documentation as the ground truth to verify that the information was accurately represented in the SBG. Whenever possible, we also relied on photos and drawings of the damage to confirm the results. However, such materials are not always available, particularly for earlier inspections.

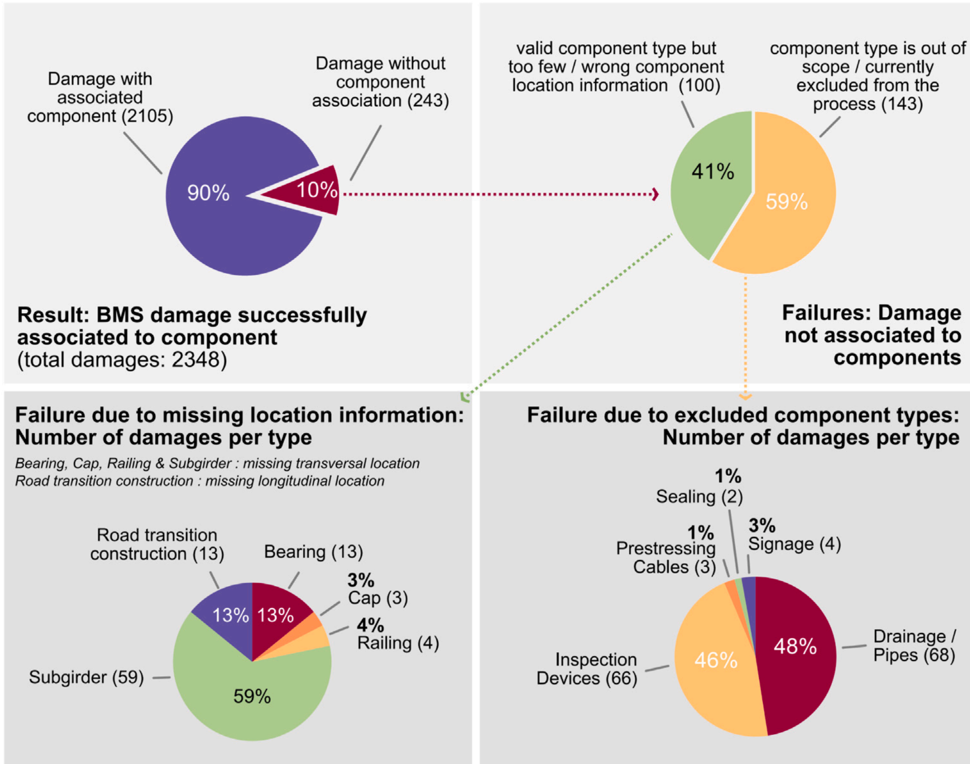


Fig. 18. Quantitative evaluation of the damage processing.

Table 2
Evaluation results of the stratified sample dataset.

Category	Definition evaluation 1	Nr.	Definition evaluation 2	Nr.
True Positive (TP)	Damage correctly and most precisely located	**240**	Damage correctly located, but possibly too large area	**286**
True Negative (TN)	Damage not located, due to missing information **or** component out of scope	**21**	(same as Definition 1)	**21**
False Positive (FP)	Damage located, but at wrong location or not as detailed as possible	**61**	Damage located at wrong location	**15**
False Negative (FN)	Damage not located, but sufficient information is available	**8**	(same as Definition 1)	**8**

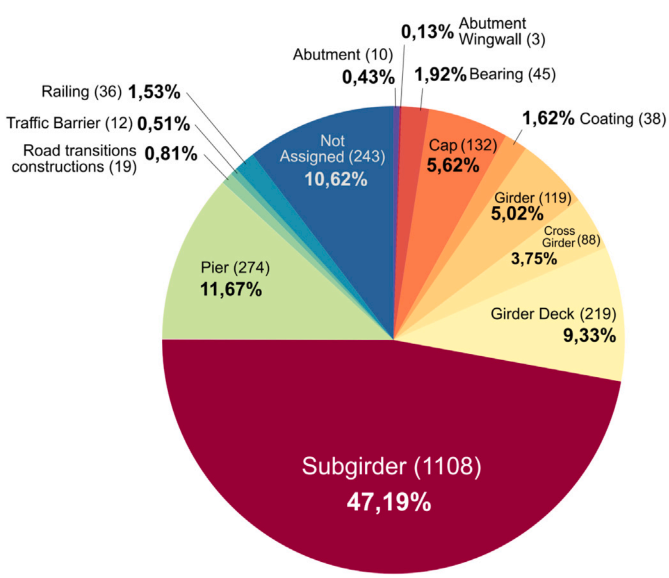


Fig. 19. Amount of processed damages per component type.

The values were calculated based on a random sample from the combined dataset. Since the use case data has an imbalanced distribution of the different damaged component types (see 19), a stratified sampling approach was applied. The sample size n was calculated using the following formula, with a confidence level Z of 1.96, an error margin E of 5%, and an unknown estimated proportion ($p = 0.5$). The total size N refers to the number of damages in the dataset (2348).

Table 3
Evaluation results of the stratified sample dataset.

	Precision	Recall	F1-Score
Evaluation 1	0.80	0.97	0.87
Evaluation 2	0.95	0.97	0.96

$$n = N * \frac{[\frac{Z^2 * p * (1-p)}{E^2}]}{[N - 1 + \frac{Z^2 * p * (1-p)}{E^2}]} \tag{1}$$

Based on the resulting sample size n of 330 and the proportions of the different damaged component types in the use case data set, the sample data set was compiled through random selection. We manually evaluated the sample using the definitions for True Positive (TP), True Negative (TN), False Positive (FP), and False Negative (FN) provided in Table 2. To gain detailed insight, we conducted two evaluations with different definitions of True and False Positives. In the first evaluation, 'True Positive' signifies that the damage localization process yielded a correct and most precise spatial representation of the damage in the SBG, based on all available damage information from the BMS. Conversely, a result is classified as 'False Positive' when it is inaccurately located or not as detailed as possible. The latter occurs if the method

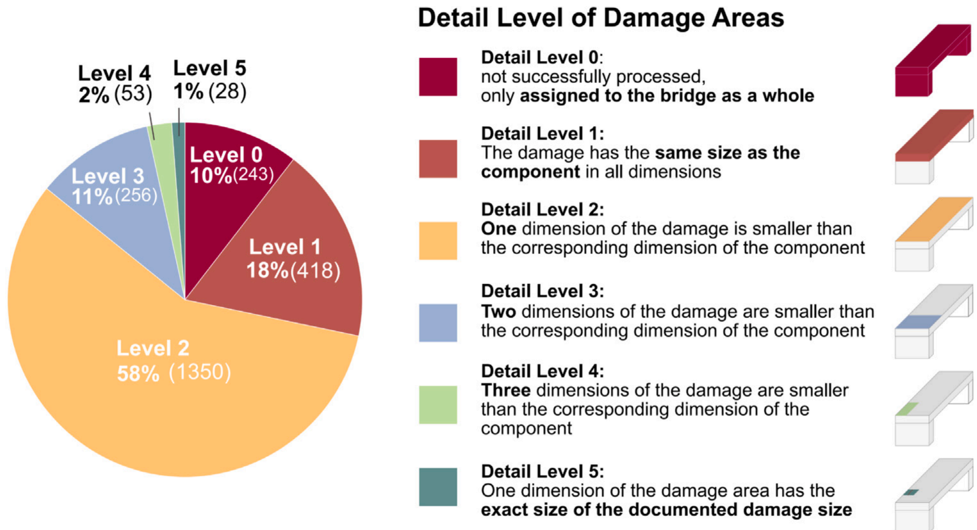


Fig. 20. Achieved detail levels of damage area representations.

