Conférence Européenne des Directeurs des Routes

Conference of European Directors of Roads

CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME

AMS FREE

Exchange and exploitation of data from Asset Management Systems using vendor free format

Final Report

Document Name:	Final Report
Version:	1.2
Date:	2022-09-15
Authors:	Stöckner, M.; Brow, I.; Zwernemann, P. (UAS Karlsruhe) Hajdin, R.; Schiffmann, F.; Blumenfeld, T. (IMC Zürich) König, M.; Liu Liu (RUB Bochum) Gavin, K.; (InGEO, Deflt)

May 2022

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Abbreviations

AMS	Asset Management System
BIM	Building Information Modelling
BMS	Bridge Management System
IAMS	Infrastructure Asset Management System
IFC	Industry Foundation Class
NRA	National Road Authorities
MR&R	Maintenance, Repair, and Rehabilitation
OWL	Web Ontology Language
RDF	Resource Description Framework
S&A	Survey and Assessment (especially for roads)
UML	Unified Modelling Language
URI	Uniform Resource Identifier

1 Introduction

1.1 Project Aim

The Conference of European Directors of Roads (CEDR) launched in 2018 as a part of CEDR Transnational Research Road Programme the call building information modelling (BIM) to improve understanding on how to access and enrich data flow to and from asset management systems. CEDR regards information as vital in order to manage their road networks appropriately. They are responsible for the complete lifespan of the network ranging from planning to design, construction and maintenance and asset management. In the CEDR Description of Research Needs (DoRN) there are two main topics of interest for CEDR: (i) Information management over the life cycle and (ii) Extensibility to legacy asset

The project should consider the output of previous CEDR projects, specifically the results of the INTERLINK-project were to. The benefit of adopting an open standard like IFC was to be harnessed together with the capabilities of new scanning/sensoring data to enrich Asset Management Systems (AMS). The combination of the strength of traditional techniques with the one of INTERLINK-project approaches based on Linked Data/Semantic Web techniques should be considered. A final point was to encourage the software industry to align their roadmap for development with the needs of CEDR members based on these results.

Based on these requirements, the AMSfree consortium developed a research approach that was contracted by CEDR for elaboration. In the point of view of AMSfree, European road administrations have well-developed decision-making systems that consider infrastructure components, i.e. roads, structures, electro-mechanical appliances, etc. and pursue the following broad objectives:

- Transparent decision-making processes for budgeting
- Consideration of longer investment periods
- Consideration of user requirements
- Consideration of the relationship between investment and long-term behavior
- Creating more resilient networks with a focus on critical corridors

The AMSFree project analysed the architecture of Infrastructure Asset Management Systems (IAMSs) used by National Road Authorities (NRAs), as well as the asset information content in current IAMSs in order to establish detailed technical requirements for linking IAMS and Building Information Models (BIMs) on a macro and micro level. The analysis is performed on a range of BIM models utilized by designers and contractors, so that the level of development (LOD) for the common infrastructure asset BIM can be agreed upon. To allow full utilization of state-of-the-art data acquisition techniques (sensors and drones etc.), requirements for existing condition assessment techniques are established and documented in an information delivery manual (IDM) for the condition assessment of assets. Based on the processes of national asset management system a generic IAMS-Process approach was developed and a related IAMS-oriented IDM was established. Extensions of existing IFC schema were developed and for linking national data formats (e.g. OKSTRA) information containers according to ISO 21597 were used. Based on this results a prototype for linking legacy databases with IFC were developed and tested with three different use cases for pavements and bridges.

1.2 Problem Definition

The fundamentals and guidelines for the implementation of Asset Management (AM) are given in ISO standards. ISO 55000 represents a rough frame with the essential core elements. An important aspect is the use of AM plans on different levels. If this is transferred to the different decision levels and task areas, strategic AM plans (SAMP), tactical AM plans and the implementation of these plans can be established. For this purpose, a desired level of service must be defined and the need for interventions (demand management) must be formulated in comparison with the actual status. Taking existing risks and available resources into account, Maintenance & Rehabilitation plans (M&R plan) , for example, can be derived together with financing plans. At the end of this process, these plans are implemented. The success of the process depends on the availability of an accurate database.

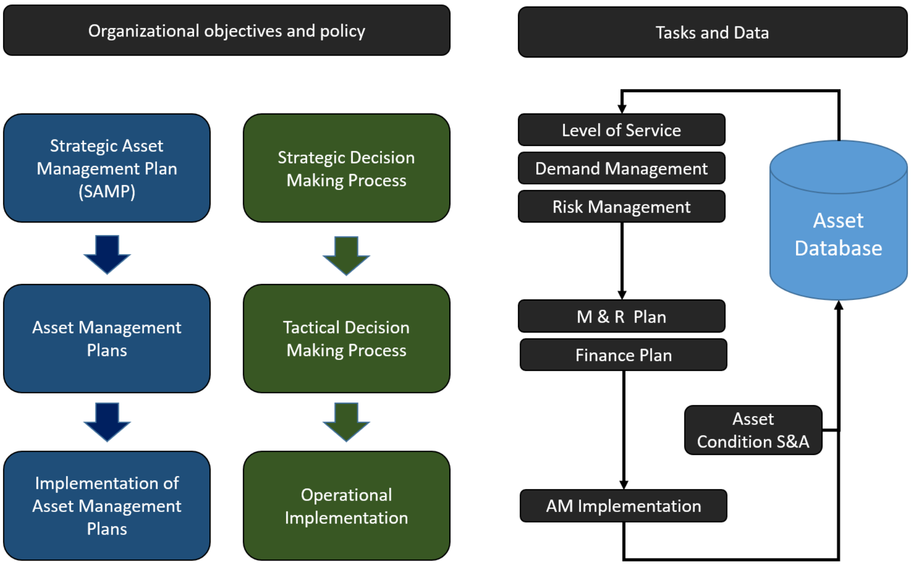


Figure 1: Relationship between AM plans, tasks and need information

The success of the AMS process depends on the availability of high-quality data. The data required includes; inventory data, condition data and data on executed maintenance intervention and their outcome. This process, which is described here in very simplified form, causes considerable problems in practical application in road organizations. There are different database systems for the different assets in the road network area exhibiting

- Different semantics,
- Different ontology,
- Different identification features and
- Different reference systems.

Another problem in this context is the inadequate transfer of data from the construction period to the operation period. On the one hand, this is due to different responsibilities, but on the other hand, it is also not precisely formulated which data should be transferred. This leads to a situation of decentralized data storage with often redundant data and unclear descriptions or even worse error-prone manual input of data on performed constructive intervention into the asset management database. A linked data concept and thus the linking of AMS and BIM seems to be a promising approach.

Since most of the infrastructure assets are existing objects, considerable potential is seen in the integration of BIM into asset management processes (Pocock et al. 2014). In one hand, the quality of decisions regarding maintenance measures can be significantly improved due to the realistic representation of the physical infrastructure objects. On the other hand, BIM enables an improvement of the existing methods of data acquisition and storage, through the seamless information exchange over the entire lifespan of the asset. In the field of transportation infrastructure, it has been shown that the subsequent merging of transportation infrastructure data that was previously collected separately from each other in different lifespan phases is often prone to errors. For transport infrastructure, the type and scope of the use of the BIM method still needs to be specified over the entire lifespan of an asset. There is a lack of uniform specifications for data exchange between the partners involved in planning and construction as well as in operation, inspection, monitoring, and maintenance planning. A general description of processes, data structures and flows within NRAs does not yet exist in a comprehensive and usable form for the application of the BIM method.

1.3 Research Approach

The aim of the AMSFree project was to develop and implement approaches to combine asset management systems with BIM. This includes concepts for exchanging linked data between Infrastructure asset management systems (IAMS) and BIM by using information containers. It includes the development of a transformation concept for data exchange between different legacy systems and a procedure for the systematic integration of existing asset data in different NRA by means of ontologies.

This final report provides a basis for data exchange between IAMS databases and BIM models. This includes the description of the proposed approach, use cases, the software and data/file formats used as well as an illustrative application of the developed concepts applied to an example road section and a bridge. It gives a detailed explanation on how to proceed as a user in updating the AMS database to physically mirror reality. The appendix includes a guideline for IFC property mapping, examples on property mapping and the IFC mapping software architecture. Therefore, this document briefly describes the IAMS and the relationship between AMS and BIM. Subsequently, the generic process and the data updates related to existing infrastructure assets are described. This method is finally illustrated in different use cases.

This report consists of seven chapters. In chapter 2 a summary of infrastructure asset management systems (IAMS) in Europe and Building Information Modeling (BIM) are described and analysed. Chapter 3 includes the state of the art regarding digital condition assessment of infrastructure.

Afterwards, concepts for data fusion and semantic transformations are described in chapter 4. The proposed approach to develop a referenced vendor-free IFC-based data structure is described in chapter 5. The elaboration of the concepts for data exchange to legacy systems is made by using information containers (chapter 6). To test and validate the proposed approach a prototype was developed and its functionality is outlined in chapter 7.

2 Comparative Analysis of IAMS and BIM in Europe

2.1 General

Infrastructure Asset Management Systems (IAMSs) currently used by National Road Authorities (NRAs) are relational databases containing the inventory, inspections and data on interventions performed on assets. Additionally, IAMSs include models to forecast future asset condition and recommend maintenance interventions and their costs. The stored data serve for maintenance planning purposes and the geometric representation of assets is limited. Building Information Models (BIM), on the other hand, include the detailed 3D geometric representation.

The use of BIM in building construction is well advanced, however, the application and maturity level of BIM for road construction is significantly lower to date. Reasons are on the one hand the limited availability of BIM-enabled software products for road construction and on the other hand the characteristics of road construction projects where the advantages of certain BIM applications (e.g., collision control) are less significant. Nevertheless, some countries have identified the benefits of using BIM in road construction and have taken steps to introduce it.

Initially, the Infrastructure Asset Management Systems (IAMS) currently used by the National Road Authorities (NRA) were examined in terms of their definitions, systems, requirements, guidelines, databases, rules and regulations. In a first approach, the approaches from the Netherlands, Sweden, Belgium, Austria, Finland, Denmark, and Germany were analysed. On this basis, the AMS of Germany, the Netherlands and Denmark were then examined in detail and the later use cases were then related to these systems.

2.2 Architecture of IAMS in EU-NRA’s

The AMS for pavements and bridges are considered in this report. In Germany, two different systems are available for each asset part, the data basis for roads is defined in the Road Database Directive ”ASB” (BMVI, 2018) and for structures in the Bridge Database Requirements “ASB-Ing” (BASt, 2013). In the following, the system for roads will be described first.

The German IAMS for the federal road network contains the results of regular condition survey and assessment process (ZEB) of the pavement surface characteristics. In the ZTV-ZEB-StB (Additional technical conditions of contract and directives for Condition Survey and Assessment of Roads) the so-called “basic data tables” as well as the structure of the “Condition Assessment File” with all necessary data contents are specified. These specifications are updated and detailed by the IT-ZEB-Standard, in which raw data formats and the data processing are described. The IT-ZEB server is used for data storage and visualisation of all condition data related to the network. Inventory data are usually stored at the end of the construction work and transferred to the road data bases of the Federal States and to the Federal Road Information System (BISStra) for the federal road network in accordance with the requirements of the Road Database directive (ASB). In this directive requirements both related the content and the quality are formulated. The proper semantic is ensured by the object catalogue for road and transportation systems (OKSTRA) (OKSTRA: original: “Objektkatalog für das Straßen- und Verkehrswesen“). For example, the IAMS for roads is composed as follows: Ideally, the section-related inventory data are saved after finishing the construction project and transferred to the road information database. The data definitions and the quality standard are defined in the ASB/OKSTRA-Documents and the IT ZEB data standard. In the operation phase, regular condition survey and assessment is performed according the ZTV ZEB as well as maintenance planning is carried out at strategic level using a Pavement Management System (PMS). These data refer from the spatial position to the specifications of the core data set of the ASB. This is followed by implementation at the tactical level as a maintenance programme as well as the implementation of construction works at the operational level. Ideally, the inventory data will be updated in the Road Information Databank after finishing the construction work. Quality level standards are carried out in the processing steps at the related decision levels.

The Swedish Transport Administration manages its infrastructure assets using several management systems. These systems cover different aspects of management in a broader sense and they are interconnected. Bridge and Tunnel Management system (BaTMan) is used for managing bridges, tunnels, embankments, support structures (with level difference on both sides larger than 1.5 m), rainwater reservoir, maritime traffic devices, height restriction portals, etc. It is an internet-based system comprising a navigation tool (WebHybris), capable of accessing the BaTMan's database. BaTMan does not contain deterioration models. Instead, some devices used for inspection have integrated deterioration models. Chaos is the Swedish Transport Administration's document management system for handling and storing road project documentation. Maximo is a web-based standardized maintenance system for management and planning of prevention and supportive maintenance. Maximo is linked with the document management system Chaos. The Swedish Transport Administration has developed the Pavement Management System (PMS) used for storing a detailed information on the condition, inspection and inventory of pavement of the state roads. Additionally, the PMS provides the history of pavement conditions. From 2019, the PMS includes the information about drainage measures.

Finnish Transport Infrastructure Agency manages the infrastructure assets using a few different systems. The system named Harja is used for road maintenance information management, whereas the Taitorakennerekisteri is used for bridges and engineering structures asset management information. The most interesting for this research project is however the system named Velho. This is a two-component system, currently in the late development phase. The first component of this system, Road Asset Information register, is an inventory database. The second component, Projects and materials, is the project and design information portal, accessible by all the stakeholders. The idea of Velho is to provide the information on the asset throughout its entire lifespan, starting from the design phase. The so-called "project-view" includes the basic information about the roads, railways, and waterways. All the information is available to all the stakeholders and interoperable with other Asset Management Systems. The BIMs stored in Velho are easily visualized here, using an external BIM tool. The "road asset view", on the other hand, enables the road asset information search, view and reporting.

The raw data from source systems is used at various levels in the organisation in aggregated form as (asset management) information. This information is contained in predefined products. Examples of these predefined products are: contracts, frameworks such as the Rijkswaterstaat (RWS) workbook, Performance maintenance plans (Prestatie InstandHoudingsPlan – PIHP's), network switching plans, programming and service-level agreements (SLAs). This asset management information consists in a coherence of data sources, functionalities and applications that will provide the desired structured storage of data and information products (Rijkswaterstaat Ministerie van Infrastructrur en waterstaat, 2018).

The main processes for Asset Management according to the Danish documents are:
A: Registration of assets, such as location, type, year of construction, etc. There will always have to be a registration of an asset, but depending on the management need, the level of detail and the use of the subsequent points B through H will vary.

B: Assessment of condition is performed and documented systematically and provides information about the condition of each asset and the entire portfolio of assets.

C: Condition based degradation models, which can specify the condition at a given time. The need for operation and maintenance is determined based on the criteria for safety, function and economics. Furthermore, scenarios can be set up for the individual asset with economic impact analyses in case of postponement and/or advancement of tasks in relation to the economic optimum time for execution.

D: Optimisation, which can identify the optimum times and types of operation and/or maintenance for the individual asset types. This comprises the safety criteria, functional criteria or financial optimality.
E: Cross prioritisation among assets is performed on the basis of statements of needs and the associated economic impact assessments. The cross optimisation is made in such a way that the resources are used in the best way possible across assets within the given grants framework.

F: Execution in the field and financial management. Performed by external suppliers after the tender; comprehensive preparation of tender documents, procurement and contracting of consultants, contractors and suppliers to assist in the execution of operation and maintenance tasks.

G: Updating of registration and condition, including coupling to BIM.

H: Follow-up and reporting, annual reports, analyses, etc.

This approach to the work with operational and maintenance tasks is at the core of Asset Management. And it should be noted, that the approach is fact-driven, i.e. on the basis of specific knowledge about our assets, their current condition and need for maintenance.

In summary, the IAMS have great similarities in basic structure, but differ in detail in engineering procedures and required data. Nevertheless, a common basic model can be formulated which will be shown in the following chapters and in particular with the later reference process and the data model.

2.3 BIM in EU-NRA's

The German Federal Ministry of Transport and Digital Infrastructure (BMVI) published the roadmap for "Digital Design and Construction" in 2015. It has invested in pilot projects to identify, in each case, the optimum approach to the application of BIM and to promote the standardization of asset descriptions. The results clearly show that important BIM applications in road construction can already be implemented. The project participants have reported positive experiences, even if certain applications could not always be implemented without problems. In addition to the implementation of pilot projects, the so-called Performance Level 1 was worked out in detail by the BIM4INFRA2020 project, which is demanded by the public sector when pocuring new projects. In order to develop the target scenario for the year 2020, a total of 20 practice-relevant use cases were identified, which are tailored to the requirements of the German construction industry. Based on the defined BIM use cases, further pilot projects were started. In addition, the BIM methodology is already being used in various DEGES projects for design and construction. (Deutsche Einheit Fernstraßenplanung und -bau GmbH). In July 2019 a BIM guide and various handouts were published. The implementation of BIM in road construction in Germany is not yet completed. In recent years, a great many experiences have been made and first guidelines have been published. The evaluation of the pilot projects has shown that further steps are necessary for a broad rollout. On the one hand, the BIM use cases must be further detailed. This includes the preparation of BIM-based tender documents. Furthermore, the actors involved must be trained in the BIM method. In addition, the technological prerequisites must be created for both the clients and the contractors. In 2020, therefore, the federal and state governments agreed to develop a master plan for the next steps and to make all the relevant foundations available to enable a phased introduction in all the federal states.

According to the Swedish Transport Administrations' strategy for digitalization (Hårrskog, 2017), Sweden has achieved a high degree of maturity in the use of BIM, so that the aspects of planning, design, investment and maintenance are included in one uninterrupted digital flow between the Swedish Transport Administration, their suppliers and the rest of society. The same strategy considers new information flows and new solutions and services generated by digitalization. Accordingly, this information is recognised as an increasingly important resource - an asset that was not acknowledged enough in the past. Currently, the information management in the Swedish Transport Administration is divided into several subject areas and processes, and coordination between them needs to be improved. The strategy points out the need for a development of an ability to handle and analyze large, sometimes unstructured, data, by regarding the information as an asset for society and providing the open data as far as possible. The Swedish Transport Administration have published the strategy for BIM (Ingemar, 2017), whose purpose is creating conditions for BIM and an efficient use of object-oriented information, based on a life cycle perspective, compliant to the Swedish Transport Administrations' processes. The strategy includes and describes the directives for how the Swedish Transport Administration should develop, adapt and implement BIM.

The Flemish Agency for Roads and Traffic (AWV), expressed the full commitment of AWV to the goal of establishing this interoperability channel (Blommaert, 2020). Except from enabling the clean communication between BIM and in-house developed AIM throughout all phases of the asset's lifecycle, the goal of AWV is to make the collected asset information available as open data afterwards and share it with all stakeholders. The AWV Object Type Library (OTL) forms the basis for the flawless integration of BIM models into the AWV's Master Data Model. The OTL specifies types of objects, their properties and relationships required by the AWV's Master Data Model, according to the corresponding constructs from the physical world. Belgium does not mandate BIM project delivery; to provide solid basis for the BIM implementation within the management system, AWV has developed a BIM protocol and BIM implementation plan for infrastructure projects. This way, required uniformity of BIM models is ensured. The accompanying BIM implementation plan provides the project-specific implementation guidance.

Through the Velho system, Finnish Transport Infrastructure Agency enables information flow between BIM and IAMS. This is implemented in accordance with the open BIM concept, by following the requirements and guidelines of InfraBIM, the infrastructure section of the Finnish chapter of BuildingSMART International. The document "Common InfraBIM requirements YIV" (BuildingSMART Finland, 2019) thoroughly specifies the required BIM content for handover. The main content includes the as-built model, as-built drawings, quality assurance material, and related documentation.

2.4 Asset information content

The content of currently used IAMSs across Europe is analysed by focusing on infrastructure asset management requirements, data requirements, and Object Type Libraries (OTLs). Asset management requirements are analysed with regard to the different construction project phases and the corresponding stakeholders. Data requirements, on the other hand, are firstly analysed in terms of type and structure. To identify and evaluate the general dataflow, business processes used in infrastructure asset management are analysed.

2.4.1 Infrastructure asset management requirements

In the planning phase, an infrastructure asset 3D-Model is created using BIM. The use of technology allows for a more accessible, yet centralised, storage space of data in comparison to the use of only reports, sketches and drawings. Ideally, the 3D-Model is to be created based on standardized OTL and data formats. This is to guarantee the interoperability and availability of the model across different software as well as across country borders.

In the construction phase, the construction manager must outline the differences between the planned asset and the built asset. Based on this documentation the “planned” DT can be updated to an “as built” model. This “as-built” model is moved to the IAMS. However, there is not always a clear link in how to automate the transition of data from a BIM model to an IAMS.

In the operation phase the information model is particularly important. The operation encompasses monitoring of the asset’s performance as well as prediction of its future performance. Here performance is understood as the condition state of the asset. For an IAMS, the relevant asset data is collected and stored and utilized for further analysis. By using BIM, more specific prediction models may be developed as described in (Isailović, et al., 2020). The monitoring procedure is dependent on the granularity of detail used by the prediction models. State-of-the-art inspection products already allow for localised damage classification.

In the maintenance phase, the data is fed back to the IAMS to know the impact of the maintenance measure on the asset’s performance.

In the demolition phase, the object’s lifespan ends, thus it must not be used any longer for current network analyses. It can be valuable for maintenance planning purposes to retain the data in the database to understand the deterioration dynamics of all assets. However, upon demolition, the data should be archived.

2.4.2 Data requirements

The analysis has shown that all data in IAMS can be roughly categorized into either alphanumeric or geometric and geo-location data. The alphanumeric data stands for all the information in IAMS that can be meaningfully described in the alphanumeric format (e.g., condition rating, material properties). Traditionally, this type of data was the only format used in legacy IAMSs. It is conditioned by a relatively rigid structure of a relational database. IAMSs provide geo-location of the asset in a form of terrestrial coordinates of a country-specific standard coordinate system, usually by means of a GIS tool. In addition, a linear coordinate of the asset (i.e., chainage) is usually provided, and sometimes the location relative to the key elements of the network. The asset’s geometry, although essential for the visual perception of an asset and its condition, is introduced to current IAMSs in a rather inefficient manner, by referencing CAD or scanned drawings.

Currently adopted business processes in IAM, or at least the business process scenario, assuming the higher BIM maturity, is thoroughly analysed in (O’Keeffe, et al.2017). The handover of as-built asset information from the building contractor to the asset manager is found to be the least efficient process in the infrastructure asset information lifetime. The inventory databases of common IAMSs are usually based on the asset type and not interconnected.

The further analysis showed that IAM process is not always homogenous across different organisations. Accordingly, this applies to the exchange data too. The inventory and inspection data, as well as the exogenous data (e.g., weather condition, moisture, and precipitation), and the condition rating vary between different NRAs. For the purpose of this analysis, the pavement condition indicators from Germany, Switzerland, Austria, the Netherlands and the United Kingdom are compared.

2.4.3 Object Type Libraries (OTLs)

As a way to clearly specify the structure and content of IAMS, some NRAs use Object Type Libraries (OTLs). An Object type library, or dictionary, represent a structured collection of object type definitions, their properties and relationships. It can be delivered in various forms, ranging from a simple table to a linked data model. OTLs eliminate problems caused by inconsistency in terminology and semantics. Thus, many NRAs recently started developing such collections. Moreover, the INTERLINK project proposed the solution for a universal European

OTL. In the integral report, a detailed overview of a few national OTLs, as well as the INTERLINK proposal is provided. Here, just a glimpse of this overview is presented.

