Towards a comprehensive digital twin of a road infrastructure system – Requirements analysis and System architecture

Heise I., Esser S., Borrmann A.
Technical University of Munich, Germany
ina.heise@tum.de

Abstract. Today, the management of road infrastructure relies mainly on disparate, unconnected systems, making comprehensive data analysis across different systems or subdomains, considering the interactions between them, almost impossible. The paper attempts to address this problem using a graph representation of the infrastructure data. It discusses the system requirements and proposes a system architecture based on labelled property graphs (LPG). It shows how the requirements can be implemented by splitting the overall system into different subgraphs in different graph database instances and enabling their comprehensive querying with neo4j. In addition, a graph structure is proposed, allowing the consideration and analysis of spatial relationships between the distributed infrastructure data. Finally, a case study demonstrates how the conceived system can be applied to existing German infrastructure data, showing how bridge data can be automatically queried in conjunction with traffic data for roads that pass over them.

1. Introduction

Road infrastructure plays an essential role in society, both socially and economically. It is, therefore, of great importance that the functionality of the road infrastructure is ensured now and in the future. This goal requires extensive measures, the necessity and effectiveness of which depend on the condition of the individual subsystems in the road infrastructure system and how they interact. The quality of maintenance can benefit significantly from a reliable information base which supports the choice of appropriate measures and decisions.

A digital twin represents a physical system in its current state, ensuring consistency by facilitating the exchange of information between the two counterparts, as defined by VanDerHorn & Mahadevan (2021). Hence, a digital twin seems a promising solution to improve the quality of road infrastructure maintenance.

In systems currently used for managing road infrastructure, updates to the digital representation are primarily carried out through established methods of condition recording, consisting of manual inspections with digital documentation of condition changes. These manual inspections are usually associated with comparatively long update cycles (up to several years), which can be shortened using existing approaches for partially automated condition recording or appropriate sensor technology. However, as their scalability to a large number of assets to be monitored and their large spatial extent is questionable, updates of the digital twin are assumed to be made using established methods of condition capturing.

Information from the digital twin is fed back into physical reality through short-term repair measures or the medium to long-term planning of major maintenance, replacement, or new construction projects. Therefore, a digital twin for application in road infrastructure operations is a digital twin with manual input, as is often the case with digital twins used for decision support (Callcut et al.,2021). The benefit of the digital twin thus lies in providing a comprehensive basis for decision-making for maintenance measures, resulting from cross-source data analysis through an overarching digital representation of the road infrastructure.

In the current road infrastructure management, the various subsystems of road infrastructure are typically managed separately in disconnected systems, leading to data silos that allow comprehensive analysis only on a very small scale, if at all, and only with a lot of manual effort. As a result, the individual subsystems are mostly considered in isolation, and their interactions are not considered further. Implementing a digital twin that represents road infrastructure with all its subsystems and their interactions would, therefore, greatly enhance the current management of road infrastructure.

This paper focuses on designing a digital representation for use in the context of a digital twin for road infrastructure management. It emphasises considering road infrastructure as a system of subsystems and their spatial relationships to each other. The concept is then applied to data from existing infrastructure management systems, demonstrating how the methodology can be used to query data on bridge condition development in combination with data from traffic counts of roads that run over the respective structures.

2. Related Research

As shown in Taherkhani et al. (2024), existing research exploring digital twin approaches to entire infrastructure systems is still in its infancy. The summarised studies discuss the potential and challenges of using digital twins, mainly based on the current systems and practices for this purpose. The widespread problem of inadequate data for cross-system thinking becomes evident: Broo & Schooling (2023) report on the dispersed and sometimes poorly maintained data on infrastructure management in the UK, which hinders comprehensive thinking and assessment. Based on interviews and surveys, they highlight challenges both in the interfaces between heterogeneous data and between different stakeholders with various systems in use. Heise (2023) also identifies the problem of distributed, heterogeneous data using the example of infrastructure management in Germany. The juxtaposition of specific use cases and the data required for them with their affiliation to their respective data silos once again shows the demand for flexible evaluation options for this distributed data. Yu & He (2022) demonstrate the potential of digital road infrastructure twins in dealing with disaster scenarios, resulting in a more comprehensive decision quality through a better overview by bringing together a wide variety of distributed, heterogeneous data, which also demonstrates the importance of semantically linking individual data silos.