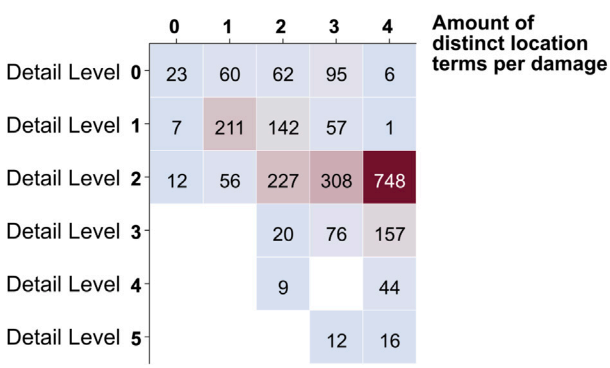


Fig. 21. Achieved detail levels per amount of location terms per damage.

fails to utilize all available data and, for example, locates damage on the left side of a beam when existing information indicates that it is, in fact, at the top left side of the beam.

As the first definition of False Positives includes results where the location is correct but (only) too large, we decided to conduct a second evaluation to determine how often the method truly fails. In the second evaluation, a False Positive signifies that the resulting damage representation is in a completely wrong location, such as a wrong component or the wrong side. True and False Negatives have the same definitions for both evaluations. A result is 'True Negative' if no representation could be created due to a lack of location information in the BMS or if the damage was assigned to a component type that was intentionally excluded from the method's scope (drainage, inspection devices, etc.). A False Negative occurs when the BMS provides sufficient information, but the process fails to create a damage representation.

Based on the results of the evaluations in Table 2, the precision and recall values and the F1-Score were calculated as follows:

$$Precision = \frac{TP}{TP + FP} \tag{2}$$

$$Recall = \frac{TP}{TP + FN} \tag{3}$$

$$F1 = 2 * \frac{Precision * Recall}{Precision + Recall} \tag{4}$$

Table 3 displays the values achieved for both evaluations. In evaluation 1, the method attained a precision of 0.80, indicating that 80% of the created damage areas correctly and accurately reflect the available information from the BMS. In evaluation 2, a precision of 0.95 is achieved. Therefore, when analyzed together, it can be concluded that 5% of the created damage areas are incorrectly located, and 15% are correctly located but larger than described in the BMS. For both evaluations, a recall of 0.97 is achieved, indicating that the method fails to create any damage representation in only 3% of cases when information is available. If a damage area is too large or not created at all, the relevant information is often stored as free text, which is not currently processed by the method. The 5% of incorrect damage areas are primarily caused by the simplified component modeling. In the SBG, the superstructure girder consists of a girder deck and single beams, while the original superstructure construction of UC 1 comprises two compound plate girders with cantilevers. Therefore, for example, damage assigned to the bottom of a cantilever is incorrectly located at the bottom of the beam, as the model does not reflect the complex geometry.

The precision value from evaluation 1 shows that about 80% of the created damage areas accurately represent all available data from the BMS. However, the quantity and quality of this data vary for each damage instance, which affects the resulting level of detail. It is not only important for certain applications that the results correctly mirror the BMS information, but also that the damage data itself is sufficiently precise. Therefore, different levels of detail in the damage representations were assessed. Note that the total number of created damage areas from both use cases was analyzed, which also includes approximately 5% of False Positives as determined above.

Fig. 20 shows the categorization of the created damage representations into five different levels of detail, based on their three-dimensional accuracy. Level 0 corresponds to 10% of damages that were not successfully processed and can thus only be assigned to the entire bridge. Level 1 indicates that the damage is the same size as the entire affected component, which occurs for several reasons: in 1% of these cases, it was noted that the damage affects the whole component; in another 54%, no further location information was available, and in 45%, the location information was stored only as free text in an annotation field.

Level 2 states that the damaged area is smaller than the affected component in one dimension (length, width, or height). This is often the case if the damage documentation indicates the specific damaged surface of a component, allowing for the creation of a two-dimensional damage area. In total, the damaged component surface could be extracted for 1208 damages, of which 883 have the detail level 2. However, this category can also include three-dimensional representations of damage that do not affect the entire component in one

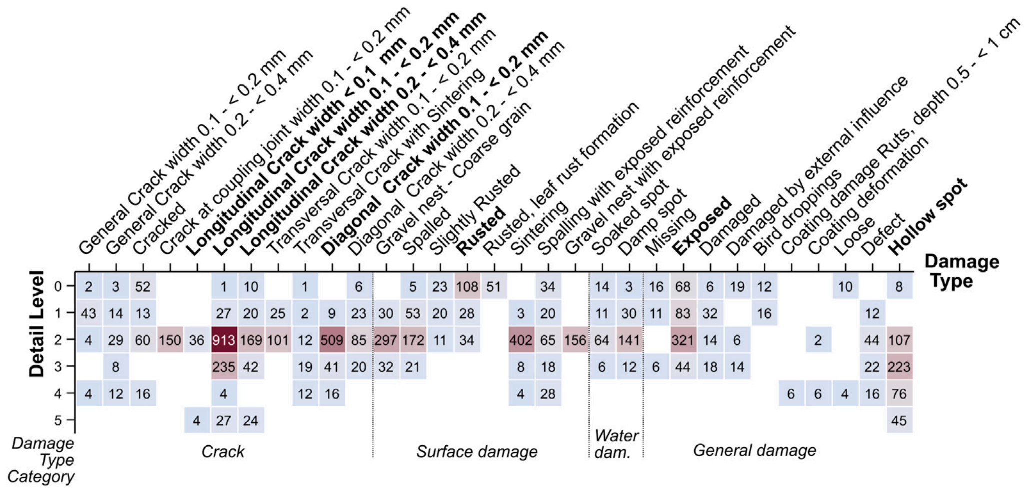


Fig. 22. Achieved detail levels for the top ten damage types per level.

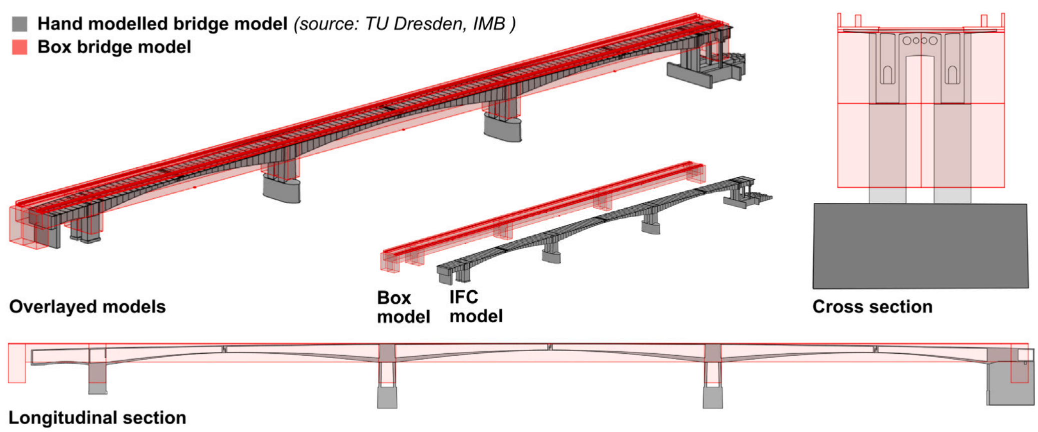


Fig. 23. UC1: Nibelungen Bridge — Automatically-derived model compared to manually created model.