The Swiss Federal office for roads (FEDRO) categorizes the inventory, inspection, and maintenance data by means of so-called catalogues, which strongly resemble object type libraries. Catalog entries are identified by two attributes: HierarchyCode and SelectionCode. HierarchyCode is a numerical unique identifier of the catalogue item, determining the entry position in the hierarchy of the catalogue. SelectionCode defines the selectability of the entry.

The German 'Objektkatalog für das Straßenwesen' (OKSTRA) is an object-oriented road modelling approach specifically for road objects. OKSTRA has been extensively documented and its potential structure and object's relations with other objects using UML diagrams. The catalogue extensively defines what objects' relations to other objects are, as well as what values the objects' attributes may have. So that an IAMS conforms to OKSTRA's standards, the required related objects need to be included in the IAMS.

The Dutch NRA, Rijkswaterstaat, established an object type library which is independent of the project and contains both object and category-specific information that can be referenced by a building model (Hoeber et al., 2015). The library covers motorways and waterways and specifies for the contractor the scope of information that has to be provided in the project. In total, the RWS-OTL consists of more than 7000 concepts, which are linked via about 10000 object relations and about 22000 specialisations (Beetz and Borrmann, 2018). The RWS-OTL makes a strict distinction between functional entities and physical objects and between seven levels of detail in the description of roadways, which are largely based on the Dutch standard NEN2767-4 and adopt the terms defined there.

AWV OTL is the Flemish object type library of all road infrastructure objects. AWV OTL provides unambiguous definitions of all object types, their properties and mutual relationships. In addition, the AWV OTL includes elements representing functions of objects, as well as the ones representing the object life cycle. The OTL comprises the Vocabulary and a Master Implementation Model. The Vocabulary provides the unambiguous definitions of elements included in the Master Implementation Model, thus explaining their meaning. Each element has a unique URI which cannot be changed once the OTL is officially established. For the more convenient usage, the Vocabulary is divided into several parts, describing the nature of an element.

As explained by Jackson, 2018, the establishment of a universal OTL, unifying object type classifications of different NRAs, is a cumbersome task. However, INTERLINK suggested a reversed solution, by proposing a universal framework for the OTL establishment for NRAs. By following the INTERLINK roadmap, object type definitions from each two newly established OTLs are likely to directly correspond to each other. INTERLINK established a unique ontology, named European Road OTL, or EUROTL. The ontology includes expressions and concepts used in infrastructure asset management. Ideally, the OTL is general enough to correspond to a variety of differently defined and understand terms.

2.4.4 Analysis of the content of common infrastructure asset BIM provided by designers/contractors – Level of Development (LOD)

Currently, BIM models are usually created in the design phase and used in the construction phase to create an as-built model. Because BIM is a relatively new technology, few workflows and information requirements have yet been systematically defined by national authorities. For this reason, contractors have tailored their own workflows and Information Delivery Manuals (IDMs) based on the experience gained from using older CAD tools. As a result, the heterogeneous content of the BIM models is highly dependent on the engineer's experience. Therefore, IDMs are described rather informally or are not documented at all. This makes the analysis of the various IDMs currently in use a challenging task. In the following, general concepts for the definition of information requirements and the related level of developments (LODs) are described.

The exchange of data and information between all project participants is very important for the use of BIM. The participants must have a common understanding of the models and the model elements. The information requirements are defined at the beginning of a project. The level of development (LOD) defines the information content of model elements to be delivered at a certain point in time, phase or use case. LOD definitions are needed for information management throughout the entire life cycle of a building, including strategic planning, preliminary design, construction, operation, maintenance, modernization, and demolition. However, the term LOD is not yet uniformly defined.

A new standard (EN 17412) for LOD is currently being developed in Europe, which describes the scope and level of detail of the information exchange in terms of geometry (LoG = Level of Geometry), information (LoI = Level of Information) and documentation. The EN 17412 specifies the concepts and definitions for determining the level of information need (LOIN) and information delivery that are part of the information exchange processes during the life cycle of buildings when BIM is applied. These concepts and principles can bring significant benefits to all parties involved in the different phases of the building life cycle by providing a common understanding of the right level of information needed at any given point in time, thereby preventing both costly overproduction and risky underproduction of information. Information sharing ensures that the right information is delivered for the agreed purpose, facilitating verification and validation processes. However, the term LOIN is not yet widely used and EN 17412 has not yet been applied in projects. For these reasons, the term LOD will continue to be used in the following.

LOD classification is based on the project development of the infrastructure. As the project progresses, more details of the model elements are required and the level of detail increases accordingly. Although there is no uniform definition for the classification of LOD, the structuring from LOD100 to LOD500 is very often used.

When defining the project-specific LODs, it should be noted that parts of these specifications are only made during the project and in cooperation with the engineering office and/or the construction company.

1. Definition of the BIM objectives in the project
   - Derivation of use cases
   - Definition of delivery timelines
   - Data formats of the results output per use case

2. Description of the model
   - Use of the model
   - Definition of the model structure

3. Determination of the LOD
   - Designation of model elements with a deviation from the LOD definition
   - Designation of the model supplier

The following basic principles should be observed when defining or using a LOD.

With regard to LOG:

- The model elements are only provided with the geometrical information required for the respective application and the current design phase.

- The geometrical accuracy must meet the requirements of the design phase and the design documents to be achieved.
- It should be possible to generate 2D plans from the model with appropriate modifications.

With regard to LOI:

- The information must meet the requirements of the use phase
- Information from earlier design phases should be transferred to subsequent phases

In consequence, the "as-built" model may only contain information that is necessary for operation and maintenance. It is the asset manager's responsibility to define the necessary information. Any information beyond that must be removed from the model and archived.

The analysis of existing documents describing LODs in the national authorities has shown that LODs ranging from LOD 100 to LOD 500 are often used. However, the definitions and detailing are very different. The survey has shown that there is no uniform LOD definition for an as-built model (LOD 500).

3 Digital condition Assessment

3.1 Current condition assessment techniques

Whilst decision-making frameworks used by infrastructure owners are very well developed, a fundamental problem remains that the hazard assessment, which is at the heart of the process is over-reliant on visual inspection combined with some local damage detection measurements. As a result the assessment is qualitative and somewhat subjective. (See Phares et al. 2004). This leaves the system vulnerable to extreme events and unprepared for future challenges. A number of innovations, e.g. in the application of drones, deployment of sensors and automatic high-speed scanning of pavements/structures are currently being developed by road owners. These techniques can provide large amounts of high-quality data on the condition of an asset. The primary aim of this project is to manage the data in such a way that it can be used to provide hazard assessment. This chapter summarises some of the most promising techniques used to collect the data.

3.1.1 Existing Methods for damage assessment

Visual inspection and NDT provide snapshots of the condition of an asset assessment whereas Structural Health Monitoring (SHM) is used to continuously monitor some degradation process. In many cases it should be borne in mind that many SHM techniques are developed for a single purpose and provide no data on other potential processes. The specific uses include; Concrete shrinkage, substructure settlement or rotation, cracking and rupture of tendons or cables. In addition, Weigh in Motion (WiM) technologies are designed to determine real load data. One of the main advantages of SHM is that it allows model updating, based on comparison with a computational model validated to the condition at a fixed time (e.g. the start of monitoring). Many reviews of technologies mix SHM methods with those that are used in routine damage detection studies. This is in-part because some of the techniques, e.g. GPR, Acoustic Emission etc. can in-fact be used for both in snap-shot damage assessment and also in monitoring degradation process, e.g. SHM. For comprehensive reviews of methods to determine material properties the reader is referred to comprehensive reviews e.g. NPRA (2005), Gastineau et al. (2009).

Ground Penetrating Radar (GPR) is a non-destructive method of subsurface imaging using electromagnetic radiation. Ground Penetrating Radar is routinely used to examine the general deterioration of concrete, particularly in bridge decks by comparing periodic surveys (Yehia 2007). GPR data allows identification of the locations of cracks, voids, delamination, and corrosion. It can also be used to map reinforcement in concrete elements with Hugenschmidt and Mastrangelo (2006) demonstrating that a very high frequency (2 GHz) antenna could determine the location and cover depth of reinforcing bars and the pre- and post-tensioning cable trajectories in bridges. GPR is also useful in the measurement of thickness of asphalt and unbound pavement layer thicknesses for quality control and quality assurance Pitonák and Filipovsky (2016), for determining damaged areas in embankments including ballast fouling, burrows, and the water content of the soil, Kovacevic et al. (2017) and to identify progressive failure due to settlement beneath embankments, Donohue et al. (2011).

One disadvantages of GPR is that the data analysis is complex and subjective. Bianchini Ciampoli et al. (2019) describe a multi-stage quality assurance procedure that comprises; raw signal correction, removal of low-frequency harmonics and antennae ringing, signal gain and band-pass filtering. Park et al. (2018) considered the problem of object detection in urban roads where signals are often weak and noisy and propose a novel a phase analysis technique to address these weaknesses. The proposed method allows the operator to objectively determine the location and nature of an object. A field test demonstrated the method could locate and identify cavities, pipes and gravel pockets in an urban road environment based on whether a signal is in or out of phase and the phase change ratio. For example, the cavity which has low permittivity has a reflection, in phase with the direct wave, whilst the metallic pipe is out of phase, see Figure 2.

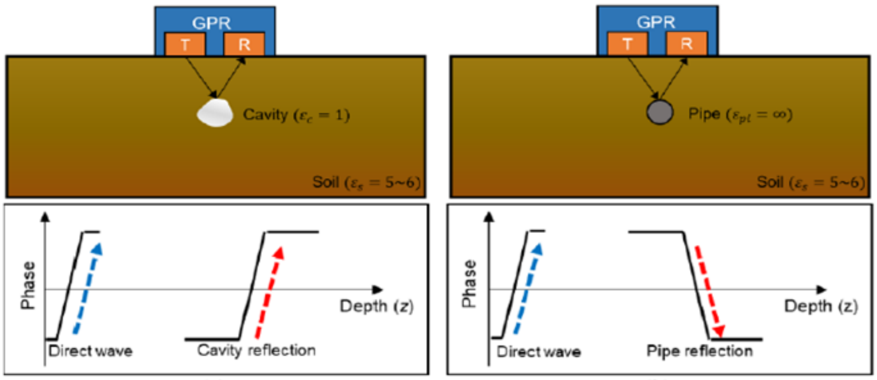


Figure 2: Phases of reflected waves from objects (a) in phase for cavities and (b) out phase for metallic pipes

Hugenschmidt (2002) and Anderson et al. (2007) used floating antennae placed on the surface of the water to show that GPR is a safe and effective way to observe scour near bridges, where the GPR tool does not need to be connected to the river bed. This is particularly useful during peak flooding times, as it allows time for preventative action to be taken. Anderson et al. (2007) prove in addition the system is capable of identifying in-fill features. For a comprehensive review of GPR applications in Civil Engineering, See Wai-Lok Lai et a. (2017).

The impact-echo method is a non-destructive method for measuring the depth of structural members and concrete road slabs using impact generated stress (Sansalone and Streett, 1998). The surface is struck with a round sphere, and the frequency (Hz) of the response is measured. From this frequency, the depth of the slab can be calculated. If the calculated depth is not equal to the actual depth of the slab this indicates that a defect such as delamination is present (Sansalone 1993) and allows the depth to be calculated (Yehia et al. 2007). The impact-echo method is commonly used on bridge decks to detect abnormalities during routine checks however, it also has applications for flaw detection in highway pavements, buildings, tunnels, piers, dams, seawalls and other structures. The test results also allow three-dimensional maps of a deck to be visualized (Gucunski et al. 2006 and Yehia et al. 2007).

Infrared Thermography (IRT) is a process in which a thermal imager is used to detect emitted heat from an object, converting it to temperature and generates an image of the distribution of temperature in the object. It can be used as a method of scanning concrete for subsurface flaws, and typically is used for assessing concrete decks. Marchetti et al. (2008) performed laboratory experiments to show the technique could identify damage (laminations) in road structures. Advantages associated with infrared thermography include rapid, easily interpreted results as well as the equipment being portable. Thermography can also be carried out with minimal traffic delays, particularly in comparison to other methods of investigating subsurface structures such as chain dragging (Maser et al. 1990, Yehia et al. 2007). However, they note there are also several drawbacks associated with using infrared thermography, particularly that variation in surface texture and debris can cause changes in intensity. Additionally, if the concrete has been overlaid by asphalt, this can lead to misleading results. Weather conditions and air temperature also need to be considered, as both of these factors affect the radiation emitted from the bridge deck (Maser et al. 1990, Yehia et al. 2007). Furthermore, if water occupies the voids rather than air the voids will not be detectable. Haisa (2016) performed a combination of lab and numerical analyses to determine the optimum period to perform an IRT survey to minimize errors due to ambient temperatures and concluded that surveys should be conducted at night-time.

Acoustic emission (AE) describes the phenomenon of the propagation of sub-audible waves due to permanent changes in a material due to energy release. In soil, many slope failures develop over-time and movements along the frictional shear plane mobilized during soil failure and as a result of rock displacement along existing discontinuities and the generation of new fractures will result in energy release some time before failure. As a result, monitoring of acoustics emissions can provide vital information on incipient failures. In concrete and other man-made materials, the release of stored elastic energy or redistribution of stresses caused by loading, chemical reaction or other potential damage processes can also be recorded. Codeglia et al. (2017) describe the deployment of an AE based monitoring system for rock falls capable of producing real-time warning of ground movements, see Figure 3. Worley et al. (2019) describe a lab and factory-based study of the application of AE for crack monitoring in concrete bridge girders. Mednis et al. (2000) used acoustic methods to detect major road surface defects such as bumps and potholes. Kongrattanaprasert et al. (2010) and Zhang et al. (2013) demonstrated that raveling, bleeding and road smoothness could be detected by microphones placed near the wheel and even alongside the roadway. Fedele et al. (2017) used microphones embedded in a pavement to record vibro-acoustic signals from passing traffic. Analysis of output allowed information about the presence and the severity of cracks to be determined.

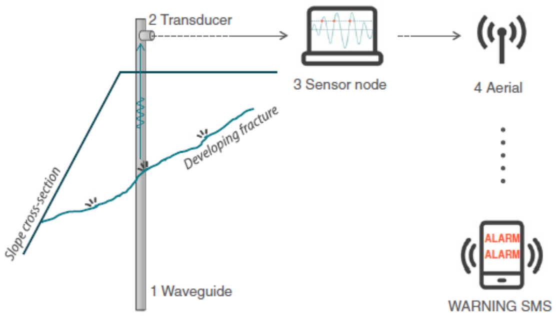


Figure 3: Simplified concept of an acoustic emission monitorin system deployed in a rock slope, after Codeglia et al. (2017)

Accelerometers record acceleration at a given instant allowing and sampling at high frequencies is possible. Following numerical integration, a displacement (or velocity) history can be obtained. They are available as relative low-cost sensors that can be attached to a structure and most modern phones and vehicles also collect acceleration data that could be useful in infrastructure monitoring. Bahrani et al. (2020) conducted laboratory and field experiments to test whether accelerometers and or geophones could be used to provide continuous measurement of the deflection of pavements under real traffic loading. Field tests were performed using two accelerometers and two geophones embedded in the IFSTTAR accelerated pavement testing facility, See Figure 4a. The geophones and accelerometers provided deflected shapes that were very close to those recorded by the reference anchor deflectometer across the range of vehicle speeds considered, see Figure 4b.

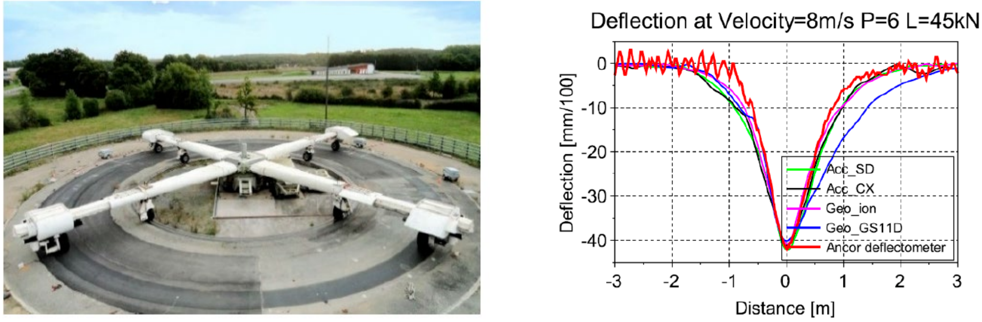


Figure 4: (a) IFSTTAR accelerated pavement testig facility and (b) Comparison of pavement deflection between deflectometer, geophone and accelerometer after Bahrani et al. (2020)

Lekshmipathy et al. (2020) investigated the use of vibration measurements made using a smartphone (collecting accelerometer and gyroscope readings) to detect damage including uneven surface (bumps), cracks and potholes on ten study roads located with the campus of National Institute of Technology Tiruchirappalli campus, India. The ability to identify defects was compared to a vision-based system. The accuracy of the vibration and vision methods was 90% for detecting potholes, see Figure 5. the vibration-based methods detected 100% of bumps, whilst the vision method could not detect these. The vision-based method detected 76% of cracks compared to 10% for the vibration-based methods. The authors note that the vision-based method has the disadvantage that post-processing was computationally expensive.

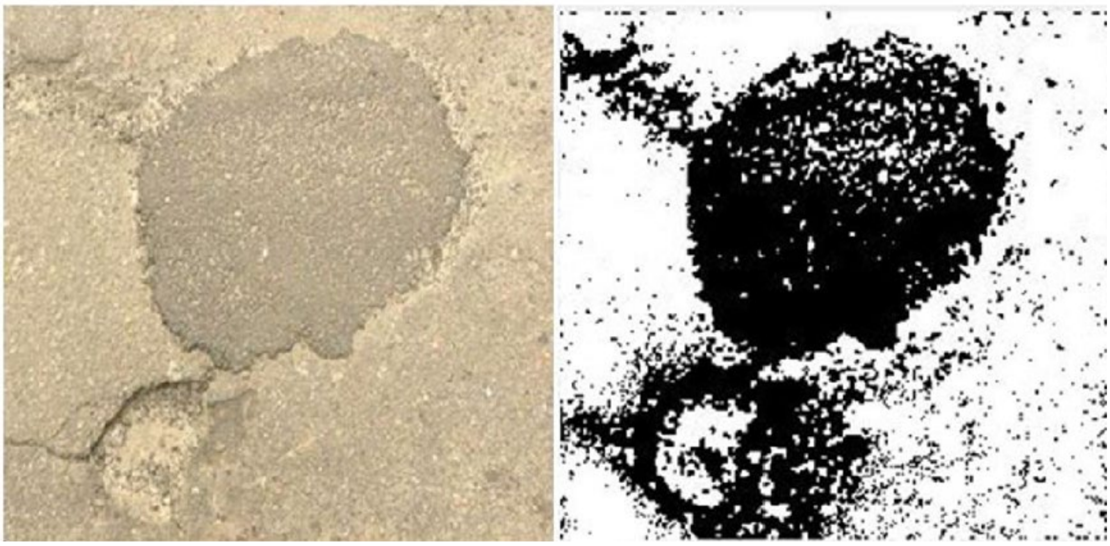


Figure 5: Vision-based detection vehicle (after Laksmipathy et al. 2020)

Prendergast et al. (2013) report a field trial performed to track the change in natural frequency of a foundation pile due to the occurrence of bridge scour. A simple 1D soil-structure interaction model was able to capture the scour process. Accelerometers placed at strategic locations of a bridge, coupled with such a simple 1D model were shown to be an effective early warning system for scour problems. In order to assess potential of the method in real-world conditions Prendergast et al. (2016a, 2016b) developed numerical models to investigate the impact of scour at the central pier of a two-span integral bridge on the natural frequency response. he work considered the sensitivity of parameters such as vehicle speed and mass, road surface roughness and the impact of sensor noise on the vibration response. The work suggested that monitoring frequency changes showed potential to detect scour. Prendergast et al. (2017) further developed a novel Vehicle-Bridge-Soil Interaction (VBSI) model to generate realistic acceleration signals from the structure due to a two-axle truck travelling at typical highway speeds (80 km/hr.). Kariyawasam et al. (2019) deployed a vibration-based monitoring system on the Baildon bridge in the UK, a 20m wide, 3–span concrete highway bridge in the UK, that had suffered scour damage of up to 1.8 deep as confirmed by diver inspections and sonar scanning. A field experiment was conducted in which the bridge response was monitored as the scour holes were filled-in (scour in reverse) was recorded. A numerical model suggested that the natural frequency of the bridge would vary between 0.14 and 0.54 Hz during filling of the scour holes. Analysis of the vibration data with a peak picking method and frequency domain decomposition gave a measurement error of 0.6-0.8 Hz. As a result, the resolution of natural frequency measurement was too low. However, there was a clear change in the mode shapes and power spectral density (PSD) of the accelerometer data for Mode 2 (Pier and deck Bending) during the repair phase between August and November, See Figure 6. In contrast the PSD of Mode 1 (1st sway mode) remains unchanged over the period, albeit with some noticeable outliers.

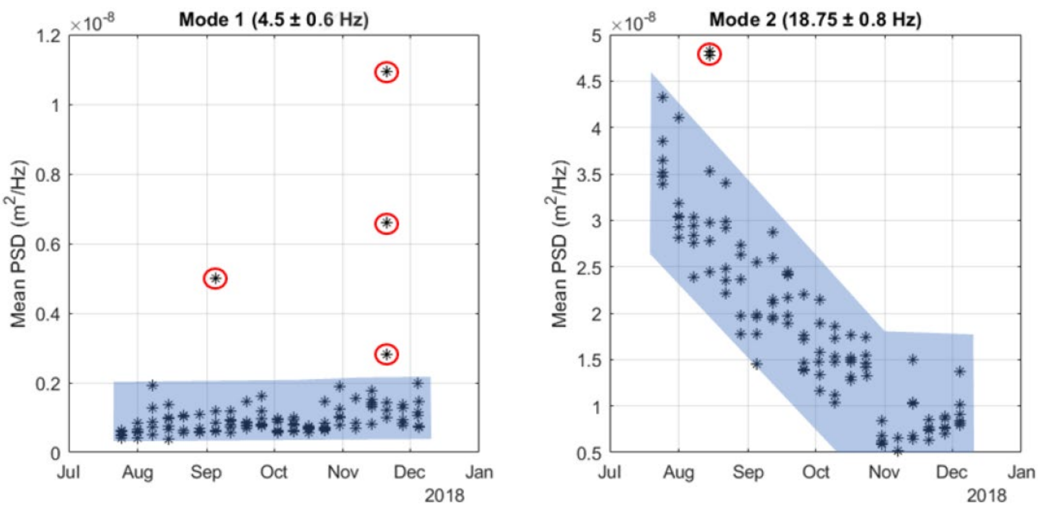


Figure 6: Mean PSD of vibrations measured on the South Pier of Baildon bridge during scour-hole filling (from Kariyawasam et al. 2019

3.1.2 New technologies and examples of their application

Recognizing the limitations of visual methods a number of workers have attempted to use digital image processing of data collected using optical techniques. Optical sensors can be classified as either active or passive. Active sensors emit energy and record reflected signals in order to provide depth information. Passive sensors use ambient light to capture information that can be post-processed, See Fathi and Brilakis (2011). Active systems include using Terrestrial Laser Scanners (TLS), infrared scanning (IS) and imaging with Red-Green-Blue-Depth (RGB-D) whereas passive approaches use close range photogrammetry (CRP), See Poposecu et al. (2019). Adhikari et al. (2013) note that 3D point clouds can comprise millions of 3D points with millimetre level accuracy. These allow the development of primitive 3D models facilitating measurement and graphical representation of the scanned object. Early applications of the techniques were in the development of geometry models of historic arch bridges, See Figure 7 (Truong-Hong and Laefer 2014). By combining TLS with GPR Lubowiecka et al.