Various methodologies for amalgamating heterogeneous data models have been explored and analysed, particularly within the Building Information Modeling (BIM) and Geographic Information Systems (GIS) integration. For example, Beck et al. (2021) and Herle et al. (2020) provide comprehensive summaries of fundamental approaches, delineating their respective merits and drawbacks. These methodologies presented are similarly reflected in the discourse on unified modelling strategies for infrastructure management. Buuveibaatar et al. (2022) delineate a solution based on the LandInfra standard, advocating for its extension to capture the diverse data models employed in South Korea to depict road infrastructure data. This proposed methodology aligns with the "integrated models" concept posited by Herle et al. (2020), wherein the substance of all data models intended for consolidation is encapsulated within a singular, exhaustive data model. However, this results in an exceedingly intricate data model that is potentially difficult to extend and handle.

Conversely, the "linked models" approach, characterised by maintaining the original data models in an unaltered state and their interconnection through semantic web technologies, has gained broader acceptance. This method presupposes the utilisation of graph-based representations for the extant data. Beetz et al. (2018) introduced okstraOWL, an ontology delineating a data model prevalent in Germany. Moreover, okstraOWL was juxtaposed with the Dutch standard CB-NL to derive concepts for linking these two standards. This examination revealed the impracticality of direct mapping due to discrepancies in the semantic structures and granularity of the ontologies. Instead, indirect linkage via queries is proposed. In an analogous vein, Marcovaldi (2018) unveils EUROTL, an ontology endeavouring to harmonise road management-related data models across Europe. Although both EUROTL and okstraOWL incorporate various types of infrastructure elements, allowing a linkage between them, they lack comprehensive strategies to describe their spatial relationships. Hagedorn et al. (2023) use existing preliminary work to transform and link existing legacy data into RDF graphs and explore their integration with other heterogeneous data resources. Although the relationships between individual infrastructure elements (in this case, bridge and road) are not explicitly considered, the web-based implementation of an ICDD structure represents a way to link distinctly structured, heterogeneous data and analyse them in a comprehensive manner. However, integrating further infrastructure subsystems with establishing the required links is rather complex, and the scalability to an entire road infrastructure system is questionable.

The works presented demonstrates developing a digital twin for road infrastructure systems presents a significant challenge due to the diverse nature of the subsystems that need to be integrated. From the research on BIM-GIS integration, it becomes evident that a graph-based approach holds promise for addressing this challenge. Although some approaches already deal with integrating heterogeneous infrastructure data, there is no concept for scalable modelling of spatial relationships between individual infrastructure elements.

3. Requirements on a digital twin for management of road infrastructure systems

Integrating different subsystems leads to specific requirements that must be matched in the respective subsystem and the overall approach. The most relevant challenges are discussed in the following paragraphs:

Scalability in terms of the size of the system to be represented: The digital representation of a road infrastructure system encompasses numerous assets across a vast area. For instance, the road infrastructure management systems currently utilised in Bavaria, a state in Germany, contain data on more than 27.800 structures and over 40.000 kilometres of road. The sheer size of the system has implications for area-wide condition monitoring methods and significantly restricts the potential applications of sensor-based approaches. Furthermore, to enable decision support based on a comprehensive overview, an approach that allows for automated evaluation of spatial relationships between the individual subsystems on a large scale is essential. This must be considered in the modelling approaches and selecting appropriate data storage systems.

Heterogeneity of the data models to be integrated: Various data models are suitable for different subsystems due to their diverse characteristics. This is evident in both existing systems (Weise & Hettwer, 2018; Buuveibaatar et al., 2022) and in research on conceptualising digital twins for infrastructure assets. In this context, a BIM model often serves as a central element for structure maintenance, as in Jang et al., 2021 and Hagedorn et al. (2023), and GIS systems are used for approaches considering entire road networks, as in Beetz et al. (2018).
Challenges arising in integrating heterogeneous data models into a comprehensive system have already been discussed extensively in research on BIM-GIS integration. Herle et al. (2020) and Beck et al. (2021) provide extensive analyses of the challenges resulting from the heterogeneity of the data models to be combined.
Based on Heise's (2023) findings, the need for linking between various sub-models depends on the specific use case at hand. Therefore, striving for *application-specific contextual linking* is advisable, as outlined in Beck et al. (2021). This approach leads to specific requirements related to differences in *timeliness, accuracy, granularity*, and *similarity*. Variations in *timeliness* occur due to differences in update cycles within digital twin contexts, particularly when correlating sensor data with less frequent inspection data and/or time-independent as-built data. Variances in *accuracy* result from the management of road infrastructure, as different institutions