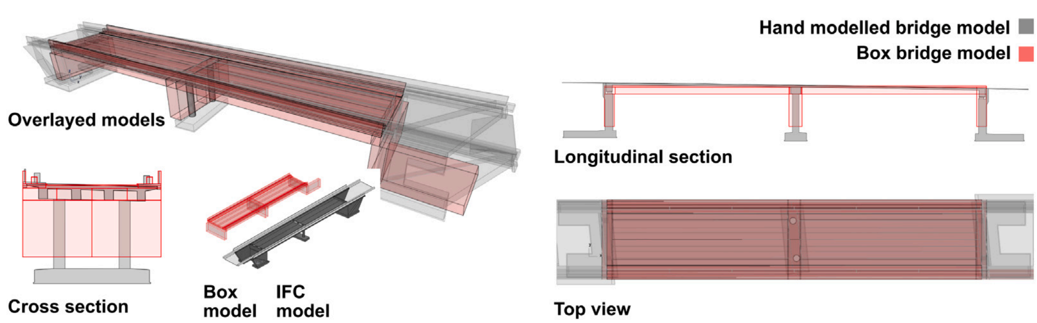


Fig. 24. UC2: Highway Bridge — Automatically-derived model compared to manually created model.

direction. Level 3 is reached when the damage is smaller than the component in two directions, and level 4 is achieved if it is smaller than the component in all three directions. These are cases when one or two terms describe a specific area of a damaged surface. For example, the left of a surface (Level 3) or the left, upper part of a surface (Level 4). The highest level achievable by the method is level 5. This indicates that the damaged area created corresponds precisely to the documented damage size in at least one direction. The example in Fig. 25 demonstrates a damage area of level 5. To attain Level 5, damage must have a specific size and a thorough description of its location, indicated by a measured distance (e.g., *"0.5 m long crack on the roadway, 3 m from the start"*). Because on-site measurements take considerable time, they are performed in detail for only a small amount of damage. Consequently, just 1% of the damages in the current dataset achieve Level 5.

As depicted in the pie chart of Fig. 20, most of the damage areas created are assigned to level 2 (58%), followed by level 1 (18%). This is because these levels can be achieved without relying on a very precise location description of the damage. Since specifying the component type is mandatory in the BMS damage documentation, and

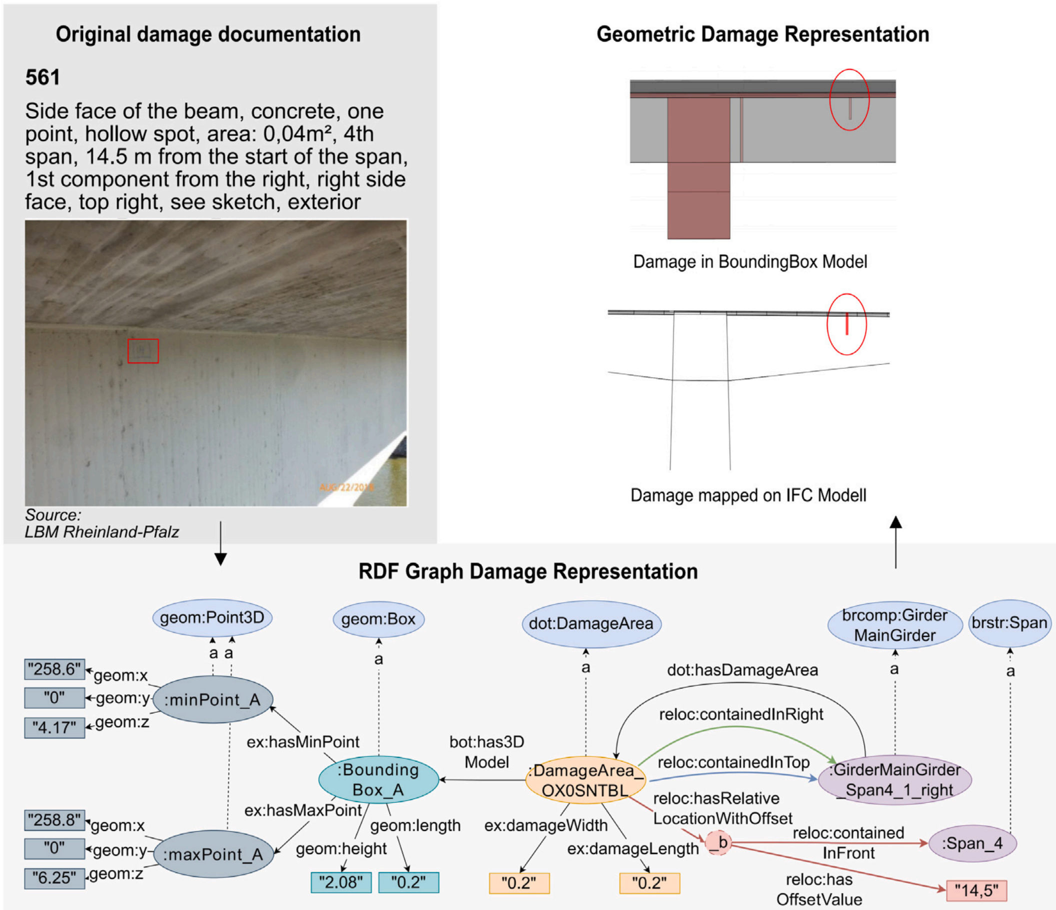


Fig. 25. Conversion of a damage entry to the graph structure and model representation.

some components occur only once per bridge, it is often easy to achieve the component assignment. The information regarding whether a surface of a component is affected is sometimes already provided by the component type description (e.g., component type: "asbkey:SideSurfaceOfBeam"). Moreover, surface information can often be inferred for specific components; for instance, if the roadway is the affected component, it indicates the upper side is intended. This enables achieving Detail Level 1 and Level 2 in some cases without further documentation of damage locations. As shown in Fig. 21, this applies to 7 level 1 damages and 12 level 2 damages.

Fig. 21 shows that the maximum is four location terms per damage, as the BMS database only provides four fields per damage to store location information. However, the figure further illustrates that most damages have the maximum number of location terms but only reach the detail level 2. This relates to the earlier observation that most damages in the use case datasets affect the sub-girders of the superstructure. These require two location terms to define the component: the span number and the position in the transverse direction (e.g., *"second span, left beam"*), plus one location term to define the surface (*"left side surface"*). As the girders and piers of UC 1 are hollow constructions, the fourth location term is applied to indicate that the component's interior is affected at 796 damages of detail level 2. However, this does not enhance the three-dimensional accuracy according to the defined criteria. Thus, due to the limitations of the BMS, the resulting representation of damage within the sub-girders cannot be more accurate using the presented method. This is also one reason for the 15% of damage areas that were found to be too large, as in these cases, further location details were sometimes written in the comment field that the method currently does not process.