(2009) provided information on internal structure of a historic bridge (including fill, layering, inclusions etc.).

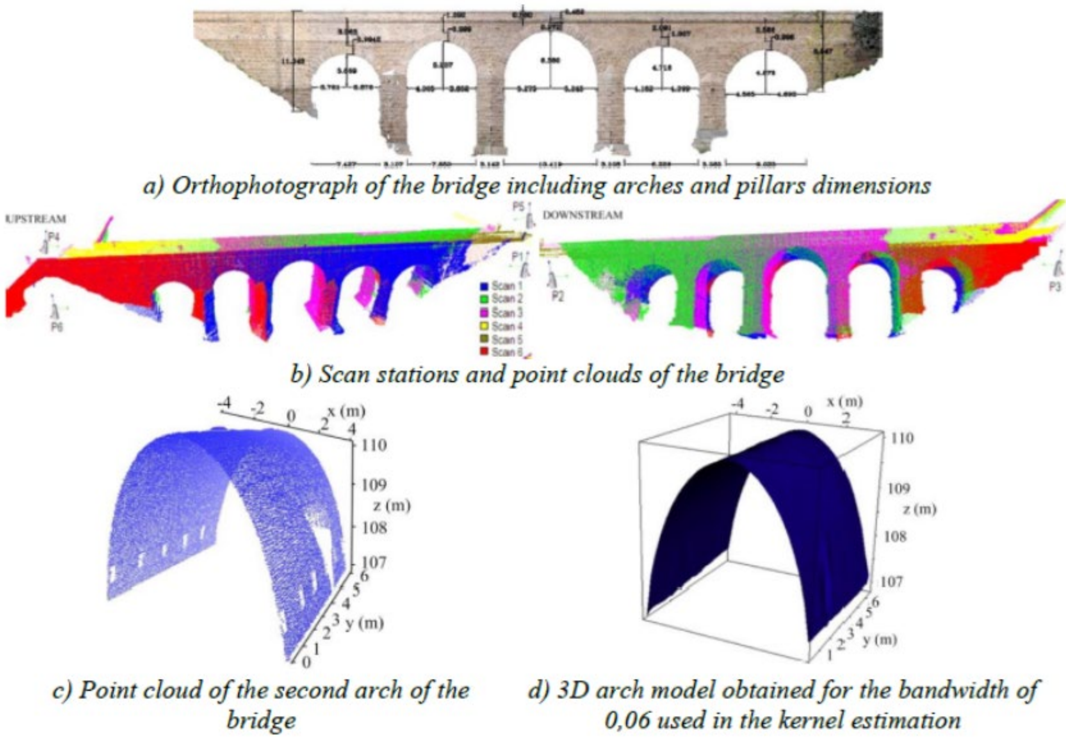


Figure 7: Development of historic archbridge models after Armesto et al. (2010)

The TLS technique has also been used to determine vertical deflections under load and clearance available under bridge soffits. The application in a number of damage detection studies showed that TLS can provide excellent data on spalling and cracking of concrete (Truong-Hong et al. 2016), with the capability to identify cracks as small as twice its sampling step. However, limitations include the high cost of equipment, limitations to full 3D scanning because of line of sight and the requirement to set-up on flat, stable terrain.

As laser scanners create a record of spatial information of the bridges, the addition of photogrammetry allows additional information that is typically obtained from inspections. Jáuregui et al. (2006) demonstrate the creation of a 3D bridge model from still photographs using QuickTime Virtual Reality. Poposecu et al. (2019) compared three optical methods (TLS, CRP and IS) for creating 3D bridge models for a database of six railway bridges in Sweden. The authors created a 3D model of each bridge, first comparing the level of detail captured, See Figure 8In general, the models created by TLS provided the highest level of detail with IS providing the lowest. The main dimensions, span, height etc. were captured by all methods. However, since the photogrammetry-based methods collected RGB data, more natural visualization was obtained.

Figure 8: 3D Models of Kallkallevagen bridge – showing different levels of detail obtained between TLS, CRP and IS (from Poposecu et al. (2019)

The ability of photogrammetry to allow real-time damage detection was investigated by Jahanshahi et al. (2011) who deployed a fixed camera system for bridge inspection using a Canon PowerShot A610 that was capable of measuring crack widths of 0.57 mm for a camera 3m from the target. A drawback of these systems is line of sight, the need for the camera to be relatively close to the target and the cost of installation and maintenance. Lueker and Marr (2014). Chen et al. (2019) present a case study where a low-cost drone was used to scan a bridge and allow a subsequent inspection using a 3D model of the bridge. Specifically, the paper deals with data acquisition, model reconstruction, and data quality determination. The methodology is applied in a scan on the Boyne Viaduct in Ireland, where the UAV scan performed using a DJI Phantom 4 with a 12-megapixel digital camera was compared to a TLS scan performed using a Leica Scan Station P20. The TLS survey only covered the side of the bridge as it was not possible to obtain access to the live rail line on the bridge deck. The 3D model was created from 153 images using Photoscan software. A series of data evaluation methods were proposed to quantify the point cloud performance in data completeness, density distribution, outlier noise level, surface deviation, and geometry accuracy. The authors concluded that the UAV offered significant advantages in data coverage, equipment cost and surveying time. However, challenges remain with regard to lower geometry accuracy than TLS and the long post-processing times required.

Isailović et al. (2020) present an approach for using point cloud data to detect spalling damage on bridges and further integrating damage information into a BIM model by semantic enrichment of an as-built IFC model. The steps required, See Figure 9 include (i) Validation of the point-cloud data using either as-designed or preferably as-built mode.

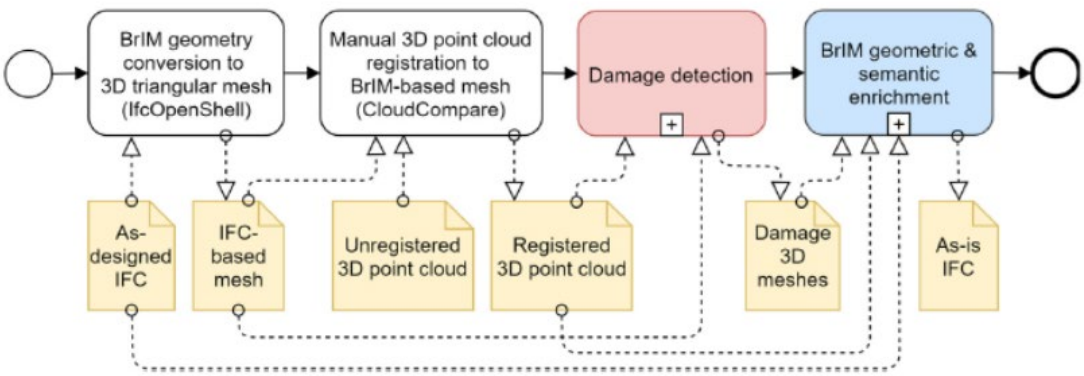


Figure 9: Methodology for detecting damage from point cloud data and incorporation as semantically rich data in BIM model of bridge (Isailović et al. 2020)

Guisado-Pintado et al. (2018) compared the efficacy of creating 3D maps for creating ground models of beach-dune zones using a drone and terrestrial laser scanner. They found both methods provided good topographic information with total survey times being lower for the UAV. Kim et al. (2015) presented a study on the use of a camera-based UAV system for concrete bridge surface crack detection. In their research, a morphological algorithm was designed for detecting and measuring crack widths, which resulted in a highly variable error (3–50%). However, in this fast-changing field, significant improvements occur frequently in terms of both hardware and software. As an example Oats et al. (2017) used a thermal camera for subsurface delamination and detection of damage in concrete. In their case study, they generated thermal and visible images for a 968 m2 area, from which 14 m2 of delamination was identified, which is an overall accuracy of about 95% compared with direct contact hammer sounding data.

InSaR

Space-borne Synthetic Aperture Radar Interferometry (InSAR) uses electromagnetic imaging of surface of the Earth collected from satellites to monitor relative deformations. The technology initially had resolution problems that meant it was most suitable for monitoring large-scale processes such as landslides and tectonic activity (Colesanti and Wasowski 2006, Colesant et al. 2003). Recent developments in the interpretation have meant that resolutions are now appropriate for monitoring infrastructure such as bridges. In addition, the availability of historic data means that it is possible to look-back and investigate historic settlement behavior, with SAR capable satellite data being available from 1992 (Bianchini Ciampoli 2019).

Mililli et al. (2019) present a methodology for interpretation of InSAR data and adoption of a Markov Chain Monte Carlo (MCMC) approach to determine pre-failure deformation of the Polcevera viaduct (known as the Morandi Bridge) in Italy. The multi-span bridge constructed opened in 1966 included A-shaped frames as primary structural elements. The bridge was built between 1960 and 1966. A detailed inspection performed in 1993 identified a number of defects including damage to the oxidation of the metallic membrane protecting the strands of one Pier. Significant remedial works were performed on this Pier whilst replacement of the strands for a second Pier was planned to start in October 2018. On August 14th 2018 the Pier due for remediation failed causing a 240m section of the bridge deck to collapse with 43 fatalities.

The line of sight data from 2009 until failure was utilized to infer 3D displacement fields at the problem Piers, See are Figure 10. The data revealed that all locations exhibited displacements that increased linearly with time (at rates typically below 10mm/yr). Pier 9 experienced an 10 fold increase in the rate of displacement, in March 2017. The study thus indicated that whilst InSAR data cannot distinguish between stress accumulation or material degradation processes it could be applied to detect changes in displacement behaviour or structural distress of bridges.

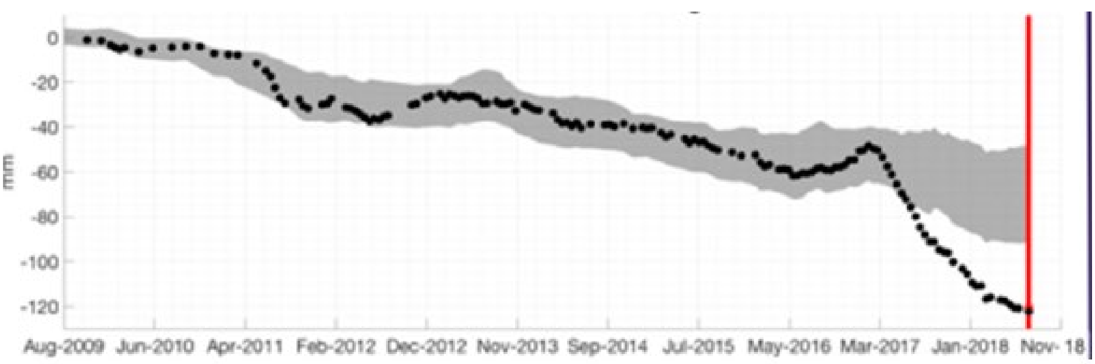


Figure 10: Time-series deformations on Piers 9,10 and 11 based on CSK/Sentinel

UMVs for the detection of Scour

There are promising technologies that can measure the sea/river beds: bathymetric LiDAR and multi-beam sounding deployed on Unmanned Marine Vehicles (UMVs). Murphy et al. (2011) describe the use of the Sea-RAI Unmanned Submersible Vehicle (USV) to undertake a post collapse inspection of the bridge substructure at the site of the Rollover Pass bridge in Texas which collapsed during Hurricane Ike in 2008.

Clubley et al. (2015) combined sonar and marine laser technology in a survey of a railway viaduct crossing the River Hamble in the UK. A desk-based risk assessment has classified the bridge as a medium scour risk. Therefore a diving inspection every four to six years was required. These investigations identified no scour at the bridge or notable changes in the river bed profile over time. In contrast the multi-beam sonar survey identified erosive scour at the bridge piers, see Figure 11 where dark regions identify the presence of erosive scour features.

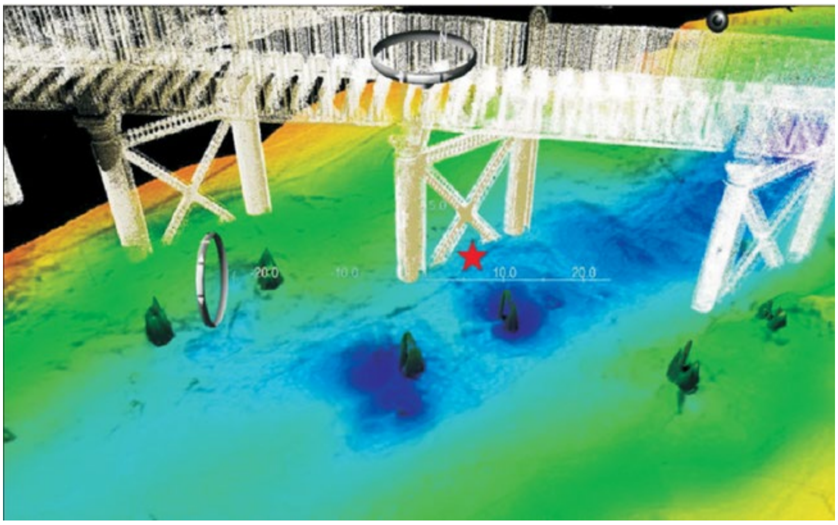


Figure 11: Multi-beam sonar survey with marine laser structural overlay (Clubley et al. 2015)

3.1.3 Data fusion using new technologies in decision making

There are a number of novel technologies that can produce direct or in-some cases indirect measures of damage to roads and bridges. It is apparent that certain techniques are reaching high technology readiness levels for measuring specific quantities. Given each methods unique abilities there is growing interest in combining technologies and fusing data to allow owners to get a complete picture of their assets. In road assessment products as the Fugro Automatic Road Analyser[1] are already commercially deployed. This offers a range of measurements from a single survey including; Digital imaging, GPR, rutting, texture and distress data. In this section we describe briefly the use of data fusion to investigate the regional settlement of a transport network or make maintenance planning decisions of man-made earthworks.

Ground settlement

Because laser scanning cannot give information on internal degradation processes, Biancini-(SAR) data with GPR to infer information about the material forming the structure. They performed a field investigation on a 9.8km section of the railway line in Foggia, Southern Italy.

[1] https://www.fugro.com/our-services/asset-integrity/roadware/aran-automatic-road-analyze

GPR acquisition was performed using a train mounted, multi-frequency antennae (1000 MHz and 2000 MHz). The InSAR data were collected by the Sentinel 1A mission between April 2017 and January 2018. The interpreted data revealed one location (red point in Figure 12 where the displacement rate was in the range 20-24mm/yr. The GPR survey identified a number of high attenuation (anomaly) areas, associated with clayey, compressible materials in this area.

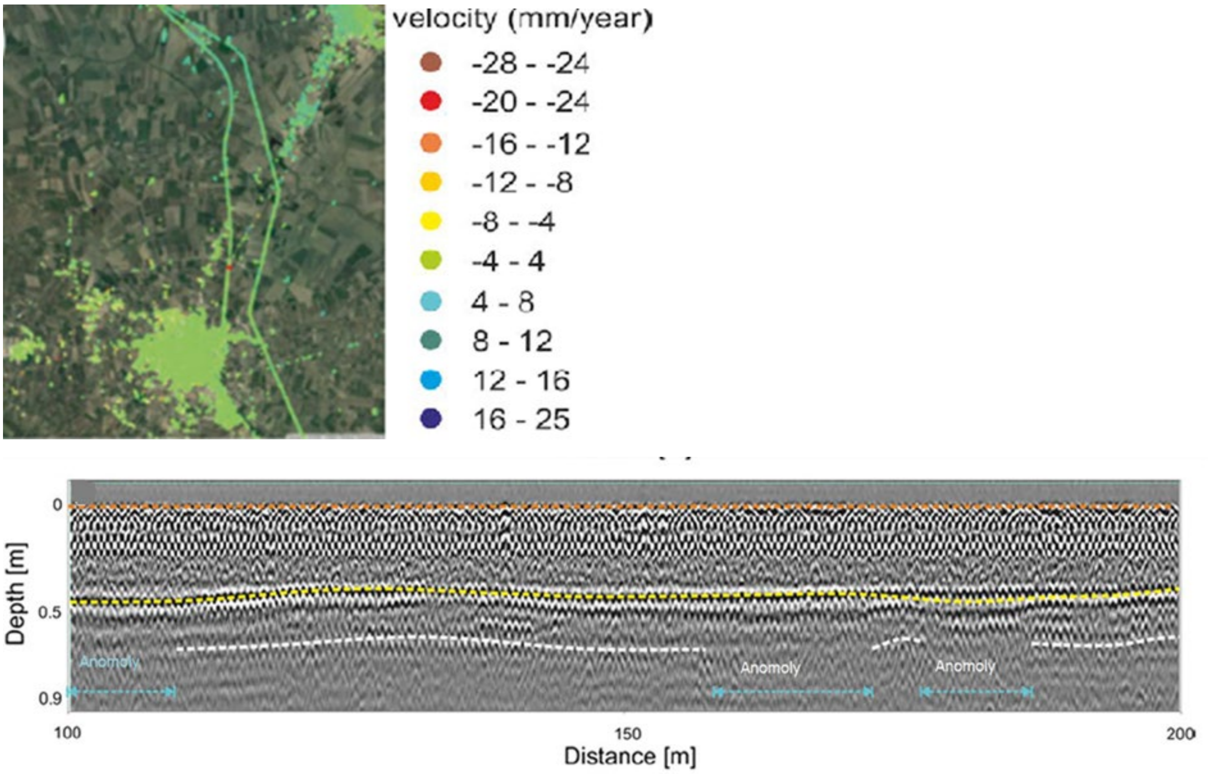


Figure 12: InSAR data (top) and GPR data (bottom) used to investigate subsidence on an Italian Rail line (Bianchini Ciampoli et al. 2019)

Maintenance priorisation of embankments

Kovacevic et al. (2019) describes a methodology to first determine the current condition of embankments using a combination of ground penetrating radar (GPR) surveys, visual inspection, and historical data about maintenance activities. These attributes were then used for the development of a multi-attribute utility theory model used as a support for decision making process for maintenance planning. The methodology was demonstrated for the condition categorization of 181 km of embankments on the Croatian rail transport network. The GPR data was obtained using a combination of high-frequency antennae (at least 1 GHz) to investigate shallow features such as ballast pockets and ballast quality (fouling) and lower frequency antennae, for example up to 400 MHz (depending on the embankment height), to map deep irregularities within the sub-base and embankment material.

3.1.4 Summary

It is necessary to assess the physical and functional conditions of critical assets such as road pavements and highway bridges at regular intervals to ensure they still meet their service requirements. Whilst automated systems have been developed for pavement evaluation in the case of bridges this condition assessment continues to be mainly performed through visual inspection. A number of studies have highlighted the limitations of this approach. In the modern era where climate stressors affect our infrastructure, degradation of condition can be rapid and we need to harness new technologies to maintain safety and maximize mobility.

The report identifies a number of technologies that can produce direct or in-most cases indirect measures of damage to roads and bridges. It is apparent that certain techniques are reaching high technology readiness levels for measuring specific quantities. Given each method's unique abilities there is growing interest in combining technologies and fusing data to allow owners to get a complete picture of their assets.

3.2 IDM for condition assessment

3.2.1 Workflow for creating an IDM

A major challenge when setting up a process map in the context of data exchange processes is to determine the level of detail. An Information Delivery Manual (IDM) focused on the exchange of the results of the condition assessment and condition evaluation between the road or bridge operators and the inspecting organization is described. Even if an internal staff member can also implement a condition assessment, there are always two different roles with different areas of responsibility.

As the result of the IDM, the information scope is specified for the handover to the inspector and delivered as a result to the operators. Subsequently, it should be possible to import the results into traditional as well as BIM-extended asset management systems. A process map based on the condition assessment is created to describe this purpose of data exchange as shown in Figure 13.

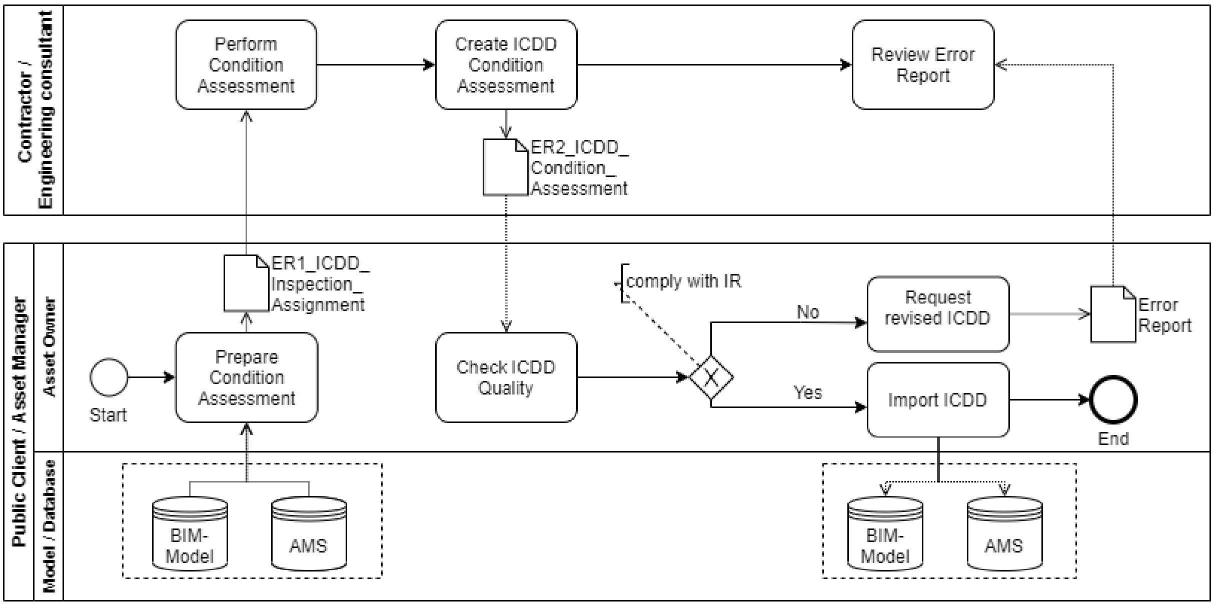


Figure 13: Generic process map for condition assessment

Specialization and detailing are then carried out for the information to be exchanged at the two main data exchange points. The first data exchange point describes the transfer of information required to perform inspections assignment from the road operator to the inspector. The second data exchange point deals with the transfer of the results of the condition assessment to be integrated into the asset management systems. The exchanged data is prepared as a whole package using ICDD according to ISO 21597 (Information Container for linked Document Delivery). The individual processes and data objects contain:

- **Prepare Condition Assessment:** Information necessary for the condition assessment is compiled in an information container as a template transferred to the assigned persons. It includes the specifications, which characteristics are to be captured, and how the raw data and results are linked to the BIM model.
- **Perform Condition Assessment:** The actual damage detection and condition assessment are carried out without consideration of the internal processes of the inspecting organization.
- **Create ICDD Condition Assessment:** The captured and interpreted data is prepared on the basis of the information requirements. The provided templates are used to document the information by the inspecting organization. The completed result collected in the ICDD is delivered to the operators.
- **Check ICDD Quality:** The information container should be validated in a formal and technical examination at this step. The technical validation requires comprehensive experience and can be supported by suitable visual representations. The formal validation includes compliance with the information requirements, e.g.checking the link types defined in the container if it conforms to the link types specified in this document.
- **Import ICDD Condition Assessment:** The valid condition assessments, including the underlying data, are then integrated back into the asset management systems and linked BIM data environments in the final step.