specialise in specific areas, leading to perspectives with a more detailed focus on certain aspects over others. *Granularity* differences stem from varying perspectives on road infrastructure, ranging from national to specific component levels. Discrepancies in similarity arise in infrastructure management, especially when infrastructure components are simultaneously documented in different systems, as is the case in German infrastructure management, where bridge road surfaces are described in both the structure management as a bridge component and road management systems as a road section.

Distributed data storage and maintenance: The diversity of individual subsystems and the resulting variation in operational tasks has led to an infrastructure management organisation in practice characterised by specialised institutions working in different systems tailored to specific requirements. Heise (2023) and Weise & Hettwer (2018) illustrate this using the example of German infrastructure management. Luiten et al. (2018) describe this across Europe, and Buuveibaatar et al. (2022) also outline this in the context of South Korean infrastructure management. Since the variety of tasks in managing different aspects of road infrastructure will remain, the specialisation of each institution will remain unchanged, leading to the distributed management of infrastructure data. Consequently, managing distributed data will be essential for creating a digital twin for a road infrastructure system.

4. Concept

As outlined in Herle et al. (2020), techniques from the Semantic Web are commonly employed when implementing the *linked models* approach to integrate disparate systems. In our approach, we also utilise graph representations of infrastructure data. However, rather than employing the resource description framework (RDF), we opt for labelled property graphs (LPG) due to their more compact structure. Nevertheless, other graph representations for semantic data, such as RDF triples, could also be used.

To effectively capture the complexity and heterogeneity of the road infrastructure, we break down the entire system into subsystems and further into sub-subsystems. The division into subsystems also considers various perspectives in infrastructure management (described in section 3), creating units with homogeneous characteristics despite the significant heterogeneity. Each subsystem is then represented by its own graph. As a result, we establish a construct of graphs that depict road infrastructure elements at different levels of granularity, accuracy and abstraction. These graphs can be saved in diverse databases, enabling flexible management of access permissions. Furthermore, these databases can be housed in distinct management systems, allowing their hosting on various servers. The partitioning of the graph representation into subgraphs effectively meets the criteria for distributed data storage and maintenance.

To integrate each subsystem into the overall system, it is represented as a node in a graph that describes the next higher level of detail/abstraction. The contextualisation of road infrastructure assets, such as roads and bridges, is achieved through allocation to linear reference elements. Further levels of detail can be recorded for each subsystem in additional graphs, either as a subdivision into further subsystems or as a representation of subsystem-specific details.

We only model relationships between an element/subsystem and its next higher supersystem, which creates a tree structure with far fewer explicitly modelled relationships. This tree structure enables efficient filtering of objects of interest using the explicitly modelled relationships and then deriving only the necessary implicit relationships between the objects under consideration for the specific use case. As a result, the number of explicitly modelled spatial relationships is significantly reduced, thus satisfying the scalability requirement.