Fig. 22 shows the achieved detail levels per damage type. The diagram focuses on a subset of the ten most frequent damage types at each level. The definition of damage types is derived from the BMS. The most common type overall is a longitudinal crack measuring 0.1–0.1 mm in width, followed by a diagonal crack with a width of 0.2–0.4 mm, and hollow spots as the third most prevalent damage type. In line with the overall distribution of damages across detail levels, level 2 is frequently the most common detail level among all damage types. Since longitudinal cracks often occur at the sub-girders, the corresponding damage areas typically only reach detail level 2 for the above-mentioned reasons.

It is noticeable that only for the aforementioned longitudinal crack and the hollow spot, detail level 3 was reached significantly more often, and detail level 5 was only achieved for longitudinal cracks and hollow spots. Thus, based on this limited data, it can be assumed that only severe damage is documented with absolute measurements, resulting in a more accurate outcome for the presented method.

The damage type that could most often not be processed is *"Rusted"*, followed by *"Exposed"*. Rust was typically documented on the drainage pipes and fixed ladders, which were excluded from the method. *"Exposed"* was often documented at beams, which could not be located due to insufficient information (see Fig. 18 at the bottom left).

Another factor for evaluating the quality of the results is the accuracy of the derived 3D models. Figs. 23 and 24 illustrate the resulting basic bridge models (in red) for the Nibelungen Bridge (UC 1) and the Highway Bridge (UC 2), each compared to a manually created model (in gray). The accuracy of the models relies on three factors: the generally limited detail level in the BMS documentation, the geometric limitations of the method, and the absence of data entries in these specific data sets.

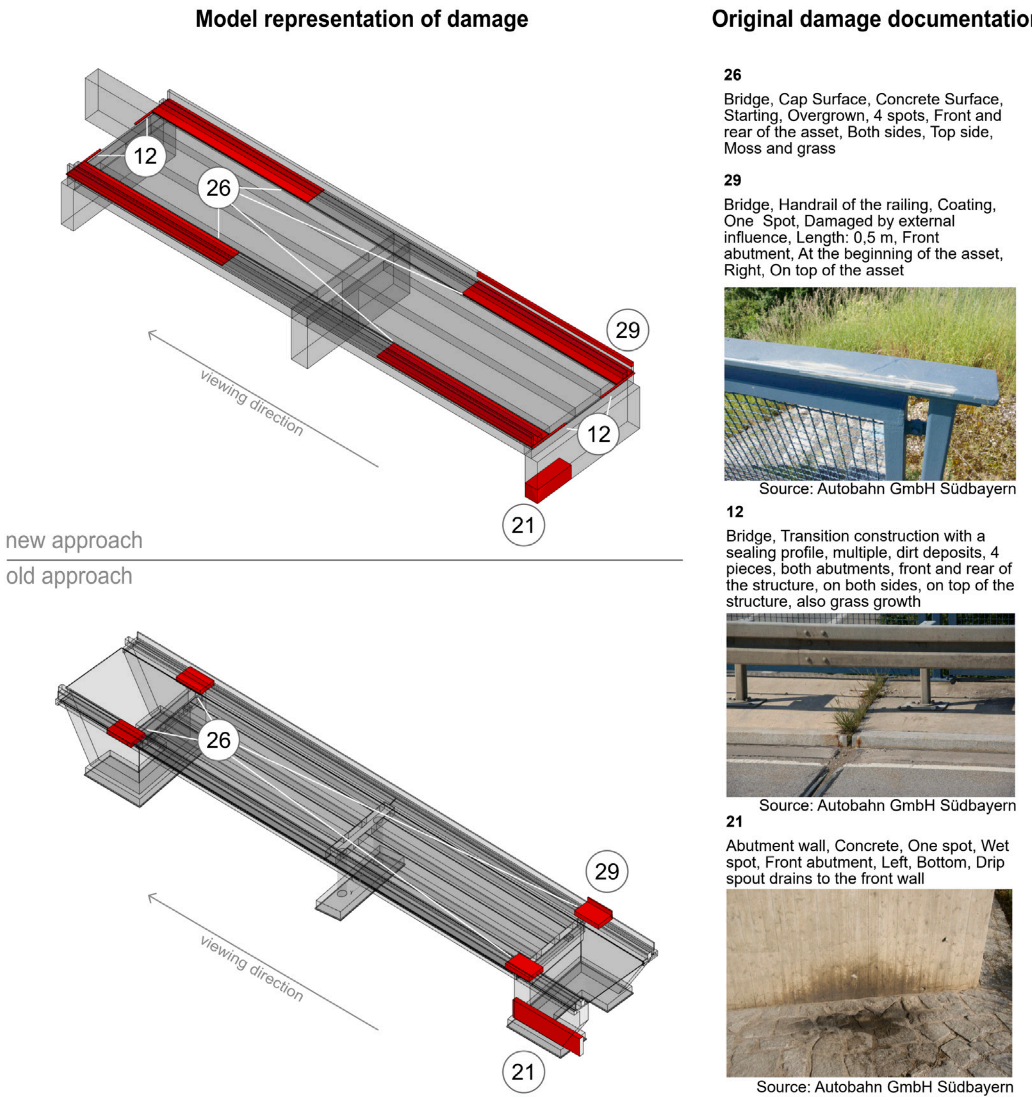


Fig. 26. Comparison of resulting damage area representations of graph-based approach (top) with former IFC-model-based approach (bottom).

In the BMS, the length and width of the bridge, along with the clear height of each span near the respective substructure component, can be documented. Additionally, the minimal and maximal height of the superstructure construction and the width of the caps can be recorded. However, the BMS data does not provide detailed documentation of sub-components, such as the widths and distances between individual beams and piers in the transverse direction. Consequently, the method can only create very rough representations of these elements, which explains the significant differences in width between the manual models and the box models for the piers and beams in both use cases. In contrast, in the case of the single wing wall of the UC 2 model, it is noteworthy that the method can also represent components that were not initially documented in the BMS but are only mentioned in damage location descriptions. This ensures that the model is sufficiently complete for the damage localization process.

As the process utilizes a rectangular visualization and coordinate calculation approach, it does not display curvatures or inclined angles; therefore, it only considers the maximum height of the superstructure. Consequently, the beams of UC 1 are not represented correctly in the longitudinal and vertical directions, which also leads to overly large damage areas in the center of the spans, where the beams are much smaller in height. Therefore, the process in its current state is particularly suitable for bridges that are not curved and have no curved components. The result of UC 2 shows how closely the generated model aligns with the manually generated model in this case. However, since most bridges have a documented minimal and maximal height of the superstructure, it is possible to implement a refined method that uses this information to create a more detailed representation.

While both use cases have well-documented bridge lengths and widths, as well as superstructure height and cap widths, there was only one documented general height value for each bridge, indicating the minimal clear height of the entire structure. Thus, all substructure components of both bridges are shorter than their counterparts from the manual models, as the clear height is less than the construction height documented in the plans. Moreover, because there was only one documented size, all substructure elements share the same height, even though the method could produce substructure elements with varying heights.