3.2.2 Information Container for linked Document Delivery (ICDD)

The Information Container for linked Document Delivery (ICDD, ISO 21597) has been developed in response to a need within the construction industry to handle multiple interrelated documents as single information delivery. The ICDD is a specification for a generic container format that stores documents using various formats and structures, along with a means of linking otherwise disconnected data within those documents (including individual parts). These documents can have any syntax and semantics. An ICDD consists of four components (see Figure 14):

- An *index.rdf* file describes the container and its contents, including the documents contained in the container.
- An ontology resources folder is used to store the ontology. To provide the object classes and properties used for specifying and linking the documents within the container, the *Linkset.rdf* and *Container.rdf* files should be included.
- A payload documents folder is used to store all the documents. In this folder it is allowed to have subfolders for storing further documents.
- A payload triples folder is used to store all links as one or more so-called *Linkset* files and may have sub-folders.

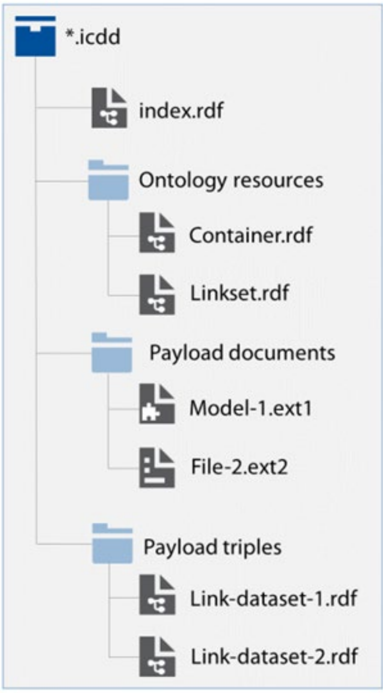


Figure 14: : Components of an information container for linked data delivery in Hagedorn (2018)

Different relationships (or link types) can be used to add information about the contents of a container, rather than extending the contents. The defined link types provide the ability to express comparison, ordering, and dependency relationships between the documents and entities within documents that form part of the payload of a container. The following link types can be used within an information container.

This contributes greatly to the value of the container by providing commentary, guidance, and explanation of the relationships between link elements which could otherwise be unclear or ambiguous, without making any assumptions about, nor being dependent on the specific type of the link elements. This allows the container to be machine readable and human interpretable.

According to the two essential data exchange points defined in the Process Map, the exchange requirement models (ERM) are now defined. The first ERM is created and delivered by the road operator. The contractor created the second model and delivered it back to the client. It should contain all inspection results and links to the BIM model.

3.2.3 ICDD Content of Condition Assessment

Depending on the type of infrastructure and the assessment technology, three different technologies of condition assessment for bridge and road can be considered:

- visual inspection for bridges,
- dynamic response analysis for bridges and
- ground penetrating radar for roads.

The ICDD content are specified and described for the data exchange in process map. The information containers differ fundamentally according to the ontologies, links, and documents used and stored. The container for the three use cases can be defined with the recommended content shown in the following description. These containers must be determined or modified in accordance with the user specification.

Visual inspection of bridges

The visual inspection of a bridge is carried out for all important components. All damages should be documented both textually and visually. The documentation is based on a given template. A report should be created for each inspected component. The report is assigned to the component. If damages are present, the report is accompanied by a detailed description and corresponding photos. The corresponding structure of the two information containers is shown in Figure 15. The left table shows the documents of the Exchange Requirements (ER) model for inspection assignment. The right table shows the documents of the Exchange Requirements (ER) model for condition assessment.

Requirement Container		
Name:	Visual Bridge Inspection Assignment	
Identifier:	ER1_ICDD_Inspection_Assignment	
Description:	**Name**	**Type**
Index:		
	Index.rdf	rdf
Ontology Resources:		
	Container.rdf	rdf
	LinkSet.rdf	rdf
	ExtendedLinkset.rdf	rdf
	ExtendedDocument.rdf	rdf
	DamageClassification.ttl	rdf / ttl
	ConditionClassification.ttl	rdf / ttl
	BridgeClassification.ttl	rdf / ttl
Payload Dcuments:		
	BridgeModel.ifc	ifc
	ReportTemplate.xsd	xsd
Payload triples:		
	ifc2BridgeInstanc.rdf	rdf
	instanc4BridgeClassification.ttl	ttl

Result Container		
Name:	Visual Bridge Inspection Results	
Identifier:	ER2_ICDD_Condition_Assessement	
Description:	**Name**	**Type**
Index:		
	Index.rdf	rdf
Ontology Resources:		
	Container.rdf	rdf
	LinkSet.rdf	rdf
	ExtendedLinkset.rdf	rdf
	ExtendedDocument.rdf	rdf
	DamageClassification.rdf	rdf / ttl
	ConditionClassification.rdf	rdf / ttl
	BridgeClassification.rdf	rdf / ttl
Payload Dcuments:		
	BridgeModel.ifc	ifc
	LocalPlacement.ifc	ifc
	Report.xml	xml
	ImageDamage.png	jpg/png/gif
Payload triples:		
	ifc2BridgeInstanc.rdf	rdf
	instanc4BridgeClassification.ttl	ttl
	DamagePlacement.rdf	rdf
	ReportLinking.rdf	rdf
	ReportVisualDetails.rdf	rdf

Figure 15: Structure of information containers for the visual inspection of bridges

Each folder contains documents listed in Figure 15. The folder **Ontology Resources** includes Container.rdf and LinkSet.rdf as the standard ontologies for defining the documents and links contained in the container, and the extended ontologies ExtendedLinkset.rdf and Extended-Document.rdf for the user to insert and use a self-defined ontology within the container.

The folder **Payload Documents** of the requirement container includes *BridgeModel.ifc* and *ReportTemplate.xsd.* The *BridgeModel.ifc* is the as-built model of the bridge in IFC format. All relevant geometrical and semantic information must be included that is required for the contracted inspection. Alternatively, semantic information can also be provided as ontology-based datasets. The as-built model is not changed during the inspection. Additional information to be managed later in the BIM data environment can be added as external information. *ReportTemplate.xsd* defines a data schema for submitting the condition assessment in the form of a report using XML. This document can be understood as a kind of form to be filled in by the contractor. Mandatory fields and optional fields can be specified. The report template is usually based on national guidelines. The ontologies for classifying components and damage should be used within the report. The information requirements of the asset owner regarding the inspection result must be considered. *Report.xml* is added in the result container instead of *ReportTemplate.xsd*. In addition, the *LocalPlacement.ifc* and ImageDamage.png are also added in the folder **Payload Documents** of the result container. *LocalPlacement.ifc* is an extension of the as-built model of the bridge (*BridgeModel.ifc*) to define areas for locating information for condition assessment. *Report.xml* contains the inspection result under consideration of the defined template. The amount of information must be sufficient to display a conventional (often paper-based) inspection report. This includes the metadata of the inspection, the evaluation of essential components, the damage assessment, etc. *ImageDamage.png* specifies an image to a recorded damage. Different data formats such as png, jpg, or gif can be allowed for the images in the container. Furthermore, several images can be contained in containers. Each image is assigned to exactly one damage description within the report.

The folder **Payload Triples** of the requirement container contains ontology-based semantic information *instance4BridgeClassification.ttl* and the links saved in a linkset file *ifc2Bridgeinstance.rdf*. *Instance4BridgeClassification.ttl* defines the bridge elements with the appropriate classification as sematic information regarding the national standard used. *Ifc2Bridgeinstance.rdf* contains the links between the elements of bridge model (*BridgeModel.ifc*) and defined semantic information of the bridge classification (*ifc2Bridgeinstance.rdf*), which enables the classifying of IFC elements as bridge components. In the result container, the *DamagePlacement.rdf*, *ReportLinking.rdf* and *ReportVisualDetails.rdf* are added in the folder. *DamagePlacement.rdf DamagePlacement.rdf* contains the links between the bridge model (*BridgeModel.ifc*) and the placement of information regarding the condition assessment (*LocalPlacement.ifc*), which enables, for example, the assignment of a damage area relative to a bridge component. *ReportLinking.rdf* contains the links between the individual reports and the corresponding components and damage descriptions. *ReportVisualDetails.rdf* contains the links between the description or evaluation of an individual damage, the exact position of the damage in the model (*LocalPlacement.ifc*) and the corresponding image of this damage.

Dynamic response analysis for bridges

With a fixed mounted sensor, the frequency of the bridge is determined during service (i.e. its response to traffic and environmental loading). An exact numerical analysis of the sensor data allows the detection and monitoring of scour around bridge foundations. For this condition assessment, the information such as sensor measurement data and the scour analysis at the foundation are returned as results. The corresponding structure of the two information containers is shown in Figure 16.

Exchange Requirements Model		
Name:	Dynamic response analysis for bridges	
Identifier:	ER1_ICDD_Inspection_Assignment	
Description:	**Name**	**Type**
	Index.rdf	rdf
Ontology Resources:		
	Container.rdf	rdf
	LinkSet.rdf	rdf
	ExtendedLinkset.rdf	rdf
	ExtendedDocument.rdf	rdf
Payload Dcuments:		
	BridgeSensorModel.ifc	ifc
	SensorDataTemplate.xsd	xsd
	ReportTemplate.xsd	xsd
Payload triples:		
	RequestedReports.rdf	rdf

Exchange Requirements Model		
Name:	Dynamic response analysis for bridges	
Identifier:	ER2_ICDD_Condition_Assessement	
Description:	**Name**	**Type**
	Index.rdf	rdf
Ontology:		
	Container.rdf	rdf
	LinkSet.rdf	rdf
	ExtendedLinkset.rdf	rdf
	ExtendedDocument.rdf	rdf
Payload Documents:		
	BridgeSensorModel.ifc	ifc
	SensorData.xml	xml
	Report.xml	xml
Payload Triples:		
	SensorLinking.rdf	rdf
	ReportLinking.rdf	rdf

Figure 16: Structure of information containers for dynamic response analysis for bridges

The folder **Ontology Resources** includes only the standardized and extended ontologies for the container in both containers. The folder **Payload Documents** of the requirement container contains *BridgeSensorModel.ifc, SensorDataTemplate.xsd* and *ReportTemplate.xsd*. *BridgeSensorModel.ifc* describes the as-built model of the bridge using the IFC format. It is assumed that the sensors to be evaluated are described as separate objects in the IFC model. For this purpose, the IFC class *IfcSensor* can be used. The sensor can be positioned very precisely and provided with a geometry. *SensorDataTemplate.xsd* specifies the scheme for recording the individual data sets. The template is defined according to the used sensor. *ReportTemplate.xsd* specifies the data schema to describe the analysis result. In the result container, *SensorData.xml* and *Report.xml* replace the predefined data schema with the measurement data of the sensor and analysis result data.

The folder **Payload Triples** of the requirement container includes *RequestedReports.rdf,* which defines links to describe for which bridge or part of bridge an analysis of the sensor measurement should be performed. On this basis it can be checked that at least one report has been created based on the given template. In the result container, *ReportLinking.rdf* replaces *RequestedReports.rdf*. *SensorLinking.rdf* is also added, which contains the links between used sensors on the bridge and the actual measurement data of the respective sensor. In principle, different documents can also be linked for a sensor with measured values depending on the measured values and the measurement times. *ReportLinking.rdf* contains the links between the analysis results and the measurement data of the sensors.

Ground penetrating radar analysis for roads

The detection of road condition with the Ground Penetrating Radar (GPR) is a proven and widely used technique. It enables the asset owner to detect cavities within the pavement and assess the thickness of the pavement layers. An inspection with this technique can create very large amounts of raw data, not giving any direct result. Instead, it requires further processing for damage detection. The raw data are generally stored and managed in a central repository. The evaluation of the road condition and the findings of pavement surface damage or pavement structural damage are reported to asset managers. To meet this requirement, the two containers are created, as shown in Figure 16.

Exchange Requirements Model		
Name:	Ground Penetrating Radar for roads	
Identifier:	ER1_ICDD_Inspection_Assignment	
Description:	**Name**	**Type**
Index:		
	Index.rdf	rdf
Ontology:		
	Container.rdf	rdf
	LinkSet.rdf	rdf
	ExtendedLinkset.rdf	rdf
	ExtendedDocument.rdf	rdf
	PavementClassification.rdf	rdf
Payload Dcumente:		
	RoadModel.ifc	ifc
	RoadSections.ifc	ifc
	ReportTemplate.xsd	xsd
	DrillCoreTemplate.ifcxml	xml
	GPRAnalysis.xsd	xsd
Payload triples:		
	RequestedReports.rdf	rdf

Exchange Requirements Model		
Name:	Ground Penetrating Radar for roads	
Identifier:	ER2_ICDD_Condition_Assessement	
Description:	**Name**	**Type**
Index:		
	Index.rdf	rdf
Ontology:		
	Container.rdf	rdf
	LinkSet.rdf	rdf
	ExtendedLinkset.rdf	rdf
	ExtendedDocument.rdf	rdf
	PavementClassification.rdf	rdf
Payload Dcumente:		
	RoadModel.ifc	ifc
	RoadSections.ifc	ifc
	Report.xml	xml
	DrillCores.ifc	ifc
	GPRData.xml	xml
Payload triples:		
	ReportLinking.rdf	rdf
	DrillCoreLinking.rdf	rdf
	GPRLinking.rdf	rdf

Figure 17 Structure of information containers for ground penetrating radar analysis for roads

The folder **Ontology Resources** includes beside the standardized and extended ontologies for the container in both containers also domain ontology *PavementClassification.rdf.* This should be an ontology to classify the individual layers of a road. Since the classification of the pavement is carried out according to national standards, the definition of this ontology should correspond to national regulations. The folder **Payload Documents** of requirement container includes *RoadModel.ifc* with the as-built model of the road using the IFC format and *RoadSections.ifc* with areas for the analysis by using GPR. In addition, data schema as templates for report, properties and analysis *ReportTemplate.xsd, DrillCoreTemplate.ifcxml, and GPRAnalysis.xsd* are also included. In result container, *Report.xml* with the analysis results, *DrillCore.ifc* for drill cores with the predefined properties, and *GPRAnalysis.xml* with the pipe data for measurement replace the data schema templates.

The folder **Payload Triples** of requirement container includes *RequestedReports.rdf*, which defines links to describe for which road section with drill core model and GPR analysis data should be created. The result container includes three linkset files. DrillCoreLinking.rdf contains the links between drill cores, their assignment to a road section, and which drill cores were used for which calibrations within the report for homogeneous sections. *ReportLinking.rdf* contains the links between the inspected road section and the average layer thicknesses based on the measurement data. *GPRLinking.rdf* contains the links between the raw data and the corresponding averaged layer thicknesses listed in the report.

3.3 Analysis of IFC regarding condition assessment

3.3.1 IFC entities for Infrastructure and the condition data

Assignment and meaning of the classes for the AMS

In recent years, Industry Foundation Classes have been continuously expanded. In Version 4.3 Release Candidate 2, they include new classes for infrastructure modelling. In particular, the new classes for the description of road entities e.g., *IfcRoad, IfcKerb, IfcOpenCrossProfileDef, IfcSectionedSurface, IfcCourse, IfcPavement* are available. Furthermore, important properties related to road construction and operation, e.g., ApplicationTemperature, WeatherConditions, PavementRoughness, PavementTexture, DesignSpeed, DesignTrafficVolume, and LaneWidth were also provided. An overview can be found in the official documentation for IFC 4.3 RC2. Additional classes e.g., *IfcBridge, IfcDeepFoundation* and property sets for the modelling of bridges have also been included in the current release candidate. For the representation of important bridge elements, no new classes were introduced. Instead, existing types were extended to describe the classes in more detail. For example, the class *IfcBeamTypeEnum* now has a value *GRIDER_SEGMENT*. In addition to the description of individual elements of a road or bridge, it is possible to provide further information for modeling surface damages or other changes of the surface with the classes *IfcFeatureElement and IfcSurfaceFeature*, that defines a surface feature for modification of the surface of an element. There are also several predefined types that can be used for classification of the surface features.

The ability of IFC to dynamically add individual sets of properties means that all possible information about a particular area on the surface of an element of a road or bridge can be described. The information can be positioned both absolute and relative. The classes e.g., *IfcLocalPlacement, IfcLinearPlacement, IfcAxis2PlacementLinear, IfcAlignment, IfcReferent,* can essentially be used for this purpose.

In order to describe the digital model according to the respective guidelines of the national asset management systems, the IFC scheme offers the possibility of submitting the object elements with an individual classification. For example, the well-known classifications Uniclass (GB), DIN 276 for cost estimation or ASB-ING (DE) can be integrated in this way. A relation-entity IfcRelAssociatesClassification can connect the IFC-entity IfcClassification as well as IfcClassificationReference with parts of spatial structure elements (*IfcBridge*), physical elements *IfcBuilingElement* (as a subtype of *IfcElement*), or positioning elements.

As basic information, relevant semantic information of the design element could be included directly in the IFC model. This semantic information could be derived from various sources, e.g., construction, previous inspections, or maintenance work. Semantic information can easily be added as a property set. For the feedback of the condition assessment, the inspection result could be, among other possibilities directly added to the design model as a user-defined property set.

The information obtained, such as images or documents, are external files that can also be linked to the IFC model using *IfcDocumentInformation* using a URI. *IfcDocumentInformation* contains comprehensive attributes that describe the metadata of a document to be linked.

Nowadays, sensors are often used to monitor the condition of a building or to support the control of technical equipment. Information about a sensor can also be mapped in an IFC model. The class *IfcSensor* can be used as a subtype of *IfcDistributionControlElement*. To describe the sensor, different sensor types are predefined in *IfcSensorTypeEnum*. The existing sensor types clearly show that sensors are mainly intended for technical building equipment (heating, ventilation and air conditioning). However, it is also possible to employ user-defined sensor types. This makes it possible to model sensors with the correct type designation in the IFC model, e.g. sensors such as accelerometers or stress detectors whose measurement data are used for stability analysis. With the relationship *IfcRelAssignsToProduct* a sensor can be assigned to a component. In addition, there are extensive predefined property sets that can also be used to describe the metadata of a sensor. For example, the manufacturing information can be supplemented with the property sets *PSet_ManufacturerOccurrence* and *PSet_ManufacturerTypeInformation*. A user-defined property set can be added to a sensor element for additional properties. Figure 18 shows an example of a component linked to a sensor.

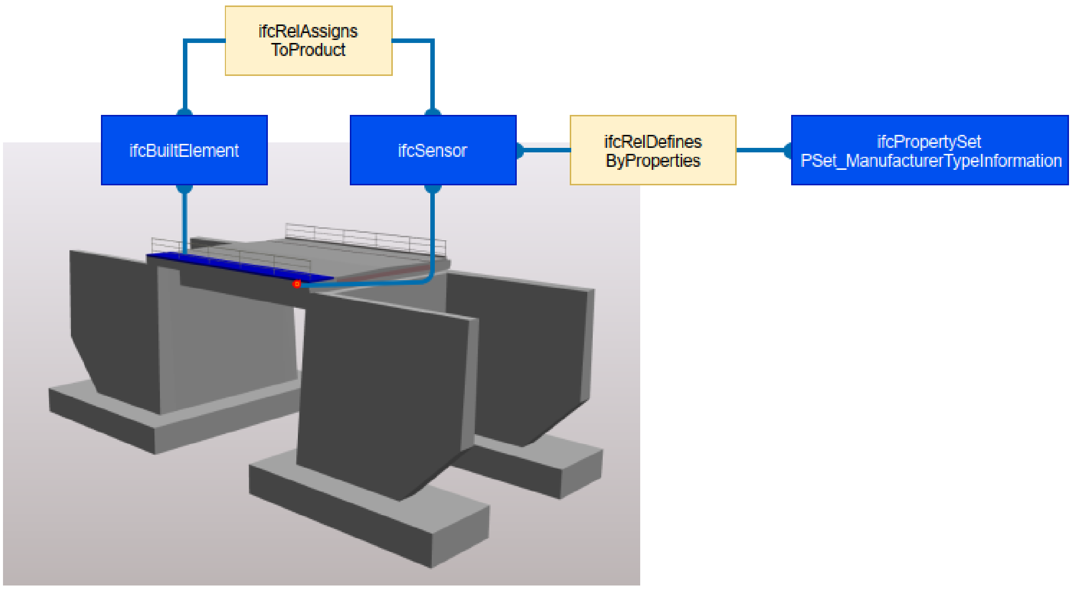


Figure 18 Integration of a sensor for monitoring a bridge component

3.3.2 IFC Extension for Damages

An extension to the IFC standard for structural testing of bridges is proposed in Tanaka et al. (2016). The concepts provide new IFC entities for modelling inspection areas with *Ifc-MeasuredRegion*, repaired areas with *IfcRepairedRegion,* and deterioration or damage with *IfcDegradation* or *IfcDegredationElement*. The *IfcDegradationElement* is intended to present the temporal development of damage. It describes a damage condition at a certain inspection with time data. With the new relation entity *IfcRelConnectsToMeasureRegion*, the instance generated as type of the new entities will be connected with standard bridge elements. With *IfcRelConnectsToTimeVariations* the damage can be linked at different timestamps (see Figure 19). In addition, *IfcTasks* can be used to define an inspection, assessment or maintenance in an IFC model with the *TaskTime* and *PredefinedType* attributes added.

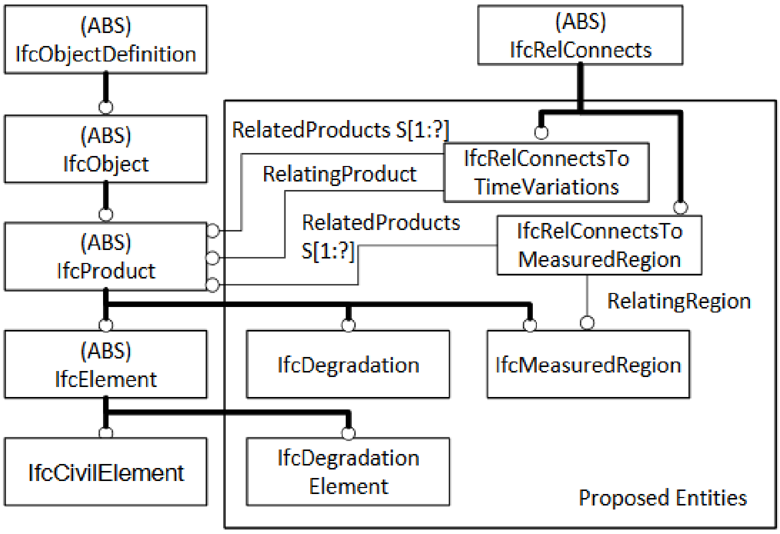


Figure 19 IFC extension for damage modelling in Tanaka et al (2016)

3.3.3 IFC Extension for Monitoring

A Structure Health Monitoring (SHM) system uses sensors to monitor the stability of a structure, as shown in Figure 20. A complete SHM system with sensor networks could be digitally modelled by extending the IFC.