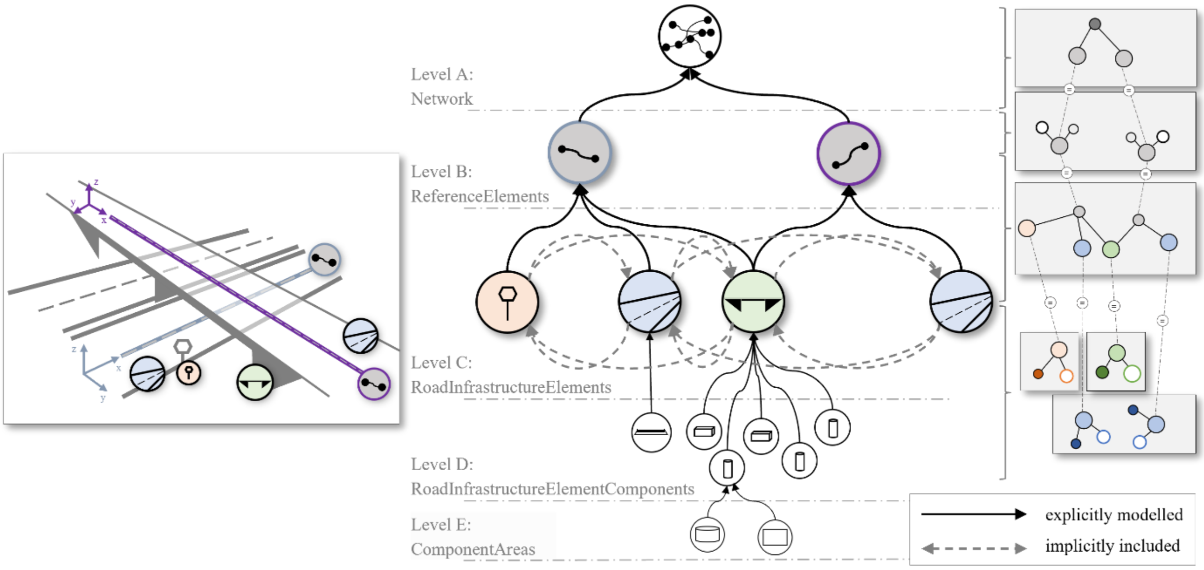

Figure 1: General Concept of a graph-based Digital Twin incorporating heterogeneous infrastructure systems with their different scales

Technical implementation

The Neo4j graph database has been chosen as the appropriate storage solution for LPG graphs. Each graph representation mentioned earlier is stored in a distinct standard database instance. An additional instance is defined as a composite database. As per Neo4j (2024), composite databases form the technical foundation for querying distributed data across multiple Neo4j instances by storing references to other database instances (constituents) as aliases instead of actual data. These constituents may or may not belong to the same database management system as the composite database. However, a query to the composite database can access all constituent databases. Therefore, if a scenario calls for a comprehensive data analysis in different graph databases, it can be achieved by sending a query to the composite database, which accesses the constituents via the aliases it contains, as illustrated in Figure 2.

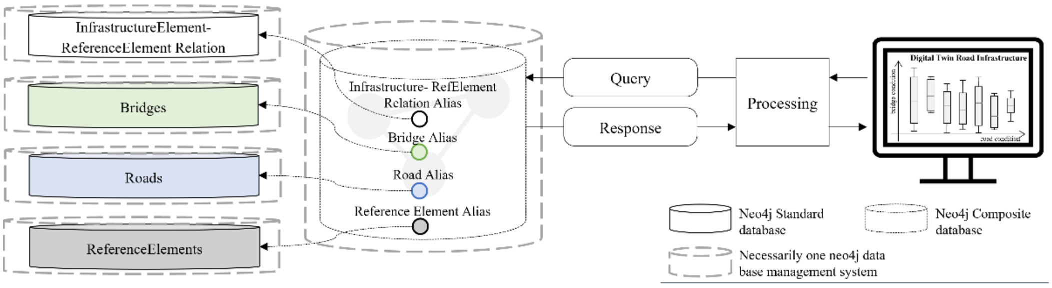

Figure 2: Proposed system architecture for implementing comprehensive use cases

Additionally, it is crucial to ensure that different representations of the same element in various graphs can be linked. It's important to note that individual nodes in LPGs do not inherently have a unique identifier, as provided by the IRI in the Semantic Web context. Neo4j addresses this issue with constraints. We have implemented two constraints for each label. Firstly, a property existence constraint requires all nodes with the corresponding label to have a property following the pattern {label name}+"_ID". Secondly, a property uniqueness constraint ensures that the value of this property remains unique throughout the entire database. This guarantees that each node can be uniquely identified by label and ID in a database.