However, considering that the models were fully automatically derived, the resulting representations are sufficient for providing a spatial overview and supporting localization and three-dimensional visualization of the inspection data. Additionally, it is essential to acknowledge that the bridge models are primarily used as an intermediate step to process and represent the damage entries, rather than serving as the primary and stand-alone outcome of the method.

Fig. 25 showcases the representation of the inspection data based on the created model, along with the input data from the BMS and

Table 4
Qualitative comparison of the presented method with state of the art methods for bridge and/or damage model generation presented in Section 2.2.

Category	Bridge & Damage model						Bridge model		
Methods	This	[12]	[22]	[10]	[8]	[43]	[39]	[40]	[42]
Geometrical Accuracy	–	++	++	++	++	–	++	+	–
Semantic Accuracy	+	++	+	+	++	–	–	+	+
Completeness	–	++	+	+	+	+	++	++	+
Automatization: Bridge Model Generation	++	++	– –	– –	+	–	++	+	++
Automatization: Damage Model Generation	++	++	+	+	++	– –	N/A	N/A	N/A
Integration of historical/existing data	++	–	– –	+	– –	–	–	+	++
Independence from new data acquisition	++	– –	– –	–	– –	+	– –	–	+
Applicability for large-scale use	++	+	–	– –	+	+	+	–	++
Interoperability of results/use of open formats	++	+	+	–	+	–	+	+	–

the graph representation of the damage. The example illustrates the accuracy that the method can achieve when a damage location is well documented. However, it must also be said that some damages that are precisely located in the SBG and have been classified as 'True Positive' are displayed inaccurately in 3D due to the imprecise geometry of the models. For example, damage from UC 1 is located in the SBG in the middle, at the top of the left side surface of a beam, but the simplified modeling of the beams makes the damage area much larger than it actually is. This also supports the fact that the method is currently primarily suitable for straight-lined bridges and components.

The accuracy of the damage representation of the presented graph-based method, compared to the previously developed IFC-model-based method (see Section 3.1.2), is shown in Fig. 26 for UC 2. The advantages of the new method become apparent for damages 12 and 21. Since the old approach relied on the completeness of the external bridge modeling, damage 12 (at the transition structures) cannot be depicted, while the new process creates these components using the available BMS data. Damage 21, located at the bottom left of the abutment, is also accurately represented only with the new method. In the old process, the abutment was modeled in conjunction with the wing walls, leading to a misinterpretation of its "left side". For representing damage at the start of the bridge (26, 29), an absolute value is used to indicate "the front" in the old approach, whereas in the new approach, one-third of the length is utilized. While the absolute value may provide a more accurate representation for damage 29, both representations could be suitable for damage 26.

In summary, the results indicate that the method can almost completely extract damage information from the BMS within the defined range of component types, achieving a high level of precision, and convert it into spatial graphs and models. For simple bridge geometries, reliable 3D representations are achieved. However, the accuracy of the 3D models for complex bridge geometries is insufficient to replicate the level of detail attained in the SBG in 3D as well.

Thus, the method particularly enables structured, object-oriented access to BMS data and supports spatial analyses at the graph level. While the usability of the 3D models for detailed observations is mainly limited to bridges with simple geometries, the models provide a direct spatial overview and model-based access to BMS data even for complex bridges. This already adds value for bridges that currently lack any 3D representation.

To enhance the results, the text from annotation fields should be incorporated into the method's processing. This would improve both the precision and recall values, as no existing information would be overlooked. Still, the level of detail of the resulting damage areas depends on the input data and can only be improved to a limited extent by modifying the method. If only an entire surface of a component is described as a damaged area, the method cannot generate a more detailed result. However, a more detailed component geometry would increase the accuracy of the 3D damage representation, even for damages with less precise location descriptions. Additionally, including the currently excluded component classes would provide more comprehensive results, as it could increase the component representation rate to 81%, enhancing the damage localization rate by 6% to 96%.

6. Discussion

The proposed method enables the automatic derivation of spatial representations of bridges and damage from textual BMS data. This approach improves the overview and accessibility of the existing data by creating an object-oriented graph structure and a three-dimensional representation.

Regarding Research Question (RQ) 1, the method successfully generated geometry models of BMS data for inspection information management purposes. The resulting models can represent 90% of the damage but are not sufficient for accurately representing all bridge components. Mainly, equipment elements and bearings cannot be represented, since their localization relies heavily on construction plans. If these elements are to be included in the model, the method could be combined with deep learning-based object detection approaches to extract the construction axes' IDs and positions from 2D drawings. Initial work on object detection in bridge construction has, for instance, already been published by Faltin et al. [41] and Mafipour et al. [59].

The selected approach for addressing RQ 2 is a rule-based process that converts relative, natural-language location data into spatial relationships and representations. Spatial and bridge-specific knowledge is encoded in dedicated algorithms, mapping tables, and predefined queries. This strictly rule-based method enhances the performance of the process, is directly applicable to individual data sets, and can incorporate national guidelines for data documentation. However, it remains limited to the structured information entered into specific database fields, the static mapping of location terms to RELOC properties, and the definition of template relationships for only a subset of component types.

To reduce the method's dependence on structured data inputs and inflexible mapping tables, it can be enhanced with Natural Language Processing (NLP). Research by Liu and El-Gohary [45] and Gao et al. [60] has demonstrated the ability to analyze continuous texts from bridge inspection documentation for damage-related information using NLP. Since location details are often stored in the annotation fields due to the constraints of the BMS structure, this would improve the precision of the current process. Furthermore, applying NLP solutions to retrieve the input information would expand the method to BMS data from other countries, which mainly use free-text descriptions to record component conditions and damage.

The strictly rule-based process could be enhanced with flexibility and applicability by avoiding the direct incorporation of rules and spatial bridge knowledge into the code. Information regarding the spatial relationships among bridge components or the spatial interpretation of natural language terms may be formalized using ontologies and rule languages, such as the Shapes Constraint Language (SHACL), the Semantic Web Rule Language (SWRL), or Description Logic (DL). This approach allows the rules to be stored and defined externally and independently from direct application. Much of this knowledge is already captured by established bridge design standards and could be extracted from them.

The formal representation of spatial relationships (RQ 3) was achieved by developing the RELOC ontology. The ontology defines the meaning and topological dependencies of spatial relations expressed through natural language words. With this ontology, the graph of the previously implicit BMS data can now be spatially queried. For example, the data set of a particular bridge can be queried, such as for the most damaged area, while spatial analyses across multiple bridge graphs can also be conducted to identify correlations between damage types, locations, and progressions.

Since natural language primarily describes the relationships between the outer boundaries of different objects (e.g., something is 'to the right of' something, something is 'at the bottom'), a boundary representation (BREP) approach was chosen for geometric visualization, implemented by defining minimal and maximal coordinates for each object. However, this solution only applies to straight bridges with straight components and overlooks the axis-based design of bridges.