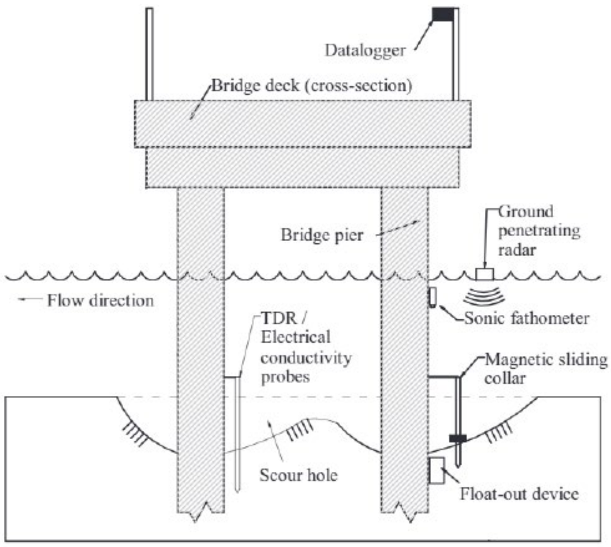


Figure 20 Scour monitoring instrumentation in Prendergast et al. (2013)

In Theiler & Smarsly (2018), the extension of IFC with comprehensive user-defined IFC entities for sensor technology is presented. For an IFC-supported SHM system, the existing IFC schema is not able to capture a sensor network needed for the whole system. However, IFC offers the possibility to extend the schema with user defined entities. By extending the IFC schema, the entities for a sensor network is integrated in the IFC schema with semantic information. The basic idea is to generate a reference model by taking into account the existing standard for SHM along with sensor modelling languages and ontologies. The relevant information for monitoring can be collected in a so-called “monitoring-related mode”. By integrating the two models, the important semantic information about the sensor, the standard of the SHM and monitoring information will be matched. If the existing IFC object model (version IFC 4) is extended by the semantic model, so-called IFC monitors are created.

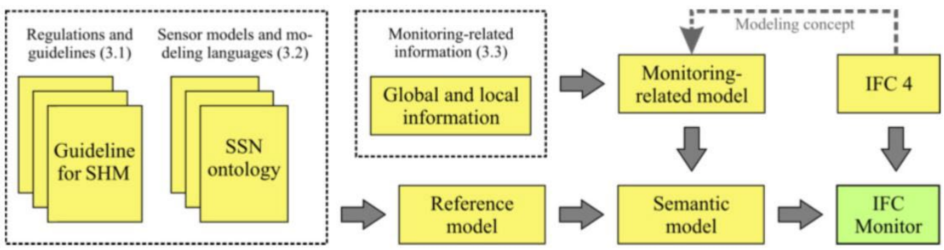


Figure 21 Conceptual approach towards IFC-based mapping of monitoring-related information in Smarsly & Tauscher (2016)

4 Data Fusion and semantic transformations

4.1 Definition of an AMS reference process model

4.1.1 General Approach

Currently asset management systems consist in many cases of several systems which are poorly connected. In addition, there are other data sources that are not owned by NRAs, but relevant to asset management. These data need to be used, processed, and displayed together. Unfortunately, the semantics of these data is not consistent, and transformation may be needed. In a research project (Bernard et al., 2015) the inconsistency was tackled by establishing a reference database that import the unchanged source data and then transform them to be used in an asset management system.

Based on the results of work packages 2 and 3, a reference process model for the national road authorities (NRA) is developed. The current procedures and maturity levels of asset management can be derived from work package 2. Ultimately, all relevant system information from the NRA is included, so that a uniform understanding of the overall asset management process was derived. The following basic assumptions were made:

EN ISO 55000, whose elements represent the basic requirements and the framework for the process model, were followed. EN ISO 55000 describes three levels, a strategic, a tactical, and an operational level. Their tasks must be clearly defined, as it has been documented in previous reports. Nevertheless, there is a country-specific understanding of each level, which has been funnelled into a general model in the present context. However, a system definition must be made as to which tasks are performed in asset management and where is the boundary to traffic planning considerations.

The general process model describes an AMS, and its sub-processes relevant in the context of this research project are identified. At the same time, this means that the developed data model should be able to accommodate data exchange between sub processes of the AMS. Depending on the tasks within each sub process, data requirements have to be defined as well as the level of detail and data content. A bottom-up approach is adopted, in that the requirements are defined at the object level. The network level is then described by aggregating the data at the object level.

The approach used in the current project was based on Figure 22. The model presented there intentionally does not contain an assignment to an object-related or a network-related view. For this purpose and the common understanding, it is not necessary and can now be carried out in accordance with the specifications of EN ISO 55'000 and the national approaches as described above.

In Figure 23 a distinction is made between the definition of strategic asset management plan and operational asset management plan. The operational asset management plan is subdivided into the inspection, maintenance planning and the implementation of the maintenance measures. The tasks in the present context are thus clearly outlined; the focus of the processing therefore refers to the operational asset management as described there. In an overarching consideration, relevant information from Belgium, Austria, Sweden, Finland, the Netherlands and Germany could be evaluated. These results were used to confirm the previous results from WP 2. In detail, the AMS approaches and process models from the three selected countries, namely Denmark, Germany and the Netherlands were analysed in detail and from these results, the general process model was derived. Subsequently, the basic structure of the data flow was presented, whereby different data requirements are presented depending on the national data processing models. In some topics, there is a high degree of conformity, but in other tasks, different technical approaches were used, which makes it difficult to define a common and unique data model. However, this is not considered necessary from a technical point of view. For instance, the integration of bearing capacity measurements, which are an integral part of pavement evaluation in Denmark but are not used in Germany. In such cases, it is not necessary to show data models that are only used nationally, in the context of the project. This is taken into account below by showing common areas of application, also by at least showing examples for nationally required extensions.

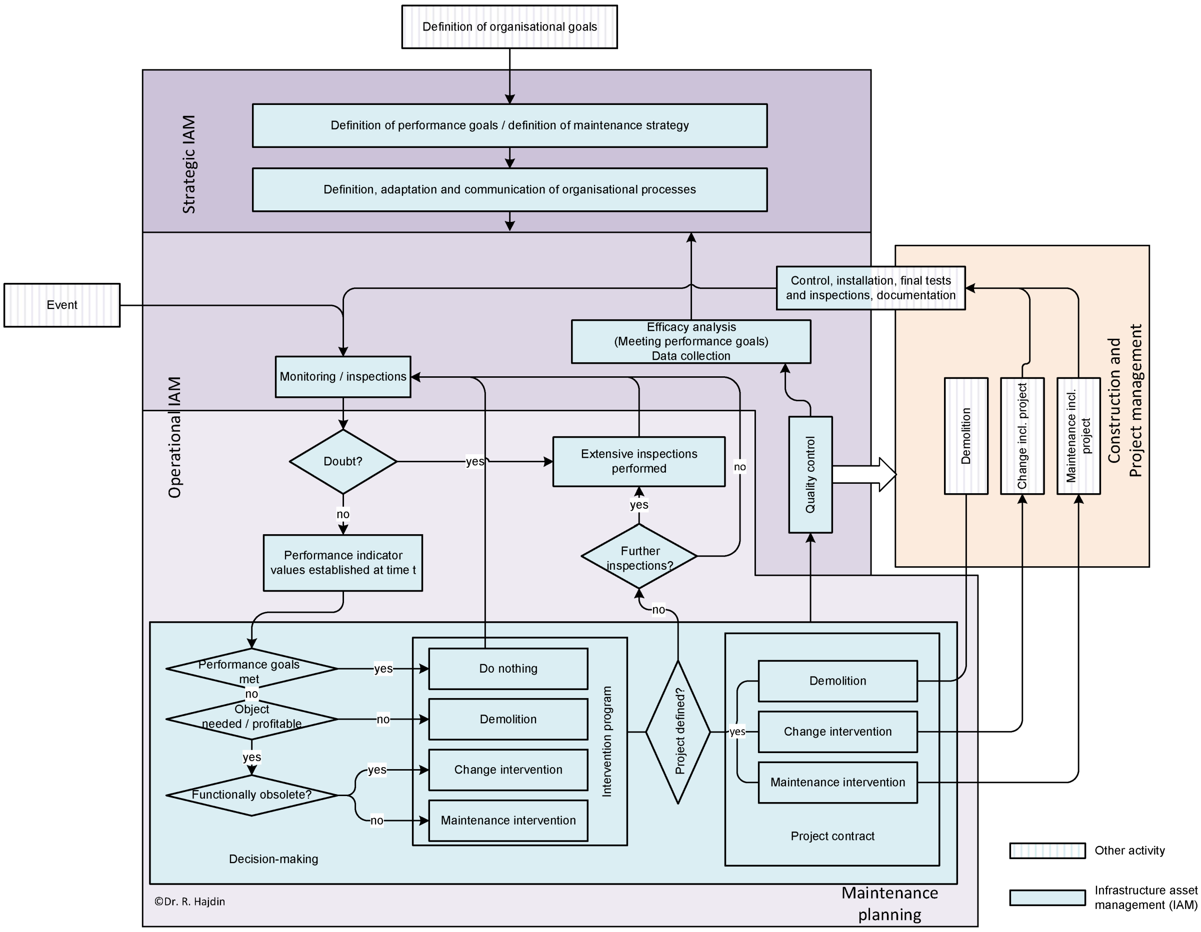


Figure 22 Processes of an Asset Management

Based on this consideration, the processes of an asset management system must be described adequately regarding the workflow between different stakeholders. Therefore, a process model based on the from the results from chapter 2 and 3 is derived. The aim is to ensure that this process model can be applied as far as possible to the different NRAs and should be able to be adapted according to different use cases. The detailed tasks of an IAMS are shown in Figure 23.

The main challenges of asset management systems are the handover and transformation of data that are incompatible with the system’s demands. Therefore, to illustrate the suitability of the proposed AM process, three instances of data updates/feeds in the data base have been identified, as shown in Figure 24.

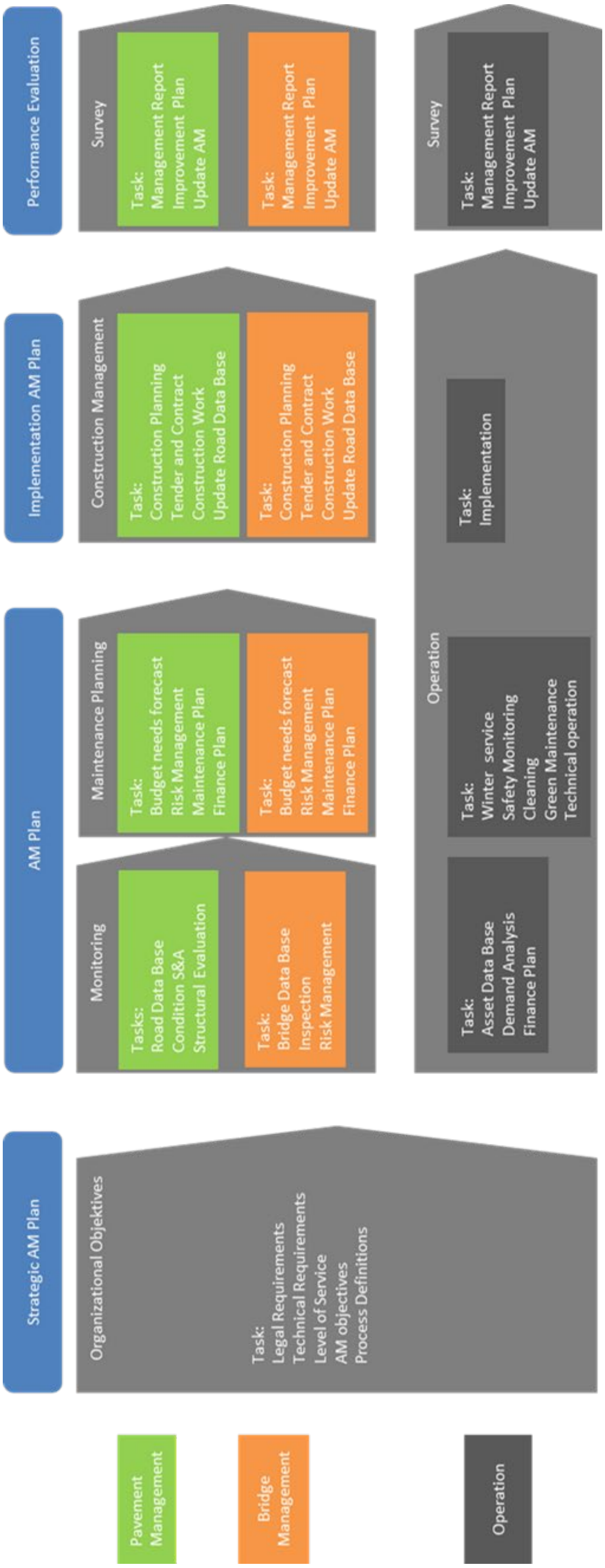


Figure 23: Main AMS Tasks

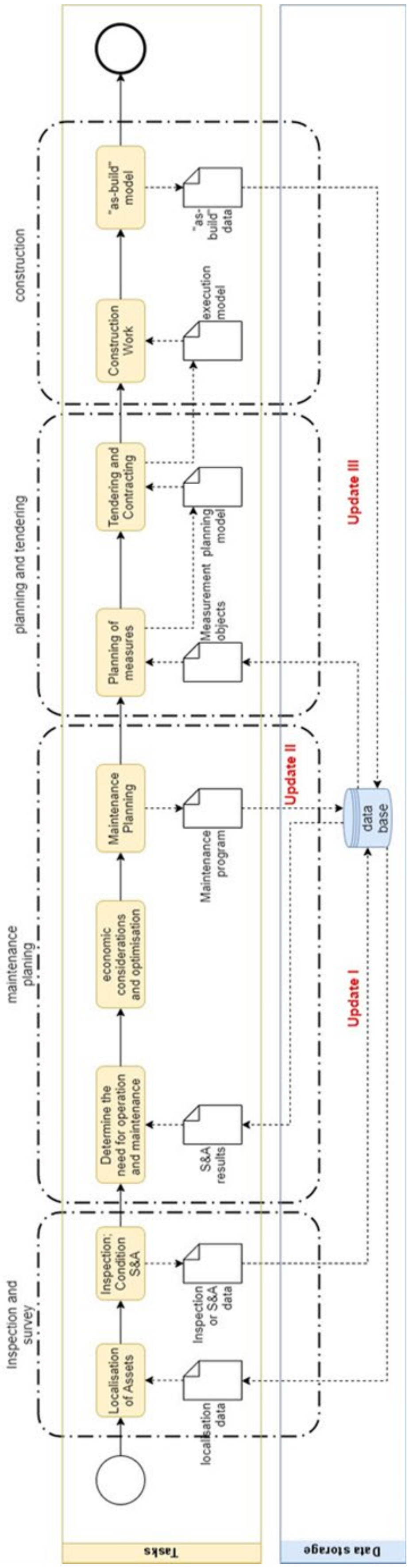


Figure 24 Main process for asset management

The basic generic model assumed for the project is the model of an IAMS according to EN 55000. This overall IAMS model shows the framework of a strategic AM Plan focused on a road administration, consisting of legal and technical requirements, determination of the desired level of service as well as of the general objectives and targets. Further elements are the tactical and operational AM, described for Pavement Management, Bridge Management and Operation. These steps are divided into inspection respectively survey and assessment, maintenance planning, implementation of measures and performance review. This overview delivers a basic structure for the further development of the generic process model and subsequently the data flow model, whereby only the sub-processes needed within the project context are considered in the following steps.

For the present project, the sub-steps in which relevant data transfer for AMS are required and of particular interest. These sub-steps are an inventory model, the data from the condition assessment and evaluation, data of the maintenance planning as well as data of the as-built model from the implementation of the measures. The process description is focused on the important data update/feeds the process is based on an existing inventory or as-built model, which adequately represents the infrastructure inventory for a lifespan consideration.

In the overall process, an existing as-built model is assumed. Then three important updates of the database are identified, referred to below as Update I, II and III. These are firstly an update of the results from the inspection or condition survey and assessment, secondly the update of the prioritized maintenance measures and thirdly the update of the "as-built" model after construction work that has been carried out. The decision for these three updates ensures, that the final work results for every sub-process should be saved, as far as they deliver the needed information for the following step in the life cycle. It is not important to define data updates/feeds results within these sub-processes, which shows only importance within the respective sub-process, but not for the life cycle itself. Tasks within a sub process are usually handled with authoring software. For example, it is assumed that during the sub process for planning measures, the update of the planning up to execution in accordance with the LOD concept is not saved back into the IFC/BIM database, but the "as-built" model should be saved. As an example, the data sets required for the inventory model is shown for a pavement section in Figure 25. A data set is a collection of related sets of information belonging to on topic and part of asset. It includes the layers with their material properties and data about traffic volume (planning data). The condition data in an as built-model can be assumed in very good condition, as it should be for a new road.

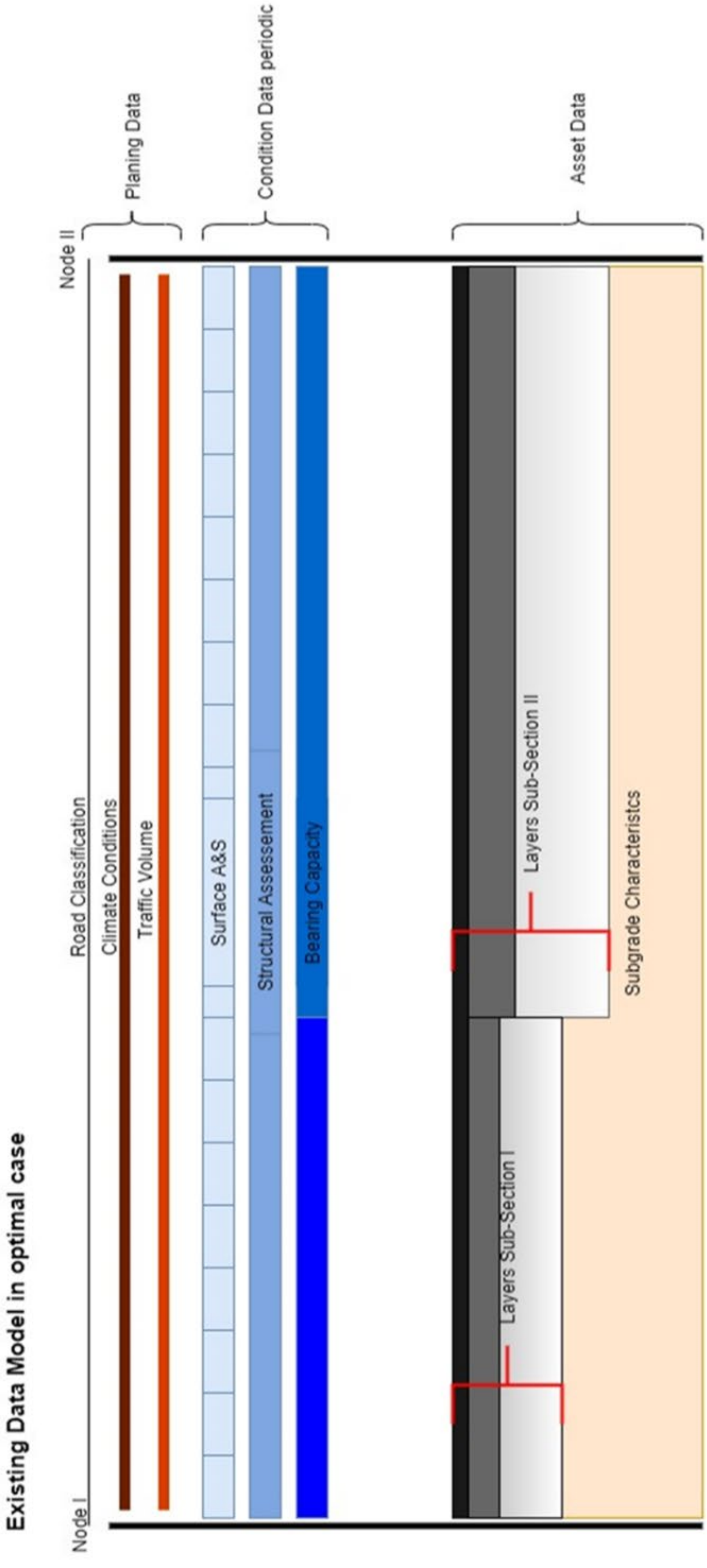


Figure 25: Data sets for the inventory model, new constructed pavement section

4.2 Data requirements for an AMS

4.2.1 Data flow requirements

As written in the previous chapters, the data requirements for an AMS are primarily determined from sub-process 2 “Maintenance Planning”. The algorithms and calculations to be performed within the different steps of Maintenance Planning represent the core requirement of the AMS, so all the data needed must be available. The data requirement should be derived from this sub-process, which will be supplied with condition data from sub-process 1 “Inspection and Survey” with update I as well as the as-built data supplied from the sub-process construction with the update III. Depending on the national approaches for maintenance planning, further data like traffic volume is needed. The described data flow, characteristic for pavement maintenance, can be seen in Figure 26 Update I provide the condition data, update III provides the as-built data, which is then required as part of the maintenance planning process. The maintenance program then provides the corresponding action lists for the AM measures.

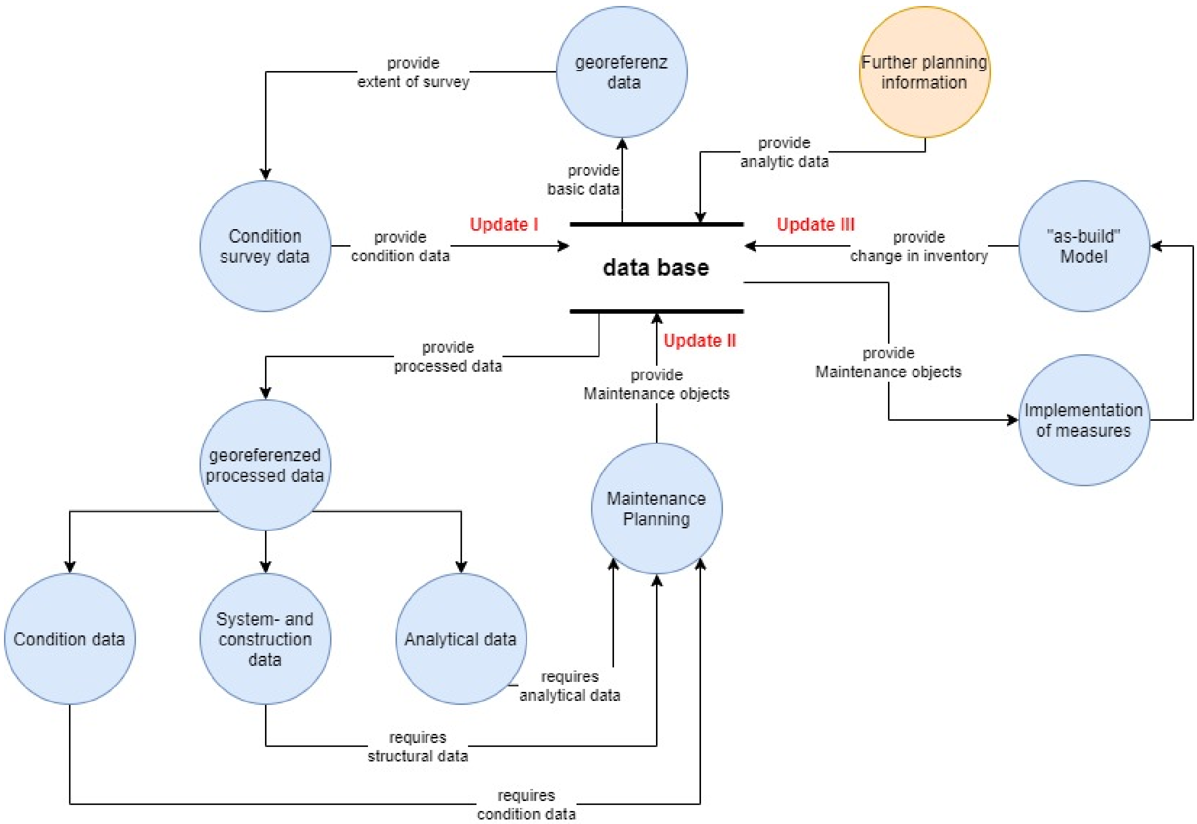


Figure 26: Data Flow Requirements for a generic Pavement Management System

4.3 Data requirements for an AMS

Condition assessment and maintenance of structures imply a slightly different data flow from the pavement condition assessment and maintenance. Unlike roads, bridges are not segmented based on the condition data. A bridge is represented in AMS as a composition of elements by default. Nevertheless, the update II includes the maintenance measure on these elements.