Modelling approaches

Implementing the tree structure outlined in Section 4 requires a graph structure that ensures the derivation of all other necessary spatial relationships between the infrastructure elements of the same level by representing the spatial connections of each infrastructure element to the higher-level supersystem. This paper focuses on the integration of road infrastructure elements (such as roads and bridges) by linking them to a reference system comprising linear reference elements (levels B and C, as illustrated in Figure 1)

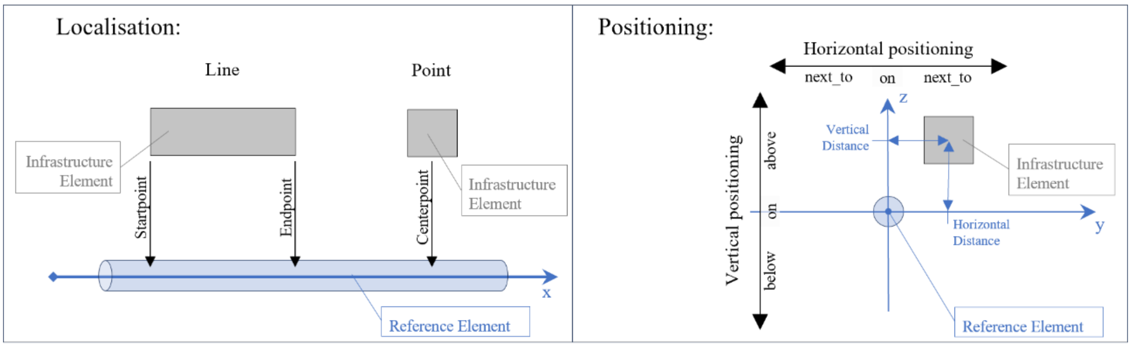

Figure 3: Concept for describing the relationships between infrastructure element and reference element

At this level of abstraction, the infrastructure elements are considered objects that occur along linear, directed reference elements. This form of structuring is more appropriately applied in the infrastructure context than a hierarchical structure, commonly employed in buildings, as it facilitates a more nuanced consideration of the impacts arising from the significant longitudinal extension characteristic of infrastructure components.

The relationship between a road infrastructure element and its respective reference element is described quantitatively as localisation in the longitudinal direction and qualitatively as positioning in the transverse direction. During localisation, the element is located according to the principles of absolute linear referencing according to ISO 19148 by specifying the distance to the start of the linear reference element. This is done either as a point object by specifying a centre point or as a line object by specifying a start and end point.

The positioning describes the position of the infrastructure element in relation to the reference element in the localised area in the transverse direction. A further distinction is made between horizontal and vertical positioning and an optional distance. The distance can be described in all positioning directions. A positive distance in the vertical direction is called *above*, and a negative distance is *below*. In the horizontal direction, a non-zero distance corresponds to the label *next_to*, regardless of whether the distance is positive or negative. A zero distance is referred to as *on* in horizontal and vertical direction. The concept is also available as a defined ontology[1] und described more in detail in Heise & Borrmann (2024).

The conversion of the data structure defined by the ontology to the LPG structure is done by modelling the individuals of each class as nodes with labels representing the associated classes. Accordingly, an rdfs:subClassOf relation corresponds to assigning a label. Individuals of the class Point are an exception. The option of assigning properties to edges in LPG allows a more compact representation, in which the individuals of Point could be modelled as an edge with a corresponding label (*Startpoint*, *Endpoint* or *Centerpoint*) and a property describing the position on the reference element. The resulting graph structure is illustrated in Figure 3 using an example of modelling the relationships between a road and a bridge and their reference elements.

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[1] https://dtc-ontology.cms.ed.tum.de/infraspatialot/index.html

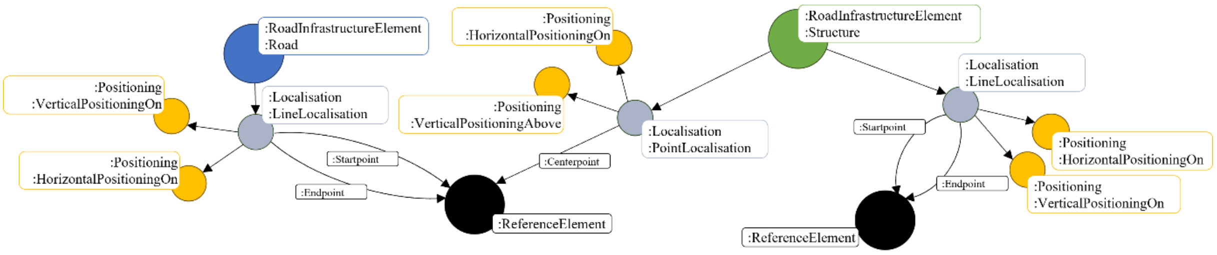

Figure 4 Graph structure in the LPG for modelling the relationships between infrastructure elements and reference elements