Post-modifying the resulting straight bounding boxes of each component could help the model fit the original geometry more closely, which would subsequently lead to more precise damage areas. For example, the representation of the beams of UC 2 could be improved by applying a deformation modifier that takes into account the documented minimal and maximal height of the beams. Thus, even for the damage areas of detail level 2, which encompass, for example, a whole side surface of the beam, the representation would be more precise, although there is no additional location information. Additionally, a less simplified modeling approach that can represent, for example, the webs, base plate, and cantilever of a box girder, rather than a single common box, could decrease the current localization failures (False Positives). Additionally, incorporating axes into the SBG's spatial reference system would facilitate the representation of curved bridges and inclinations through sweep representations. Primitive instancing could enhance the depiction of standard bridge components to create more precise models.

However, concerning RQ 4, the model and graph achieved are sufficient to ensure improved accessibility to the existing data and to provide an initial geometric model for BIM-based processes. Moreover, they support current inspection processes, making it easier to find specific damage on-site and communicate about it remotely, independent of subjective interpretation and preexisting knowledge.

The object-specific mapping and linking of BMS data enable more precise analyses than the currently used component group-based condition calculation. For example, the graph containing the located damage areas could be used as input for the automatic damage classification and assessment method presented by Hamdan et al. [8]. These or similar methods using description logic or probabilistic models could also eliminate information gaps in existing data that result from poor or incorrect documentation. Moreover, the conversion of the limited database structure to a knowledge graph with explicit links and semantic classification allows for more advanced analyses of historical inspection data. The work of Lee and Chi [61] presents, for example, an improved cost estimation workflow based on graph-based clustering of bridges with similar deterioration and maintenance needs; Zhang et al. [62] and Gao et al. [60] use bridge maintenance knowledge graphs to recommend component-based maintenance actions.

For maintenance strategies that depend on detailed geometric models and accurately identified damage, the outcomes can only act as a preliminary foundation. Nonetheless, due to the integrated Linked Data approach, the resulting knowledge graph can be linked with supplementary resources, such as point clouds, plans, images, sensors, and other models, to enhance the representation of the bridge and its status. This aligns with the next phase of the 'SpaceLink' research project, of which this paper is a part. The method described reduces the initial implementation effort for improved maintenance strategies, thus preventing manual migration, repetitive data collection, or data loss.

Another limitation of this work is that it lacks a mapping of inaccuracies in both the graph and the model. The components and damage areas of the model are rather rough representations of the actual objects, as the provided information often does not allow for a more precise depiction. Nevertheless, they are displayed in the presented process using exact coordinates and sharp-edged geometries. To reveal the true informational value behind the created model, fuzziness-based approaches could be used to map inaccuracies in both the graph and the 3D model, such as the representation of fuzzy spatiotemporal data in RDF graphs proposed in [63], or the vague visualization of geometry presented in [64]. In addition to a more adequate geometric representation, incorporating an accuracy factor is also essential for the subsequent evaluation of inventory data.

However, the shortcomings regarding the accuracy of the resulting model and the current restriction to structured input data must be considered concerning the high degree of automation and the already broad applicability (RQ 5). As shown in Table 4, the combination of automated processes for both the creation of the bridge and the damage model, without the need for new data acquisition, is unique to the presented method compared to state-of-the-art methods discussed in Section 2.2. Other methods have a similar degree of automation and can provide more accurate models; however, they depend on new point cloud data and are therefore less suitable for large-scale use.

The accuracy of the bridge models is superior in all methods that use point-cloud-based or manual modeling. Sacks et al. [12] develop a bridge model with a Level of Detail (LOD) of 300 to 400, and Hamdan et al. [8] derive a model from high precision imagery. Hartung et al. [42], who also use BMS data as a basis, also achieve better results, as the axes of the structure are modeled accurately. Only Tulke et al. [43] achieve a lower level of accuracy, as they only replace missing models with 2D placeholders. Regarding damage representation, the methods that derive damage from point clouds yield more reliable and accurate results. In [12], damage is projected onto the affected model component using texture mapping, and in [8], damage is modeled semantically and geometrically accurately in an RDF graph and as a polyline. In [22], on the other hand, the damage detected in point clouds is only roughly semantically integrated into the BIM model. In [10], the damage is modeled very accurately in an IFC model, but this approach is completely manual, and in [43], damage is only roughly represented as pins in the model.

Consequently, our method cannot match the accuracy of similarly automated methods. However, it uniquely processes historical damage, allowing for the tracking of historical conditions and damage progression, instead of only representing the condition at the time of point cloud data acquisition. Moreover, compatibility and linking to existing systems are separate from our approach, only considered by Tulke et al. [43] and Hartung et al. [42], in which Tulke et al. [43] only create an interface to view the BMS tables, while Hartung et al. [42] do not process any damage entries. Another benefit of utilizing current BMS data is that it requires no extra data collection; the process can be applied directly to about 50,000 bridges in Germany, for instance. Since maintaining documentation in the BMS remains compulsory for now, also updating the data does not require any additional effort.

However, if a point cloud is available for a bridge, it is appropriate to combine the method with the approaches of Sacks et al. [12] or Hamdan et al. [8] by linking their more accurate geometry models with the Spatial Bridge Graph of our method to integrate the historical damage, which can then be mapped more precisely due to the enhanced geometry.

Nonetheless, the method still requires testing on large data sets. The two use cases demonstrate proof of concept with promising precision and recall values, as well as a high level of automation. However, these markers need to be verified with larger and more diverse data sets to determine whether the method is suitable for large-scale use as intended. In particular, the processing of free textual input data needs to be investigated to enhance the current method, especially to facilitate its transfer to BMS from other countries.

A key requirement for this is mapping the local/national bridge vocabulary to the BROT Ontology. This can be achieved through a translation and text comparison process. Based on this, the respective country's data source could be searched using NLP methods for information about the bridge components and generic attributes, such as length, width, height, and type, to obtain the required input data for the SBG creation. To effectively localize damage, it is essential to have information regarding the type and location of components. Multiple BMSs of other countries store component information, as damage is frequently linked to primary components or groups. The location details, on the other hand, may be recorded as free text or as references to plans or images. From text, generic directional terms such as *"right", "top",* and *"bottom"* can be extracted; however, extracting location information from plans or images requires additional methods to analyze the image data.

Thus, in summary, to transfer the method to other BMS or data sources, only the retrieval of the input data needs adjustment, as the rest of the process is not dependent on the legacy/national data structure. If the retrieval is changed from very detailed SPARQL queries in the current process to more generic text-based queries that can search various data formats (e.g., PDF, TXT, tables, DBF), the method would become even more widely applicable.

7. Conclusion

This paper presented a method for extracting spatial information from text-based Bridge Management Systems (BMS) to create a spatially enhanced bridge maintenance knowledge graph and a three-dimensional model of bridge construction and its damaged areas. The results demonstrate that the fully automated process can generate three-dimensional representations suitable for model-based information management, providing enhanced spatial overviews and facilitating complex queries.

Our approach enhances the integration of historical inventory data into modern information management systems by transforming implicit data from the BMS database into explicitly spatial, object-oriented, interlinked graphs. This rule-based method depends entirely on documented data and general domain knowledge, making it an effective tool for encouraging the broader adoption of model-based maintenance practices.