4.3.1 Required data for pavements

To describe the data requirements for pavements in an IAMS, the in the European countries used methods for of condition survey and assessment as well as the further use of these results in an AMS were compared. With these results, it can be seen that the survey of the surface properties of road pavements is essentially carried out using the same groups of condition characteristics in most of the European countries. So, all countries survey and assess longitudinal and transverse unevenness, skid resistance as well as surface damages. Differences exist in the definition or the type of surface damages. Significant differences can be found for the structural evaluation of road pavements. For example, methods for determining the bearing capacity as well as methods for determining the remaining service life of road pavements are applied and used differently in Europe. In addition, in some countries, there is an ongoing process to change or extend the assessment of pavement condition and pavement quality. As a general model, the process is shown in Figure 27.

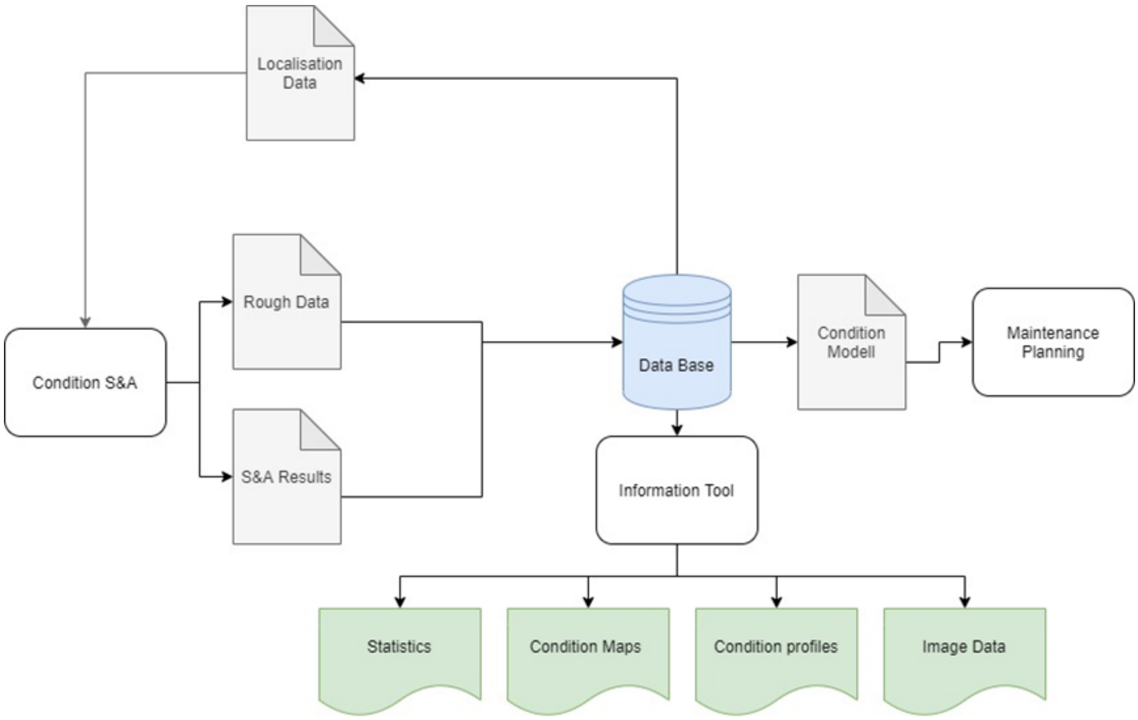


Figure 27: Generic Model for Pavement S&A

Taking these results as well as the considerations on the process analysis into account, a general model for describing the data need for maintenance planning of pavements was derived (see Figure 28). This will be regarded as a central request for the data model needed in sub-process 2 “Maintenance Planning”. This model comprises results from the condition assessment, from the structural evaluation, the evaluation of the load-bearing behaviour, further non-destructive examination methods such as the GPR and supplementary destructive examination methods, which are needed in special cases. It comprises data from both the as-built model and the condition model. The model will be scalable on a European level and can be adapted to national requirements accordingly.

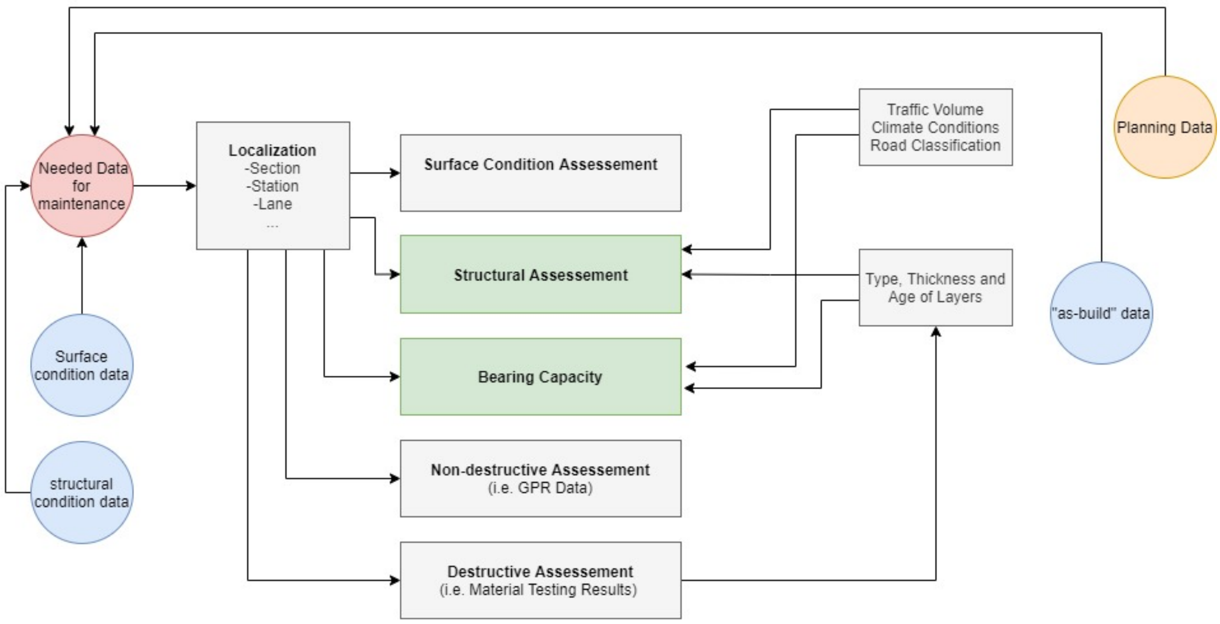


Figure 28: Data Demand for Pavement Condition Assessment

To a certain extent, European standards can help with the basic description of data requirements and properties. But these have to be in every case adapted at the national level according to the relevant technical regulations. The following standards can be found at the European level, which is used as a basis for the subsequent structuring of the database. These are in detail, without claim to completeness and as far as they are considered essential for the present context:

EN 13036-5: Road and airfield surface characteristics - Test methods -

Part 5: Determination of longitudinal unevenness indices

Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges

Part 8: Determination of transverse unevenness indices

CEN/TS 15901: Road and airfield surface characteristics;

Part 2: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCR**NL**): ROAR (Road Analyser and Recorder of Norsemeter)

Part 5: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCR**DK**): ROAR (Road Analyser and Recorder of Norsemeter)

Part 8: Procedure for determining the skid resistance of a pavement surface by measurement of the sideway-force coefficient (SFC**D**)

This includes the surface properties unevenness and skid resistance. No European specifications exist for the recording of surface damage, load-bearing capacity, structural evaluation and other destructive recording methods. Here, corresponding national regulations will be used.

Material related data should be available from the as-built model and include layer-related material data and material characteristics. Several European standards relating to construction methods are also available for this purpose. Examples are:

EN ISO 14688 ff	Geotechnical investigation and testing
EN 12697 ff	Bituminous mixtures - Test methods for hot mix asphalt
EN 13043	Aggregates for bituminous mixtures and surface treatments for roads, airfields, and other trafficked areas
EN 13108 ff	Bituminous mixtures - Material specifications
EN 14023	Bitumen and bituminous binders
EN 13877	Concrete pavements

The basic material data properties are related to a European specification, which is then translated into national regulations. In principle, the general framework is well defined, but in detail, this leads again to different properties that have to be adapted in the model. This can be seen very clearly in the so-called performance properties of asphalt according to EN 12697, in which different test methods are specified to determine uniform properties. These naturally lead to a different catalogue of properties since different parameters or even different designations are specified depending on the measurement method.

To create a common model based on these general preliminary considerations, the systems for Denmark, Germany and the Netherlands were first examined, and the data requirements were compiled in the form of the required data sets for Denmark, Germany and Netherlands are described in AMSfree Report D 4.1 “Definition of an Asset Management Reference process”. As a result of these considerations, a rough overview about data groups may give Figure 29.

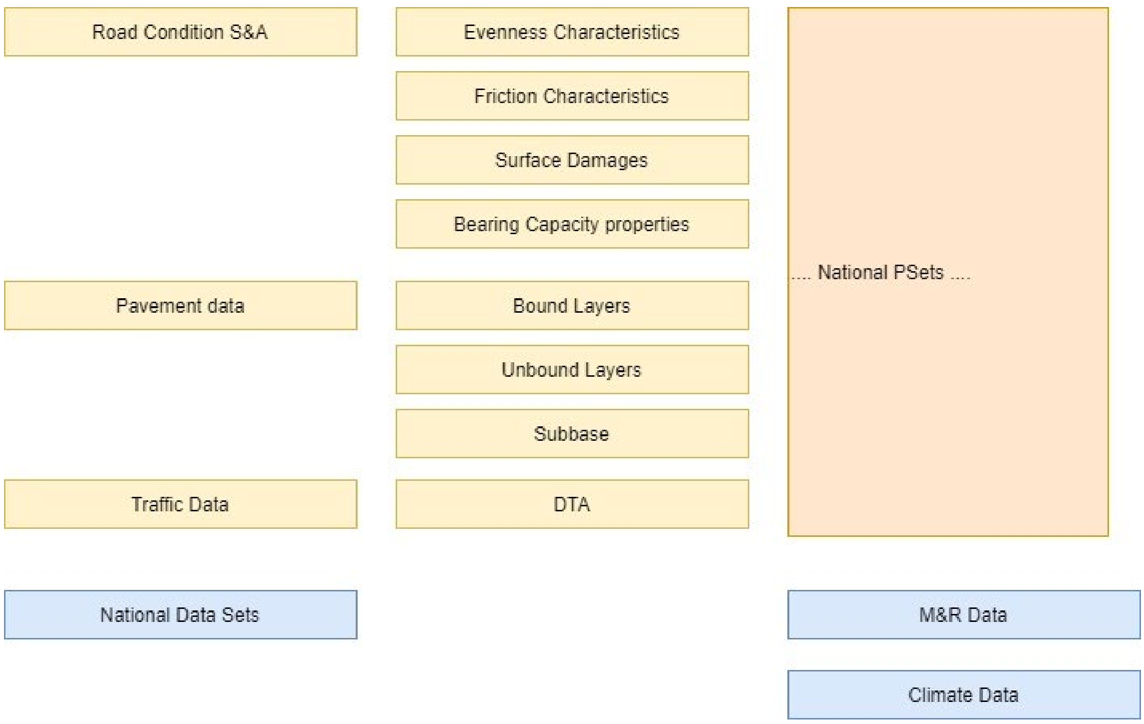


Figure 29: Required Data sets for Pavement IAMS Model

As a result of these considerations, an overview is given in report D 4.1 for the pavement AMS. It can be clearly seen that different pavement condition models will be used within the regarded countries. The generic model presented in Figure 29 works with the national data sets.

The conclusion to be drawn from the actual results is, although the basic principles for a common process and data model can be described, an implementation in detail always means integrating national requirements. Therefore, a common framework can be described, but data content and parameters have to follow that assessment techniques and maintenance calculation algorithms, which are nationally used.

In the following steps, a data model based on the previous results will be further defined, which will then be used as an example to show how the national implementation can be carried out. The approach is, as requested in the AMSFree project, connecting IAMS (legacy systems) with BIM based upon IFC.

4.3.2 Required data for structures

Being significantly more complex than roads, structures require more information to allow for efficient management. In this section, bridges are used as typical example of structural assets. It provides an overview of elements that need to be inspected, and the inspection methods used, whereas detail description of the assessed condition information is provided in the Report 4.2.

Bridges are inspected mostly visually. Visual inspection can further trigger an in-depth investigation, where non-destructive and/or destructive testing methods are used to measure the performance indicators directly or indirectly. Once identified, damage is classified and rated or are used to rate a bridge element affected by these damages. The rating can address damage occurrence, or element, depending on the national inspection guidelines.

German AMS for structures, SIB-Bauwerke (BASt, 2021), gives three ratings to each damage, element of the structure and the structure, according to the following criteria: structural safety (S), traffic safety (V) and durability (D). Damage classes are provided in the ASB-ING (BASt, 2013) database, which is described in detail in the report D4.2. As a help for visual damage classification, approx.1,700 assessed damage examples are provided in RI-EBW-PRÜF (BASt, 2021).

According to (Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2013), standard methods for in-depth testing of structures include:

- Hammer sounding (or chain dragging) of concrete surfaces to determine cavities;
- Measuring cracks and comparing the results with preliminary measurements;
- Checking the tight fit of fastenings (screws, bolts);
- Measuring deformations (e.g., deflection) for possible conclusions on loss of bearing capacity;
- Measure displacements and gaps on bearings to detect irregularities;
- Chemical investigations (measuring the carbonation depth, determination of the chloride ion concentration) on concrete parts, to assess the risk of corrosion for the reinforcement;
- Testing of concrete strength using a rebound hammer.

According to (Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2013), non-destructive testing methods include:

- Electrochemical potential measurement for determination of active chloride-induced reinforcement corrosion in reinforced concrete structures;

- Ultrasonic echo and impact echo methods for detecting cavities in the concrete, for determination of separation zones of the reinforcement, or for localization of un-pressed areas in ducts from tendons;
- Infrared thermography to localize moisture damage;
- Radar measurements, laser measurements for large-area preliminary investigation.

For a proper description of inspection findings, each classified damage occurrence needs to be assigned to a classified element. An example of the bridge inspection report with damages explicitly assigned to elements, in accordance to ASB-ING classification is provided in the Report 4.2. German NRA, BASt, does not specify which bridge elements are to be inspected, but suggests examining all visible ones.

Danish NRA, Vejdirektoratet, also mandates the examination of all visible elements within the scope of routine inspection, whereas it strictly specifies the elements to be examined during the special inspection. According to (Vejdirektoratet, 2020), the following elements, or groups of elements, are observed:

- The entire structure
- Wings
- Slopes
- End supports
- Intermediate supports
- Bearings
- Load-bearing superstructure
- Waterproofing
- Edge beams
- Safety barriers / parapets
- Road surfacing
- Expansion joints
- Drainage structures
- Underpasses
- Other Elements

4.4 Information Container for Road Maintenance Data

4.4.1 Property sets for asphalt pavements

The data sets are used to describe the condition of asphalt pavements in detail. The data sets are implemented as extended property sets using the IFC, which are then attached to the corresponding bridge or pavement segment and layers of a bridge respective road model. To ensure that the additional properties can also be queried uniformly, an ontology is defined. This means that the condition information can also be stored in a separate file based on the ontology. The external file with the condition information is then only linked to the model and not directly integrated. Both options can be used to provide the information needed for maintenance planning. The following section shows the extended property sets (ePset) for asphalt performance and asphalt condition rating.

The developed property sets for asphalt pavements are included in report D4-2.

4.4.2 Ontologies for maintenance planning of roads

Condition assessment provides important information for determining maintenance needs. To create information containers for maintenance planning, an ontology for asphalt condition assessment has been defined (see Figure 30). The same properties are used as in the example for using a property set (see previous Chapter). The ontology for asphalt condition assessment has the prefix aca. The ontology consists of eight main classes shown in Figure 30. The class *aca:SurfaceProperties* contains further subclasses for details condition of pavement surface. In addition to the classes, associated DatatypeProperty are also defined as shown in the right side of Figure 30.

The maintenance location is described using a name or identifier of the road, comprising the start point, the end point, and the lane number. For the maintenance action, information om the type of action, a detailed description, the recommended year for performing the action and the estimated costs is stored in the ontology. The maintenance program ontology is created with the prefix maintp. It contains two classes maintp:Location and maintp:Measure as shown in Figure 6. Each class include the DataTypeProperty for the basic information. This ontology can be extended for individual needs.

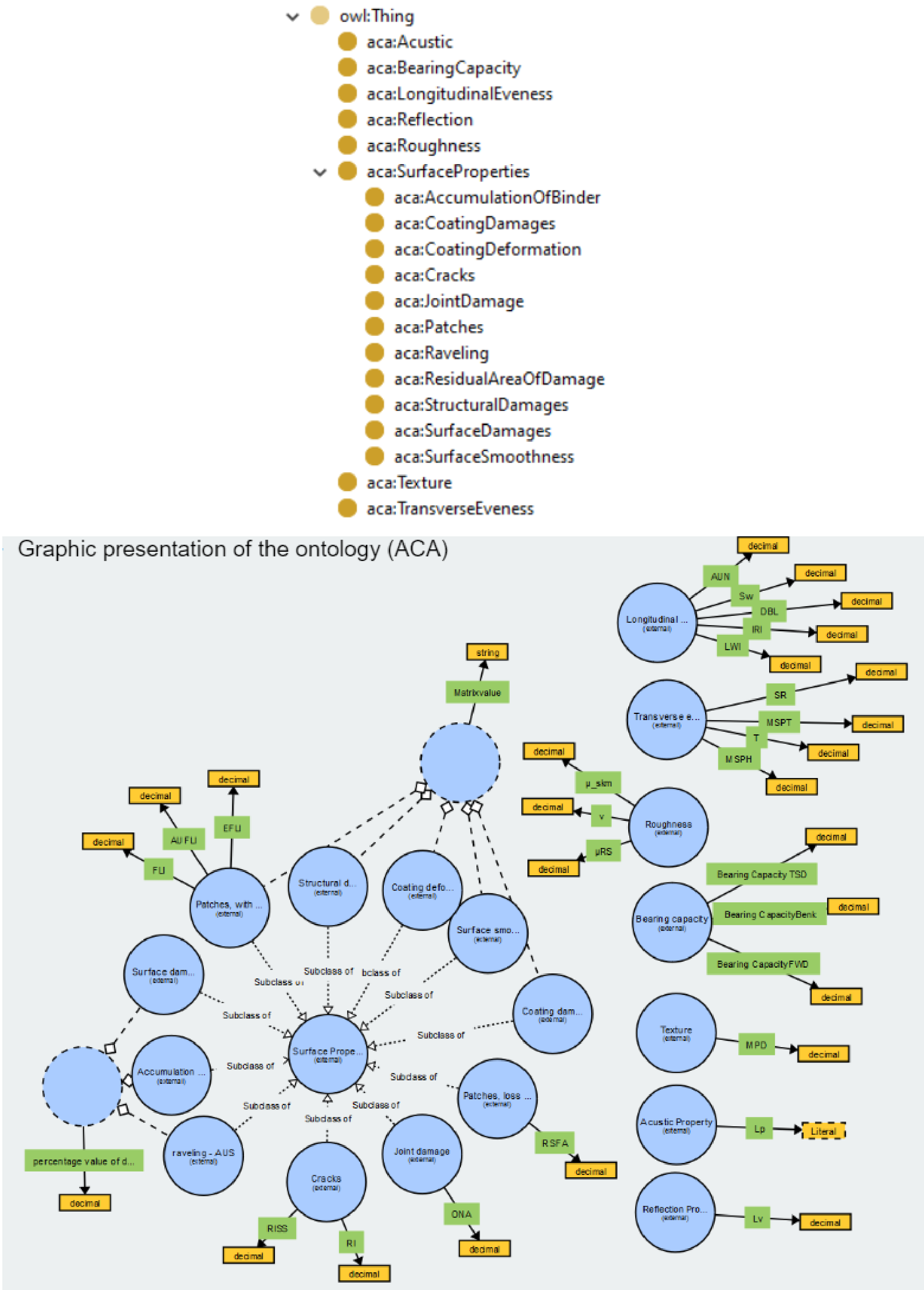


Figure 30: Asphalt condition assessment ontology (ACA)

4.4.3 Maintenance program

A maintenance program is delivered as result of the maintenance planning. The essential information can be modelled as instances of the maintenance program ontology, which can be linked with road sections. Currently, no specific report template for the maintenance program has been provided by the road administrations as an example. The developed report template of maintenance program as XML schema contains some meta information about the road, the corresponding engineer consultant and the recommend actions as shown in Figure 31.

Meta information of the road

Meta information of maintenance planning

Maintenance program of road section

```xml
<?xml version="1.0" encoding="utf-8"?>
<xs:schema targetNamespace="http://amsfree.eu/MaintenanceProgram"
    elementFormDefault="qualified"
    xmlns="http://amsfree.eu/MaintenanceProgram"
    xmlns:mstns="http://amsfree.eu/MaintenanceProgram"
    xmlns:xs="http://www.w3.org/2001/XMLSchema"
>
  <xs:element name="MaintenanceProgram" type="MaintenanceProgramType"/>
  <xs:complexType name="metadataPavementType" mixed="true">
    <xs:sequence>
      <xs:element type="xs:string" name="adminAuthority"/>
      <xs:element type="xs:string" name="roadID"/>
      <xs:element type="xs:string" name="roadName"/>
      <xs:element type="xs:string" name="roadDesign"/>
      <xs:element type="xs:gYear" name="constructionYear"/>
      <xs:element type="xs:string" name="pavementTypeMaterial"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="metaDataMaintenancePlanType" mixed="true">
    <xs:sequence>
      <xs:element type="xs:string" name="consultEngineer"/>
      <xs:element type="xs:string" name="consultDate"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="headerType" mixed="true">
    <xs:sequence>
      <xs:element type="xs:short" name="MaintenanceYear"/>
      <xs:element type="metadataPavementType" name="metadataPavement"/>
      <xs:element type="metaDataMaintenancePlanType" name="metaDataMaintenancePlan"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="roadSectionType" mixed="true">
    <xs:sequence>
      <xs:element type="xs:string" name="typeMeasure"/>
      <xs:element type="xs:string" name="descriptionMeasure"/>
      <xs:element type="xs:gYear" name="measureYear"/>
      <xs:element type="xs:float" name="measureEstimatedCost"/>
    </xs:sequence>
    <xs:attribute type="xs:float" name="startPoint" use="optional"/>
    <xs:attribute type="xs:float" name="endPoint" use="optional"/>
  </xs:complexType>
  <xs:complexType name="measureType">
    <xs:sequence>
      <xs:element type="roadSectionType" name="roadSection" maxOccurs="unbounded" minOccurs="0"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="tableType">
    <xs:sequence>
      <xs:element type="measureType" name="measure"/>
    </xs:sequence>
  </xs:complexType>
  <xs:complexType name="MaintenanceProgramType">
    <xs:sequence>
      <xs:element type="headerType" name="header"/>
      <xs:element type="tableType" name="table"/>
    </xs:sequence>
  </xs:complexType>
</xs:schema>
```

Figure 31: Maintenance program as XML schema

4.5 Information Container for Bridge Condition Assessment (IMC / RUB)

4.5.1 Ontology resources

In the context of bridges, ontologies provide unambiguous names of bridge elements and a clear explanation of their meaning. For the information containers, bridge classification ontologies will represent a supplementary information, improving readability of the payload documents, i.e., IFC files. In other words, ontologies will serve as a key for reading an IFC file. By providing an ontology for bridge element classification, any NRA will be able to relate any part of its inventory with specific IFC elements, or groups of elements.