If, for example, all road infrastructure elements that are entirely located in a particular area are to be filtered, this would be possible via a CYPHER query according to the following (assuming that the area under consideration is located on the reference element 5526219A5526218E between the positions 150 and 200 from the reference element start):

```
MATCH g=(i:RoadInfrastructureElement)−(l:Localisation)
            -[p:Centerpoint|Startpoint|Endpoint]-
            (r:ReferenceElement{ReferenceElement_ID:”5526219A5526218E”})
WHERE (p.CenterPoint > 150 AND p.CenterPoint < 200)
      OR (p.StartPoint > 150 OR p.EndPoint < 200)
RETURN i
```

5. Implementation of an example use case on real-world sample data

With the help of the proposed concept, it is shown in an example use case how data records from traffic counts can be linked to bridge condition developments based on already existing infrastructure data from Bavaria, Germany.

The traffic volume data is linked to the corresponding traffic counting centre and stored in the road management system, built on *ttSIB*, a proprietary relational database system. Access to the data is provided through a web feature service (WFS). The main challenge lies in the lack of publicly available documentation on the data structure. Therefore, a generic approach was taken to create the necessary graph representation for implementing the proposed concept. This involved fully querying all required feature types, then automatically converting all objects from the XML response into LPG nodes and storing them in a neo4j instance called *Road_ttSIB*. The feature types were utilised as labels, the object's attributes were represented as node properties, and references to other objects were treated as edges between the nodes representing the respective objects. Figure 4 depicts a segment of the resulting graph, which stems from the objects of the feature types needed for traffic count data.

The management of bridge conditions is carried out in a separate system called *SIB Bauwerke*, which is built on a relational database system structured according to the *ASB-ING* data model. Inspections are recorded as objects linked to specific structures via a structure ID. As the structure management system only supports file-based data exchange, we obtained a copy of the database for use in the research project. We then employed SQL queries to extract the bridges and their corresponding inspections. Using this extracted data, we automatically created nodes for each bridge and inspection in an additional neo4j instance called *Structures_SIBbw*. The relationship between the structures and their associated inspections was modelled as an edge connecting the respective bridge and inspection nodes, as illustrated in Figure 4.

The *Anweisung Straßeninformationsbank (ASB)* provides the basis for creating the *InfraNetRelation* graph, which holds information about the relationship between the infrastructure elements and the respective reference elements. As a German standard, the ASB requires all data collected on road infrastructure in Germany to include a reference to the defined ASB network. The ASB network represents the German road network, including network nodes

(Netzwerkknoten) and zero points (Nullpunkte) connected by sections (Abschnitte) and branches (Äste). Sections and branches can be reference elements in the presented modelling concept. The specific implementation of this required network reference varies between the different systems used for infrastructure data in Germany.

In the case of bridges, references to the ASB network are stored as two distinct objects within *SIB Bauwerke*. The first object contains text attributes with IDs of network nodes or zero points corresponding to the ASB network. The second object describes the bridge's position in the network using numerical keys that can be translated into predefined text. This setup allows extracting the necessary information about the reference element relation for each bridge through combined SQL queries.

In contrast, the *ttSIB* itself includes a copy of the Bavarian part of the ASB network. This means that elements of the ASB network are also accessible as objects in a separate Feature Type in the *ttSIB*. The network reference of the counting points is mainly stored as a link to a section or branch object in the respective feature type. Our generic approach to representing all counting point objects and referenced objects within the counting point objects in *Road_ttSIBgraph* allows for the automatic extraction of the ASB net reference for each counting point. This extraction is achieved using CYPHER queries and allows the modelling of relationships between the counting points and the reference elements in the *InfraNetRelation* graph.

Additionally, a neo4j composite database instance has been established, allowing for comprehensive querying of the three standard databases using defined aliases.