In Germany alone, about 33,000 bridge datasets can be processed directly with this method; adapting it for curved structures could raise that number to 43,000. Additionally, our method's adaptability indicates its potential for use with structured data from BMS in other countries, needing only minor adjustments in input data queries. Therefore, the impact is substantial when considered against the implementation effort and data needs.

In future work, we want to refine the method by incorporating fuzzy representations and increasing its applicability by strengthening it with NLP methods for the exploration of unstructured data. Additionally, the scalability of the method will be tested to validate the success rates and the intended use as a viable solution to bridge the gap between legacy BMS and modern data structures. Based on a large set of BMS datasets, cross-sectional analyses will be tested to leverage the stored information for recommendation and prediction tasks.

Beyond its achieved outcomes in relation to the direct use case, the process generates curated and validated bridge maintenance knowledge graphs that can serve as ground truth for training Artificial Intelligence (AI) methods related to bridge maintenance or the spatial interpretation of natural language location data.

CRediT authorship contribution statement

Anne Göbels: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jakob Beetz:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Collection of template directional-topological bridge component relations

See Figs. A.27–A.39.

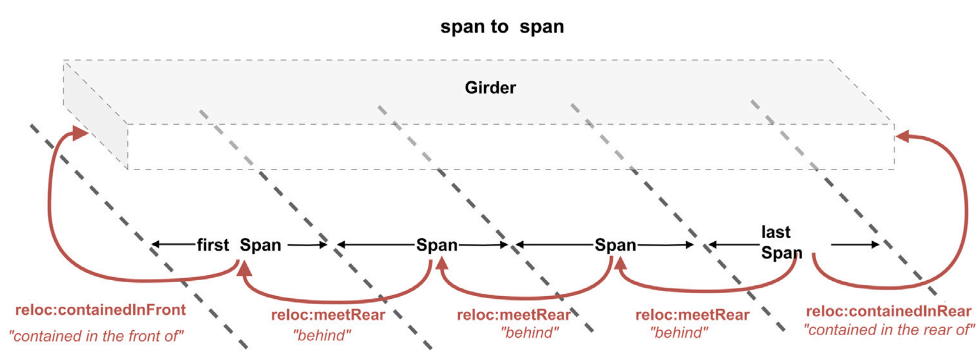

Fig. A.27. Template spatial relations of bridge spans.

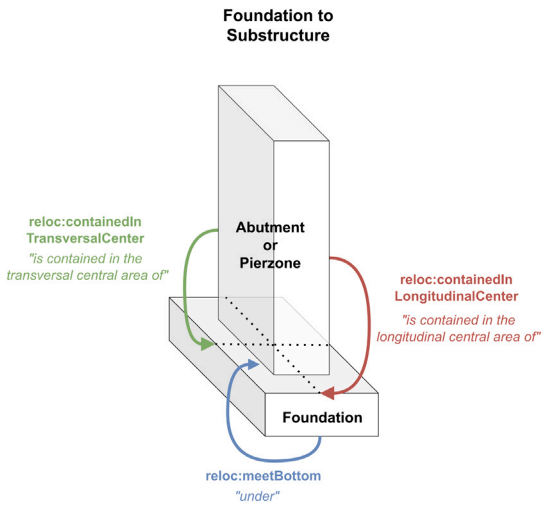

Fig. A.28. Template relations between foundation and substructure components.

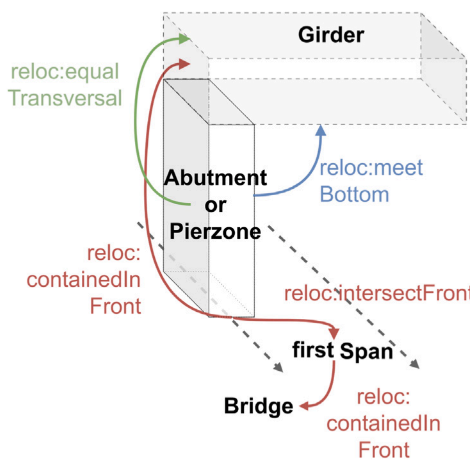

Fig. A.29. Template spatial relations of the front substructure.

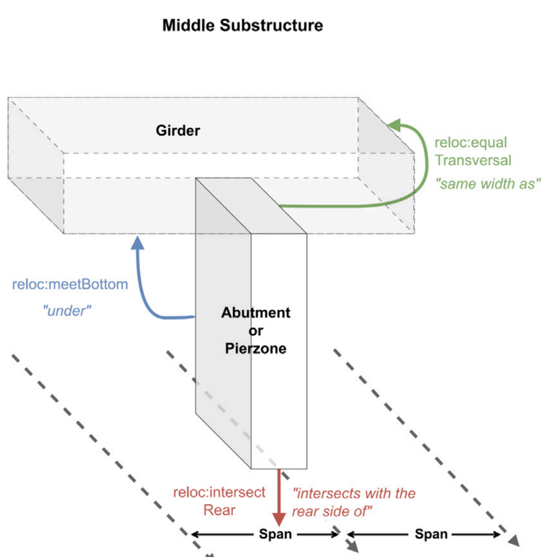

Fig. A.30. Template spatial relations of any middle substructure.

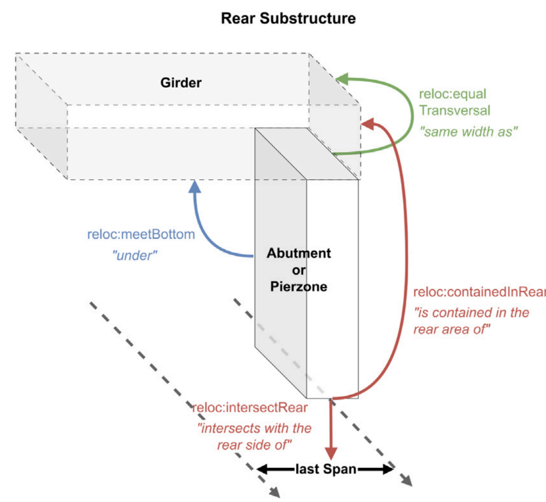

Fig. A.31. Template spatial relations of the rear substructure.

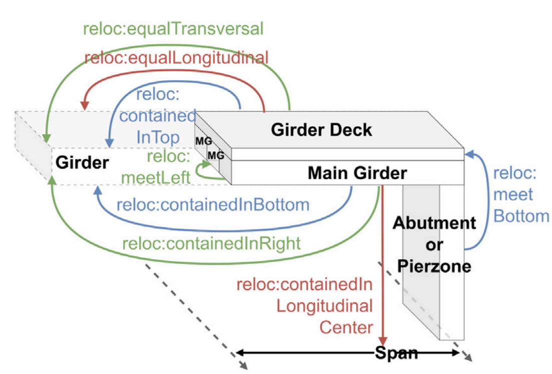

Fig. A.32. Template spatial relations between the main girder and its sub-components.