Using ontologies to classify bridge elements, two existing gaps for linking different IAMS with BIM models are addressed. The first one is caused by the different bridge decomposition (i.e., element hierarchy) used in various NRAs, whereas the second one is caused by different classification of structural elements between NRAs. Figure 32 illustrates a typical bridge decomposition difference between NRAs. For clarity, only the bridge structure is considered. Red arrows represent a hierarchical approach, whereas blue arrows represent direct decomposition. The bridge is firstly decomposed in two general element groups (red arrows): superstructure and substructure. Afterwards, each group is decomposed into separate elements. The blue arrows, on the other hand, show an approach where the bridge is directly decomposed into separate elements. In practice, this means that the "red", approach enables an information to refer to the entire substructure or superstructure, as well as to separate elements. The "blue" approach, however, limits this information referencing only to separate elements.

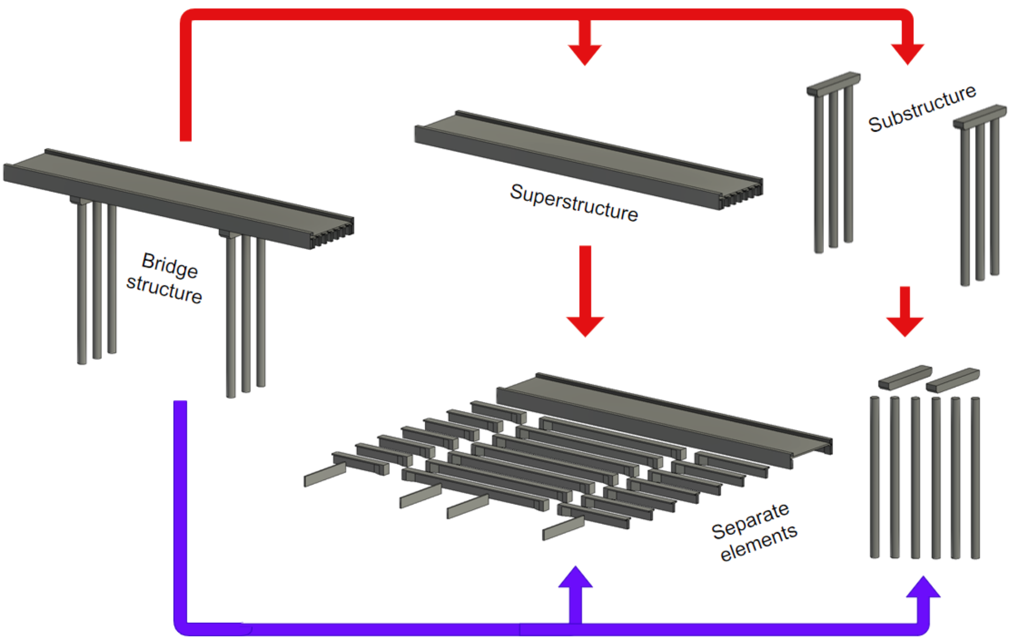


Figure 32: Different approaches of bridge structure decomposition used in different NRAs

The classification difference is mainly related with language differences but is also a result of differently established bridge management practices between countries. The lack of definitions of bridge-specific concepts in the official schema releases of the IFC data format, and limited export capabilities of the commercial BIM software are perhaps the most important implementation issues. By relating the IFC model with the element classification ontology, each bridge element will be associated with the corresponding label from the ontology. This means that element semantics will be independent of the IFC entity representing it. This means that every bridge element could be modelled as IfcBuildingElementProxy (IFC 4.0.2.1) or IfcBuiltElement (IFC 4.3) or combination of these, but it would be assigned to element type according to the provided element classification ontology before introducing to the IAMS. Therefore, the proposed approach fully complies with both the official IFC 4.0.2.1 scheme (BuildingSMART International, 2020), as well as with any upcoming release.

A detailed description of the classification of bridge elements in Germany, Denmark, and Netherlands can be found in report D4-2.

4.5.2 Payload documents

Bridge model

The proposed approach for establishing relations between elements of infrastructure asset from various IAMSs and corresponding BIM elements requires a reasonably fine-grained fragmented BIM. The fragmentation density needs to comply to the depth of the deepest and most detailed element classification hierarchy (as explained in Deliverable D6: Guidelines Exchange of Linked Data, these hierarchies, if exist, are converted into ontologies for further use). Out of three exemplary NRAs, German BASt has the deepest classification ontology, ASB-ING. Thus, the targeted BIM fragmentation density of the test case model complies with the depth of ASB-ING. Figure 33 shows the abutment decomposition according to (Haveresch & Maurer, 2010).

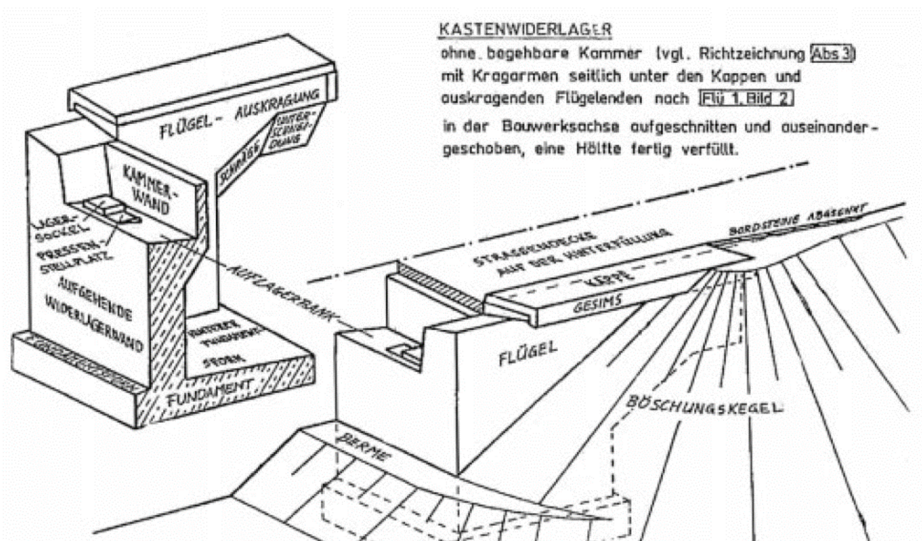
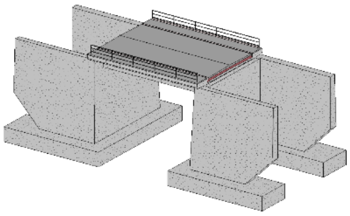
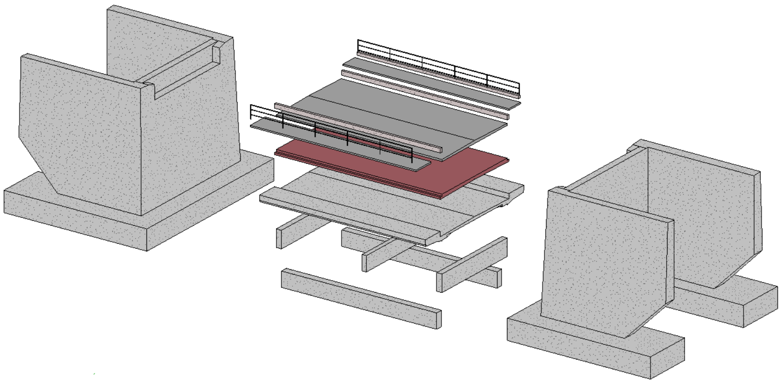


Figure 33: Abutment decomposition. Retrieved from (Haveresch & Maurer, 2010)

The exemplary BrIM is generated as a part of the doctoral dissertation research (Isailović 2020) It is a model of a 12.5 meter spanned simply supported double girder bridge made of reinforced concrete. Figure 34 shows the original model comprising 16 elements (i.e., instances of *IfcBuildingElement* subclasses).



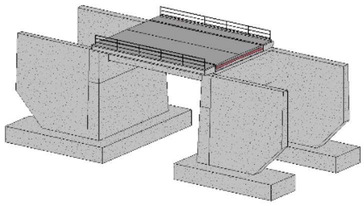
(a)



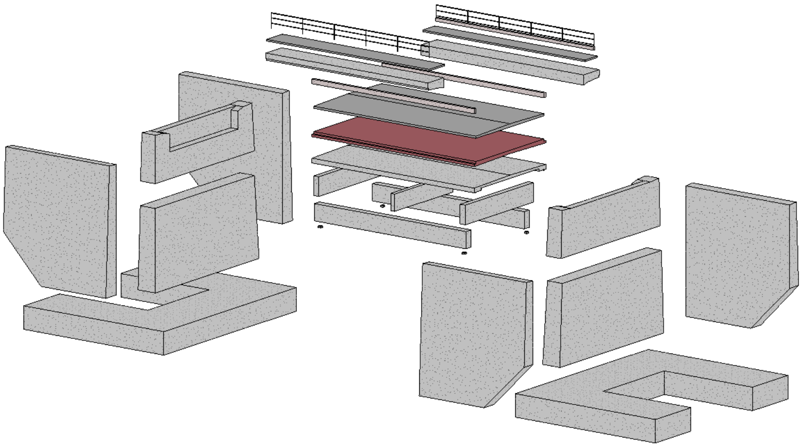
(b)

Figure 34: Original exemplary BrIM: (a) collapsed, and (b) exploded view

The original BrIM could not represent all the elements listed in the ASB-ING hierarchy. More precisely, abutments were modelled as monolithic elements, thus preventing one to address all the abutment sub elements shown in Figure 33. The deck was also represented by a monolithic element. Therefore, the bridge was remodelled by dividing the abutment into five independent elements (support bench, front wall, two wing walls, and foundation), whereas the deck was divided into three elements (one deck with two deck consoles). Finally, four bearings are modelled as simple rectangular prisms. The resulting BrIM (Figure 35) comprises 30 elements (i.e., instances of IfcBuildingElement subclasses).



(a)



(b)

Figure 35: Remodelled exemplary BrIM: (a) collapsed, and (b) exploded view

As a part of preparatory work for the prototypical software implementation, each relevant concept from all three national ontologies is related to corresponding BrIM element.

Data schema for bridge inspection reports

Currently, the result of a bridge inspection is documented in a (paper) report. The report contains the documented damage and includes an overall assessment. The form and content of such reports are country specific. Each country has its own templates. Examples from Germany and Denmark are presented below. For such reports to be digitally evaluated and linked to individual bridge elements, a data schema must be defined. For this purpose, XML schemas have been developed for the individual countries. In report D4-2 the content as well as the implementation of a report using XML for Germany and Denmark is described.

4.5.3 Inspection finding

Once the damage is identified and classified, in order to be completely described, its location needs to be represented in an unambiguous way. Whereas assigning a damage to the specific element provides an information on the rough location of the damage, the precise damage location is still missing. To fill this information gap, the report D3.2, named “Information Delivery Manual (IDM) for condition assessment”, proposes defining areas for locating information for condition assessment, in a form of the extension of the BIM model of the assessed asset (i.e., *LocalPlacement.ifc*. As a preparatory task for defining these areas, a real inspection report is discretized by extracting the key phrases and measures describing the damage locations.

Some changes of the original location descriptions, written in the report, has been made, so that they can fully correspond to the exemplary bridge model. The complete list of discretized descriptions of damage areas is provided in the Appendix 7.9 (damage area in the appendix table). In addition to the discretized damage location, this appendix provides the exact damage classification for each inspection finding entry, based on ASB-ING.

4.6 Reference architecture for BIM-based asset management

For asset management of bridges and roads, different data sources have to be merged and evaluated as a whole. Different approaches and legacy systems have been developed in different countries over the last decades. In many cases, individual databases and interfaces have been developed for specific applications. Geographical information systems (GIS) have essentially been used for the geographical location and description of surfaces (e.g. for road management). With the introduction of BIM, three-dimensional information is now available. BIM models provide new possibilities for the planning, construction and operation of bridges and roads.

The AMSfree project follows the approach in using existing legacy systems for BIM-based asset management with the help of Linked Data concepts. In contrast, a central database in the sense of a data warehouse could also be developed, which stores only the necessary information from the legacy systems. A data warehouse is a topic-oriented, integrated, chronologized and persistent collection of read-only data to support management in its decision-making processes. However, a major challenge of a data warehouse approach is that the information from the individual connected databases must be transferred to the central database at regular intervals.

Therefore, the main difference of the Linked Data approach is that no data is copied and instead used directly from the individual data sources for the asset management processes via standardized queries. A similar approach is used in ISO 21597 to exchange data by using information containers. The proposed reference architecture for BIM-based asset management consists of a total of five layers (cf. Figure 36):

Data layer: it comprises the existing legacy systems for asset management. It is essential that only one source is responsible for managing data required in Asset Management processes. If information needs to be stored in two databases, the system responsible for management must be clearly identifiable.

Access layer: It must be possible for each legacy system to access the data contained. Different access options usually exist for the different systems. A user login is usually required for access. A system should also have the opportunity of integrating a single sign-on concept. With the single sign-on concept, a user can access all services for which he is authorized from the same workstation after a one-time authentication without logging on to the individual services each time.

Ontology layer: Uniform access to data is provided using the Resource Description Framework (RDF). For this purpose, the data models of the legacy systems must be modelled using RDF. In general, RDF provides standardizations for the vocabulary used to characterize ontologies. To prevent the ontologies and RDF description from becoming too complex, only relevant information from the underlying systems should be modelled. If all systems are mapped in this way, standardized query languages (e.g., SPARQL) can be used to access the data. SPARQL is an RDF query language to retrieve and manipulate data stored in RDF format. The ontology layer must be implemented and available for each data source or system.

Linking layer: A linking layer can be built to link the different data sources using the RDF approach. The link layer is also implemented using RDF. Similar concepts are also provided in ISO 21597. In addition, higher-level ontologies can also be defined. This allows terms to be merged even though they have different names or identifiers in the individual systems. Uniform queries can be realized across all data sources through the linkage and the additional ontologies. This approach is also the basis of the Semantic Web and has already been successfully implemented for other applications. In addition to SPARQL, GeoSPARQL can also be used to enable geographic queries. GeoSPARQL is a standard for representing and querying geospatial linked data for the Semantic Web from the Open Geospatial Consortium (OGC). The definition of a small ontology based on well-understood OGC standards is intended to provide a standardized exchange basis for geospatial RDF data which can support both qualitative and quantitative spatial reasoning and querying with the SPARQL database query language. The linking layer should be operated centrally by the respective national authorities.

Application layer: The application layer is only considered in a simplified form in the following. The application layer is used for the higher-level use of the data. Services for importing and exporting data as well as options for analysing and visualizing data are implemented. For this purpose, individual queries or update commands are implemented on the basis of SPARQL. In addition to updating, the standardized visualization of geometric data in particular is a major challenge. For geometric querying, various concepts have been developed in recent years for the IFC data format and other GIS-based data formats. In the context of the AMSfree project, only a rudimentary examination can be made with regard to geometric queries. The research project's focus will be on importing, exporting, and retrieving selected information for bridge and road asset management.

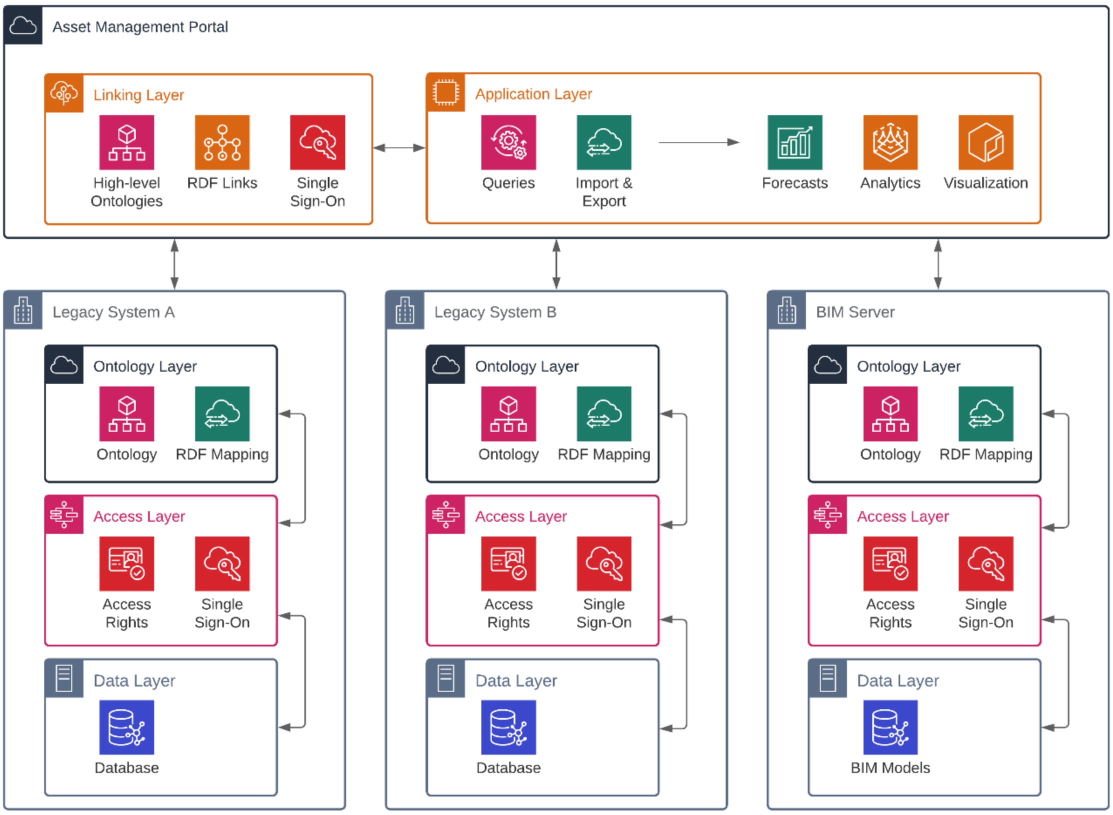


Figure 36: Reference architecture for BIM-based asset management

5 Development of a referenced vendor-free IFC-based data structure

5.1 IAMS-oriented Information Delivery Manual (IDM)

By introducing Information Containers, the information transfer between a Building Information Model, BIM and Infrastructure Asset Management System, IAMS is established. For the information from the Information Container for linked Document Delivery (ICDD) to be fully utilized, an information exchange between BIM and ICDD on one hand, and between ICDD and IAMS on the other, needs to be enabled. Whereas the former one is enabled by the providing the resource ontologies, the latter one needs to be established by means of Information Delivery Manual (IDM) for the integration of RDF-based data from the information container (i.e., Data structure compliant to the ICDD - ISO 21597) into the existing IAMS (relational database).

In order to precisely depict the scope of information exchange between ICDD and IAMS, and example of a use-case for condition assessment is shown in Figure 13 in the report section 3.2. The focus here is on the information flow between ICDD and the AMS database by the activity “Prepare Condition Assessment” and “Import ICDD Condition Assessment” defined in the process map. In a simplified form, this information flow is shown in Figure 37. On the left-hand side is the ICDD, whose content depends on the use case. On the right-hand side, the Infrastructure Asset Management (IAMS) database is shown. In between, a sub-process of the data transfer between ICDD and IAMS is shown. The same form of information flow can be applied for use cases on maintenance, considering roads and structural assets.

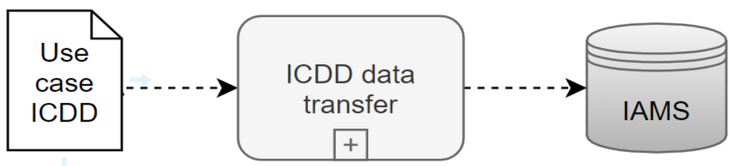


Figure 37: Simplified process model for transferring data from ICDD to the IAMS database

The sub-process “ICDD data transfer” is described in more detail in an expanded view, shown in Figure 38. The proposed process model heavily relies on the approach thoroughly described by (Liu et al., 2021). The data transfer utilizes the information transformation schemas proposed by (Costa & Sicilia, 2020). The ontology is mapped to the IAMS database following the approach of (Afzal et al., 2016).

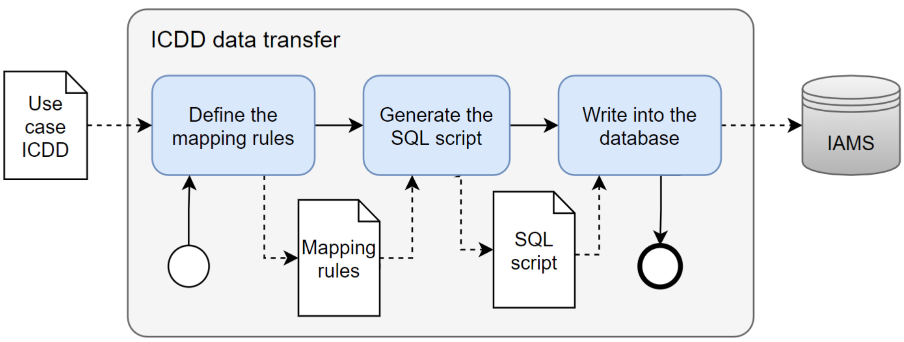


Figure 38: Process model for transferring data from ICDD to the IAMS database (BPMN)

As opposed to the information exchange between human actors, here all the activities including the data exchange is done automatically. Firstly, the rules for mapping the ontology entities to the database are defined. Here, the ontology type may refer to the multiple object instances in the BIM model, thus needed to be mapped to the multiple database entities. (Costa & Sicilia, 2020) labelled such mapping scenarios as “many to many attributes”. Once the mapping rules are defined, the SQL script targeting the correct database entities is generated. This is done by means of SPARQL-Construct queries. A detail working example, including the SPARQL code, is provided by (Liu & Hagedorn, 2021). Finally, the SQL script imports the ICDD data to the IAMS. A thorough specification of this process model is shown in Figure 39.