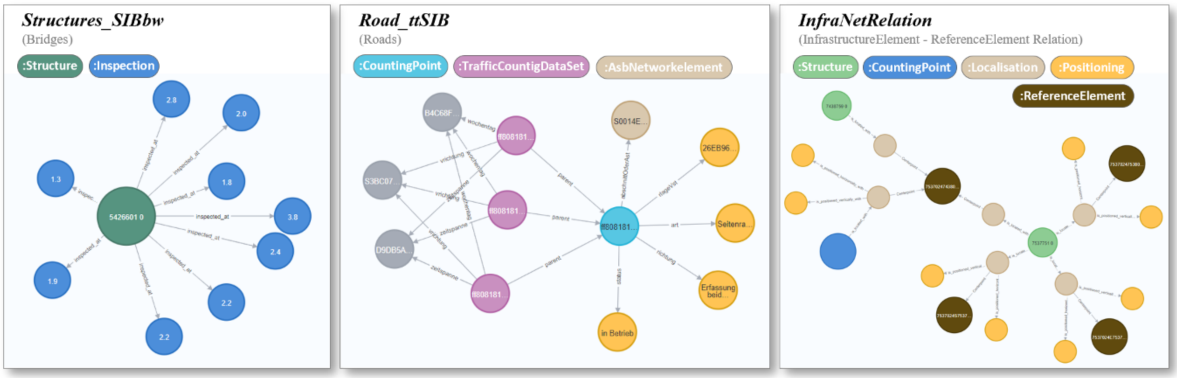

Figure 4 Graph representations established for the Use Case implementation

With this setup, it became possible to use a single CYPHER query to query all bridges (with condition information) within the Bavarian structure management system and the traffic counting points (with traffic counting datasets) that record the traffic that crosses the bridge in a linked manner. The *InfraNetRelation* graph is used to correlate *:Structure* and *:CountingPoint* nodes to a shared *:ReferenceElement* via a *:Localisation* node, thereby deriving their spatial relation from the direct connection of their respective :*Localisation* node to a *:VerticalPositioningOn* node. The data retrieved from this query allows for an analysis of the correlation between the traffic flow on each bridge and its structural condition development over time.

6. Results and Discussion

This paper presents the concept of a comprehensive digital twin for the operations and maintenance of road infrastructure systems. The approach considers the road infrastructure a complex supersystem comprising numerous interacting subsystems. The resulting challenges of heterogeneity, scalability and distribution of the data to be integrated are discussed. The concept presented attempts to find a digital representation based on LPG that takes these challenges into account and, at the same time, keeps the relationships between the subsystems in such a way that they can be analysed automatically. To achieve this, the road infrastructure is segmented into subsystems, which are then further divided into smaller subsystems, each depicted by its own graph. This approach results in the representation of road infrastructure through a series of distinct subsystem graphs in separate database instances. By running comprehensive queries on a composite database, the separate subgraphs of the individual subsystems are queried comprehensively. This enables a cross-subsystem perspective without losing the subsystem-specific aspects.

To derivate spatial relationships between infrastructure elements, linear reference elements are used for spatial structuring. The spatial relationships of the individual infrastructure elements to linear reference elements are explicitly described in such a way that the spatial relationships between the road infrastructure elements can be derived as required for the respective use case. The concept is utilised to automatically connect datasets concerning bridge conditions with datasets on traffic counts on roads that traverse the bridge. Therefore, the bridge conditions stored in the structure management system in relation to individual structure inspections and the traffic count data stored in the road management system related to individual traffic counting points are linked based on their graph-based representations. These linked data records can be used to identify correlations between the development of bridge conditions and the recorded traffic data for all bridges.

Further extensive data analyses are feasible, including linking data pertaining to infrastructure components, such as correlating accident data with bridge construction types. Furthermore, incorporating more detailed levels of granularity holds great potential. For instance, the existing German infrastructure data includes gradient information from roads, providing insights into potential low points in bridge areas, which can be linked to documentation of water-related damage on bridge components in these low-point areas. The main challenge there lies in mapping the various spatial structuring systems used within bridges, at the road infrastructure level, and across other integrated subsystems. This mapping will be a key focus of future research. In this context, the integration of not only national data models and their spatial structuring systems is of interest, but also the integration of widely used data models such as IFC, which is particularly promising due to the possibilities it offers for the axis-related description of geometry and positioning.

The approach presented in the paper has some limitations related to the availability of road infrastructure data in graph format. To address this issue, the legacy data was transformed into graph-based representations. However, the paper did not address how to effectively ensure the consistency of the legacy data with its graph-based representation. Further research in this area could enhance the approach.

Additionally, integrating other data sources, such as high-frequency changing data like sensor data stored in relational time series databases, was not considered. Approaches to integrating these data resources could extend the presented approach as well and push it toward a digital twin concept.

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