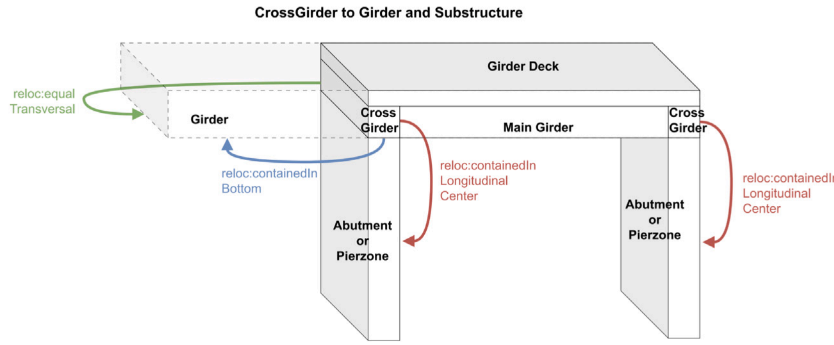

Fig. A.33. Template spatial relations of cross girders.

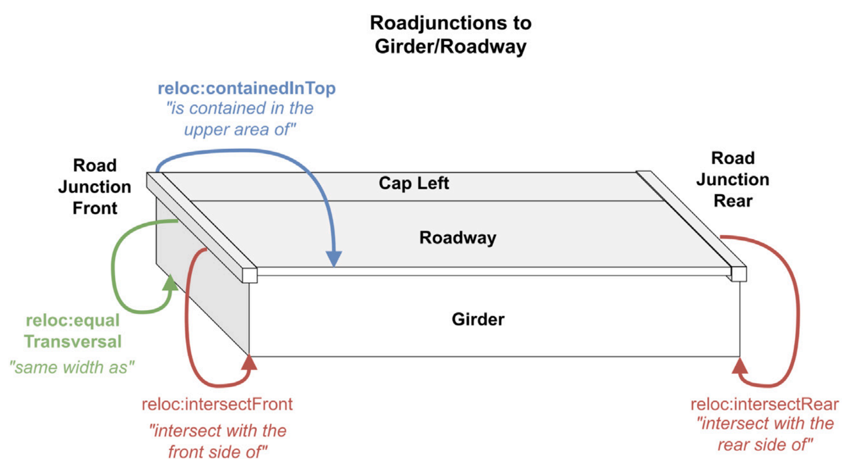

Fig. A.34. Template spatial relations of the road transition constructions.

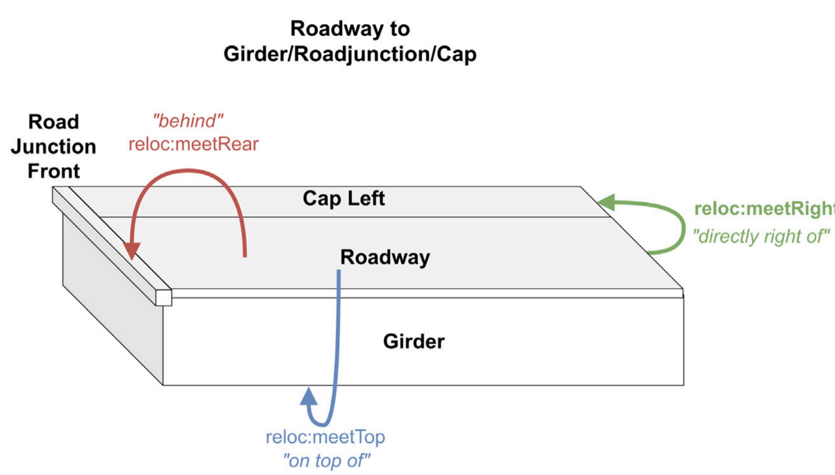

Fig. A.35. Template spatial relations of the roadway.

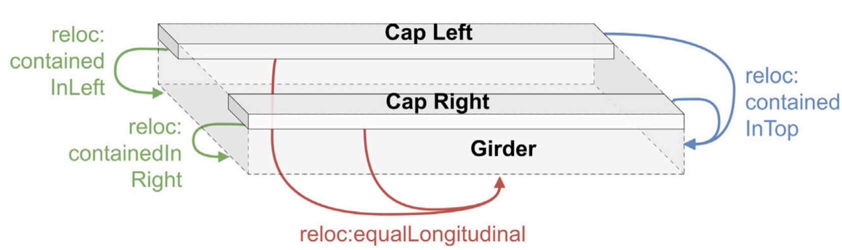

Fig. A.36. Template spatial relations of caps.

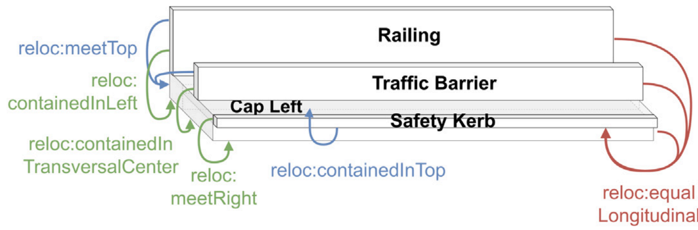

Fig. A.37. Template spatial relations of safety equipment (on the left).

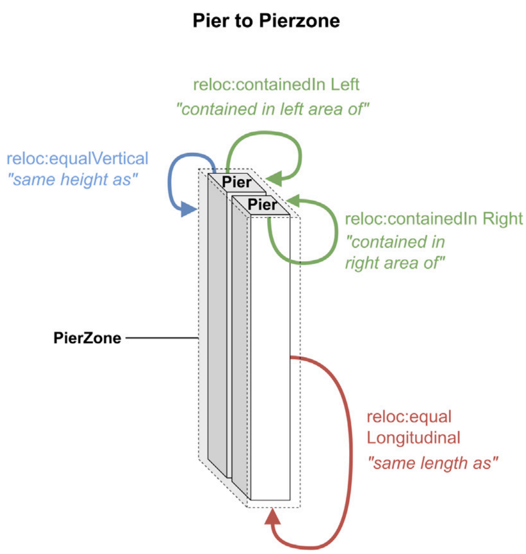

Fig. A.38. Template spatial relations of individual piers to pier zone.

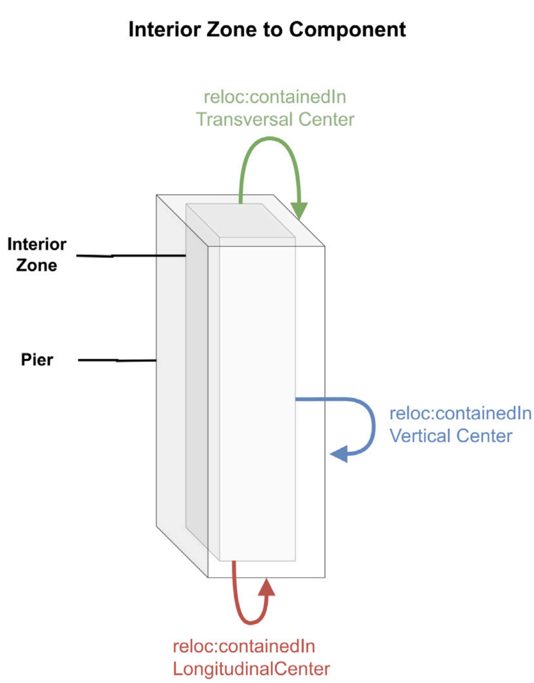

Fig. A.39. Template spatial relations of interior zones of components.

Data availability

The input and output data for UC 2 and the output data for UC 1 are available in an online repository https://github.com/Design-Computation-RWTH/BridgeGraphs_Dataset. The input data for UC 1 (BMS data) is confidential.

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