Process Model			
Name:	PM_ICDD-IAMS_data_transfer		
Identifier:			
Authors:			
Create Date:			
Document Owner:			
Task	Name		Description of Task
	Define the mapping rules		Pairing of ontology types from ICDD with corresponding IAMS database entries
	Generate the SQL script		Automatic generation of the code for the SPARQL-Construct query which singles out the entities to be written into the IAMS database
	Write into the database		Automatic fill of the IAMS database table with the selected data from the ICDD
Exchange Requirements	Name	Type	Description of documentation
	Use case ICDD	ICDD	Information Container for linked Documentation Delivery whose content depends on the use case.
Object Data	Name	Type	Description of Object Data
	IAMS		Infrastructure Asset Management System

Figure 39 Process model for transferring data from ICDD to the IAMS database (table specification)

5.2 IAMS-oriented Application and Extension of the IFC Standard

According to the requirements for the use of digital models in operation, e.g. inspection and maintenance plan, the associated information containers for bridge inspection and pavement maintenance planning have been defined in terms of content and linkage between the different data source. The necessary ontologies for these activities have also been developed according to the national guidelines and standards from three of the project funding countries (Germany, Netherlands and Denmark). The Model View Definition (MVD) for the exchange of the IFC model according to the defined use case is created. Using ontologies, the semantic information of the inspection and maintenance plan can be captured as rdf-based data in the information container.

The IFC model primarily provides the geometry in sufficient granularity of the structure and the pavement. Nevertheless, it is possible to add semantic information directly within the IFC schema as properties. If property sets are added directly to the IFC model, appropriate software must be available and attention must be paid to ensuring that fundamental structures are not changed during the IFC export. By exchanging models via IFC, the exchange requirements of the defined use case must be complied with. These can be defined as rules using the MVD. It provides a technical solution to capture the use case specific rules in a machine-readable format mvdXML (Borrmann, König, Koch, & Beetz, 2015). The user can define an own MVD on the specific requirement as mvdXML. Although the mvdXML can be defined using any text editor, a free tool IFCDOC.EXE (IfcDoc Tooltik, 2021) provided by the bSI can be used for generation of user-defined mvdXML. As presented in (Chipman, Liebich, & Weise, 2012), the mvdXML must contain two constituents: templates and views. Templates provide reusable concept as templates, which include the applicable schema, the applicable entity, the rules with attribute definitions. The view contains a set of model views, which include the exchange requirements and the referenced concept.

Based on the defined property sets for the pavement and asset management activities, there are three MVD examples defined with the selected properties:

1. MVD handover for operation with drillcore properties
2. MVD bridge inspection with condition assessment properties
3. MVD maintenance plan with measurement properties

In example 1, the properties shown in Table 1 must be contained for the drill core modeled as *IfcBuildingElementProxy.* The defined MVD is considering this information requirements shown in Figure 40.

Table 1 ePSET_Stiffness_FourPointFlexuralTest

Name	**Property Type**	**Data Type**	**Description**
e6	P_SINGLEVALUE	IfcReal	strain, corresponding a long-term durability of 106 cycles
A0	P_SINGLEVALUE	IfcReal	parameter A0 of fatique curve
A1	P_SINGLEVALUE	IfcReal	parameter A1 of fatique curve

```xml
    <Views>
        <ModelView applicableSchema="IFC4" uuid="ccebc969-c653-4fcf-beae-490d8900d874" name="Model View for drill core">
            <ExchangeRequirements>...</ExchangeRequirements>
            <Roots>
                <ConceptRoot applicableRootEntity="IfcBuildingElementProxy" uuid="1ad6be69-2f8a-4511-8b34-9e58e9dfe927" name="Concept Root for drill core">
                    <Applicability>
                        <Template ref="25c1a3ac-8d85-4626-8539-bddddc58e1fa"/>
                        <TemplateRules>
                            <TemplateRule Parameters="SetName[Value]='drill core'"/>
                        </TemplateRules>
                    </Applicability>
                    <Concepts>
                        <Concept uuid="debf4990-515f-4228-bf0a-2efcf9e37657" name="Concept for drill core">
                            <Template ref="25c1a3ac-8d85-4626-8539-bddddc58e1fa"/>
                            <Requirements>
<Requirement exchangeRequirement="5edcf49f-80d7-4894-97a0-854177a6844c" requirement="mandatory" applicability="export"/>
                            </Requirements>
                            <TemplateRules operator="and">
<TemplateRule Parameters="PropName[Value]='e6' AND PropNominalValue[Exists]=TRUE AND PropNominalValue[Type]='IfcReal'"/>
<TemplateRule Parameters="PropName[Value]='A0' AND PropNominalValue[Exists]=TRUE AND PropNominalValue[Type]='IfcReal'"/>
<TemplateRule Parameters="PropName[Value]='A1' AND PropNominalValue[Exists]=TRUE AND PropNominalValue[Type]='IfcReal'"/>
                            </TemplateRules>
                        </Concept>
                    </Concepts>
                </ConceptRoot>
            </Roots>
        </ModelView>
    </Views>
</mvdXML>
```

Figure 40: The selected code of mvd example 1 - model view section

In example 2, the properties shown in Table 2 must be contained for all bridge components modeled as *IfcObject*.

Table 2 ePSET_Condition

Name	**Property Type**	**Data Type**
durability	P_SINGLEVALUE	IfcReal
traffic safety	P_SINGLEVALUE	IfcReal
structural safety	P_SINGLEVALUE	IfcReal

In example 3, the properties shown in Table 3 must be contained for the pavement road modeled as *IfcBuildingElementProxy.*

Table 3 ePSET_Maintenance_Measure

Name	**Property Type**	**Data Type**	**Description**
year			

P_SINGLEVALUE

IfcDate

recommended year of measure

measure

P_SINGLEVALUE

IfcText

description of measure

cost

P_SINGLEVALUE

IfcReal

estimated cost of measure

5.3 Linking Guide to the OTL

Depending on the national standards and guideline, the necessary ontologies for bridge inspection and pavement maintenance plan are defined for three countries. These ontologies differ to each other. For the infrastructure, a European road object library (EUROTL) as ontologies were developed in the INTERLINK project for the gathering and exchanging the asset information throughout the life-cycle of assets. This ontology provides a set of classes, which support the basic information needs for asset management. For using this efficiently, the nationally defined ontology should be linked with it.

The recommendations from the INTERLINK project are followed to create understandable and reusable ontologies. In general, an ontology can be defined by the languages RDFs, OWL and SHACL. These languages provide classes, data, their relationships, and restriction types that can be used to define attributes and objects as well as constraints. As suggested by INTERLINK, the ontology should be modeled in "The Simple Way" (Böhms, O'Keeffe, Stolk, Wikström, & Weise, 2018). This means that OWL and SHACL are combined for modeling in the direct way. The value attributes can generally be modeled as owl:DatatypeProperty's, and the relationship as owl:ObjectProperty's. Although the constraints can be modeled as OWL constraints. The class, property and data type names should be human readable. To improve readability for classes, properties, and data types, additional annotations can be added using rdfs:label. The rdfs:comment can be used for the description.

In the case of decentralized data, ontologies and datasets are usually created, edited, and stored by different parties. To link this data, RDF, OWL and SHACL have specific vocabularies that can be used to define the links. To actually mark two things as the same, owl:sameAs must be used, as suggested by INTERLINK. It also introduces three levels of linkage:

1. Class-level linking means how to map classes and properties in different ontologies.
2. Model-level linking means how to relate the different models to each other
3. Instance-level linking means how to relate the instances or objects to each other

The linking data sets on the instance-level can be realized by the information container according to (ISO 21597-1, 2020), that provides the opportunity to create and collect link sets. The linking Ontology for the class-level can be realized by creating an alignment ontology.

The predefined ontologies for bridge damage, condition assessment, and maintenance programs for pavements can then be linked to EUROTL using alignment ontologies shown in Table 4 and in Figure 41.

Table 4 Overview of alignment ontologies for the predefined inspection and maintenance ontolo-gies linking with eurotl

Prefix	Namespace	Description	Illustration
CODEX2EUROTL	<http://www.roadotl.eu/codex2eurotl >	Linking between bridge damage ontology cod, codex and the eurotl	Figure 13 -a
COAS2EUROTL	<http://www.amsfree.eu/ontology/ coas2eurotl/>	Linking between ontology of condition assessment and eurotl	Figure 13 -b
MAINTP2EUROTL	<http://www.roadotl.eu/maintp2eurotl/def/>	Linking between ontology maintenance program and eurotl	Figure 13 -c

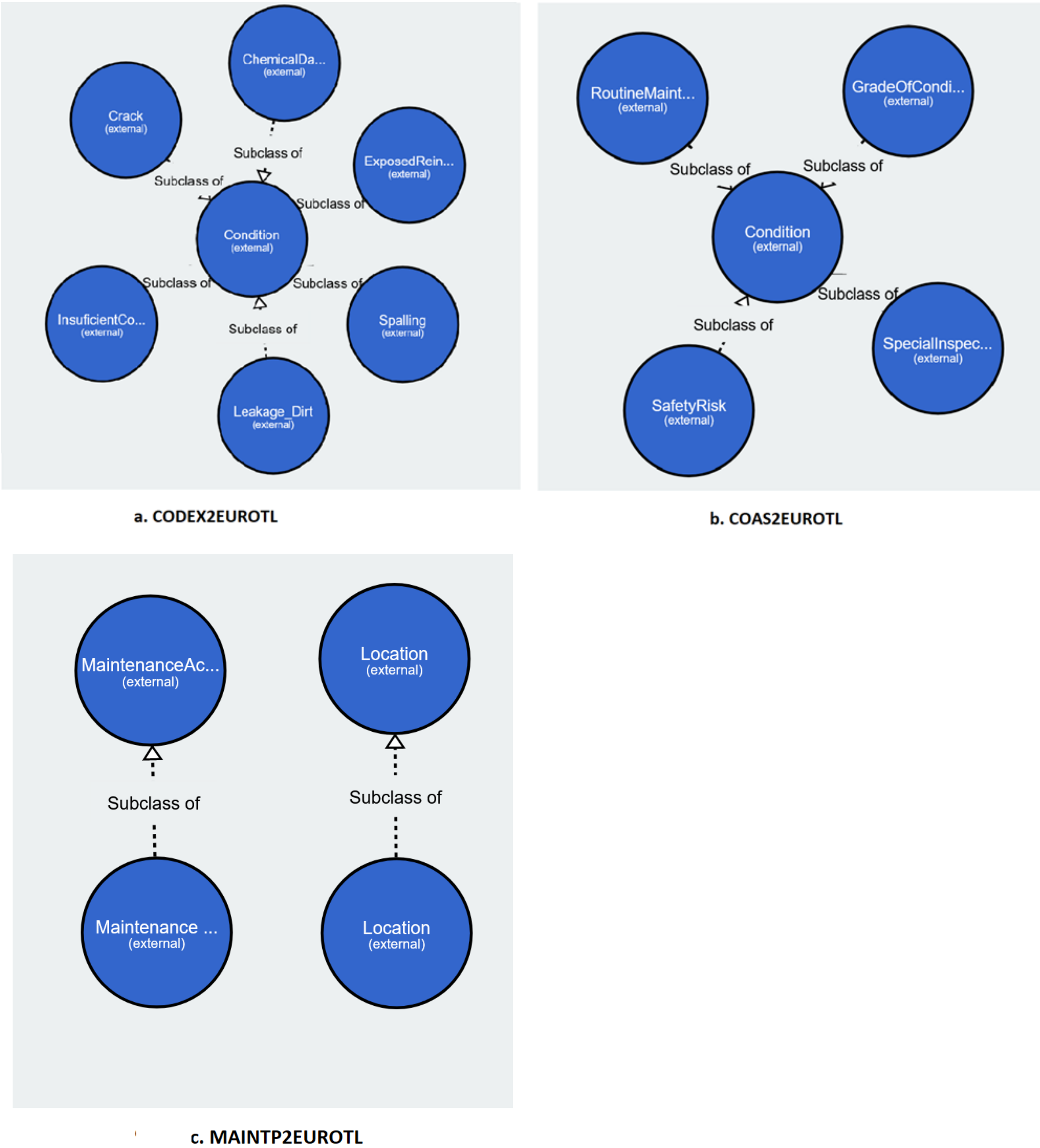


Figure 41 :Overview of alignment ontologies between domain specific ontology and eurotl

6 Data Exchange to Legacy Systems using information containers

6.1 Guideline IFC Property Mapping

6.1.1 Aim of the guideline

The aim of the guideline is to provide potential users of Building Information Modelling (BIM) from National Road Authorities (NRA) with a guideline to implement approaches developed in the AMSFree project. This document includes a guideline for exchanging linked data between Infrastructure asset management systems (IAMS) and BIM by using information containers. It includes the development of a transformation concept for data exchange between different IAMS systems and a procedure for the systematic integration of existing asset data in different NRA by means of ontologies.

This guideline provides a basis for data exchange between IAMS databases and BIM models. This includes the description of the proposed approach, including use cases, the software and data/file formats used as well as an illustrative application of the developed concepts on the example of a road section and a bridge. It gives a detailed explanation on how to proceed as a user in updating the AMS database to mirror physical reality. The appendix includes the guideline for IFC property mapping (D6.1), some examples on property mapping (D6.2) and the IFC mapping software architecture (D6.3). Therefore, this chapter briefly describes the IAMS and the relationship between AMS and BIM. Subsequently, the generic process and the data updates related to existing infrastructure assets are described. This method is finally illustrated in different use cases.

6.1.2 BIM Creation Workflow and Software Tools

Data exchange and linking between BIM models and IAMSs is significantly facilitated by using IFC file format developed by buildingSMART International (bSI). Being neutral, this format provides free two-directional access to all parts of the model. The semantic quality of the BIM model in the IFC representation depends on the IFC schema used for the IFC export. The latest official schemas are IFC4 ADD2 TC1 (ISO 16739-1:2018) and IFC2x3 TC1 (ISO 16739:2005). These schemas mainly define building-related concepts. Nevertheless, quite intensive activities on extending the official schemas are currently in progress. The soon-to-be-released IFC 4.3 will provide definitions of all the relevant concepts for the infrastructure domain. Geometry-based, the proposed approach is applicable on any IFC file, regardless of the schema version. The asset management information flowing between IAMSs and BIMs is mainly provided by the information container, not the IFC semantics. The exception is the condition assessment data conveniently stored in the IFC, using the entities defined in the latest IFC schema extensions. However, these exceptions are addressed in the prototype software processing the input IFC file, thus not affecting the BIM handover requirements.

The BIM modelling approach should be selected depending on the type of the model to be created. The following three cases are considered:

- as-designed
- as-built
- and as-is BIM modelling.

BIMs are usually produced in the design stage and updated later due to changes during the later construction project phases. The final version of a BIM should reflect the condition of a real asset at the moment of commissioning. This type of BIM is called “as-built BIM”. However, the typical workflow in the construction industry does not imply such a prompt up-date of the project documentation in the late project phases.

Instead, the final BIM usually corresponds to a particular late design phase or a construction phase. This type of BIM is called “as-designed BIM” resp. as-built BIM, which will be handover to the IAMS.

Whereas the two described types of BIM refer to the starting point of the asset’s life span (whether in the design or in the construction phase), the as-is BIM refers to the current state of the asset. Its purpose is to reflect the geometric changes of the asset caused by deterioration or maintenance actions. Creating such a model is more of an update of the as-built one, and it requires either the inspection field data or the design documentation of the maintenance works. Additionally, redundant information from the design phase will be removed or archived.

All created models (as-designed BIM model, as-built BIM model and as-is BIM model) are available individually and can be loaded individually via a prototype.

In the context of Building information modelling (BIM) software it can be distinguished between authoring software, coordination software and Common Data Environments.

Building information modelling (BIM) software includes computer-aided design (CAD software) products used commonly within the architecture and construction industries. Many of these products offer tools and libraries specifically targeted toward construction, including mechanical, electrical, and plumbing (MEP) and building information modelling (BIM). The most widely used BIM authoring software are currently:

- Revit
- Civil 3D
- Allplan
- ArchiCAD
- CARD1 (for road design)
- proVI (for road design)
- VESTRA
- Tekla

For the time being, most of the above-mentioned BIM modelling software provide the export of IFC 4.1. With regard to the alignment of roads, IFC 4.1 does not offer satisfying solutions.

During the design and construction phase of an asset many different parties are involved who update the original planning and document the construction process often simultaneously. In order to improve the coordination between all parties, special software is used i.e., coordination software.

The goal of the coordination software is to combine this data into a single, comprehensive, multidisciplinary model, that can identify the potential collisions (clashes) across these different sources. These problems and inconsistencies are detected early on and are then successfully managed by the responsible teams. This helps in mitigating problems in the multi-level design that might arise in the future stages of the project. Some of the commonly used coordination software include Navisworks, Solibri and Bexel Manager.

A Common Data Environment (CDE) is a platform for data and information exchange during project execution. It represents a medium through which the project participants transfer and update project models, contracts, and other documents. This takes effect through a connected system like the internet, intranet, or more often using cloud-based storage solutions. By using a CDE, every project participant has access to the most recent version of the project data, which results in the more effective delivery of project results. Ordinary cloud-based storage solutions such as Google Drive, SharePoint, and Dropbox are commonly used as data exchange platforms. For more advanced usage and better convenience in the project and quality management, BIM 360 (Autodesk Build) can be used, as it also offers collision detection features and provides the availability to conveniently view the project models online.

6.1.3 Working with Ontologies

Beside the IFC model, semantic information can also be digitalized and stored as instances using ontology. Ontologies are used to provide data schemas and are described by a document or a file that formally defines the relations among terms. This is needed to define how to process and interpret data. By using ontologies different data can be semantically related, data can be linked across domains and the concepts behind the data can be described. Furthermore, the linking among data from different sources can also be realized. The ontology is developed according to the needs of the asset owner. In this report, we will give a short overview about the creation of an owl ontology. The focus of the report is mainly on the use of existing ontology, for instance, EUROTL for Infrastructure developed by INTERLINK project (O'Keeffe et al. 2018). That means, how the user can create the data as instance of a domain ontology using an appropriate tool.

6.1.3.1 Ontology Creation

A domain ontology, which had to match the needs of the asset owner, can be defined by Resource Definition Frameworks (RDFs) or Web Ontology Language (OWL). To define an ontology, these computer languages are suggested by the World Wide Web Consortium (W3C). However, regardless of the computer languages in which they are expressed the ontology formally organizes the domain under consideration by defining concepts and relations between them. In more concrete terms the domain ontology used by an asset owner must describe sufficiently well the transformation of its infrastructure over time. To this end, it is common that ontologies include classes, properties and constraints included in each class and relations between classes. With a clear picture of domain ontology and the context, one can define ontology in any form even purely textual. The formal description of ontology can be provided by UML (Unified Modelling Language). With a documented and visualized scope of the required domain ontology, the tools "TopBraid Composer" and "Protégé" can then be used for definition of an OWL ontology. In the AMSfree project TopBraid Composer was used to author classes and properties of a domain ontology. TopBraid Composer provides a dy-namic input formula related to the generation process of an ontology. The process is de-scribed in Report D6 "Data Exchange to Legacy Systems.

6.1.3.2 Semantic Information using Domain Ontology

Once the ontology is defined, the instances of ontology class and property can also be created by using TopBraid Composer. With the defined relations between the classes and properties in the ontology, the instances and their relationships are stored as triples like "subject - predicate - object". The triples can be recorded in data files with XML, Turtl or RDFs format. The links between the cross-ontology instances can be created within the information container. After the short overview about the creation of an ontology and instances, the use of an existing ontology is more important for the engineer activities. An example for a pavement condition survey using European Road OTL framework (EUROTL) for data collection will be shown. The EUROTL framework provides core definitions which cover basis classes considering the infrastructure asset life span shown in Figure 15. This core definitions can be extended or linked to further existing domain ontologies (e.g. OKSTRA OWL, IFC OWL).

In the example in Figure 42, the related data of a pavement condition survey will be collected as instances of the ontology. The main parts of the survey data are:

- the activity
- road section
- condition of the section

The instances of each part can be created by following class of the EUROTL:

- the activity as instance of class “InspectionActivity”
- road section as instance of class “Lane”
- condition of the section as instance of class “Condition”

Once the activity and road section are described as instances of the ontology, more data can be captured and related to the defined road sections using available properties. If the existing ontology does not cover the whole information requirement, extensions of the ontology should be discussed and created if necessary.

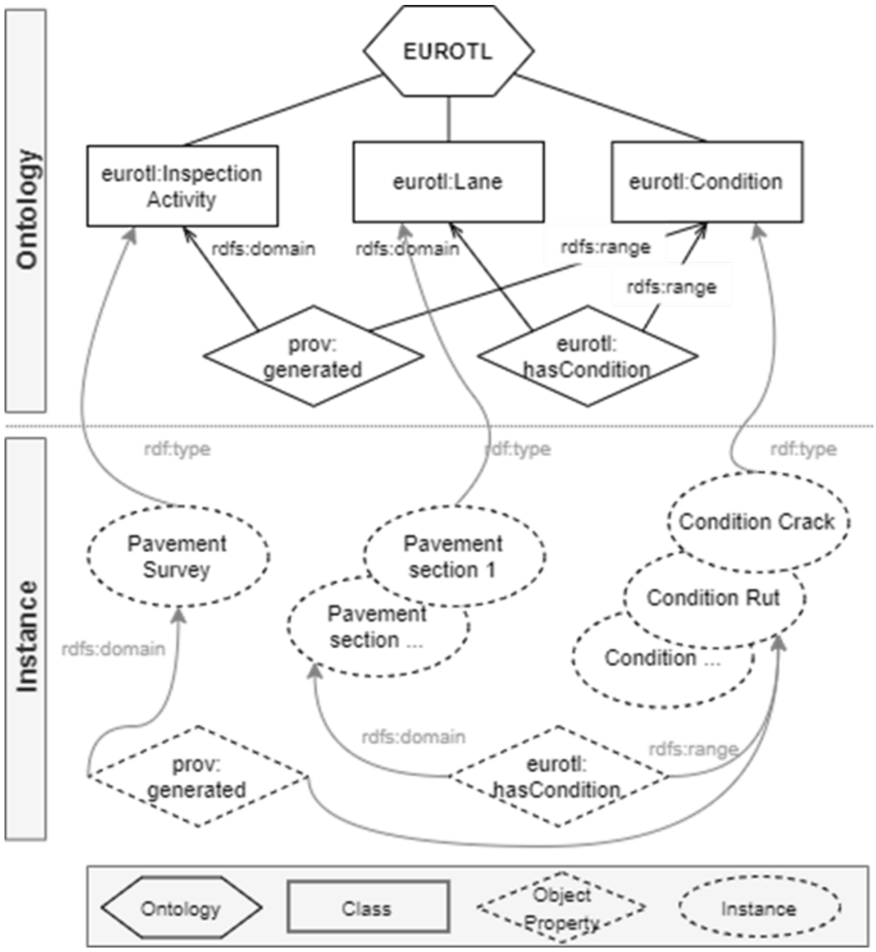


Figure 42 : Example for instances of ontology EUROTL

6.1.4 Information Container Overview

Very often, data in different formats have to be exchanged. In certain cases, it is not useful to convert all data into another format. For example, a conversion is not possible due to restrictions of the target format, or the software system only supports certain interfaces. It has also been shown that it is not always useful to exchange all information with the help of the IFC (Report D 5.2).

The ISO 21597 standard has been developed in response to the need of the construction industry to handle multiple documents as one information delivery or data drop. The ISO 21597 standard provides a specification for an information container. It enables a uniform approach to the way information is organized in data drops, providing a means to create semantic links between concepts in separate documents; it also provides a basis for additional functionality that allows a container to be customised for a given purpose, facilitating innovative software development that still conforms to the standard. The container format includes a header file and optional link files that define relationships by including references to the documents, or to elements within them. The header file uniquely identifies the container and its contractual or collaborative intention. This information is defined using the RDF and OWL semantic web standards. The header file, along with any additional RDF/OWL files or resources, forms a suite that may be directly queried by software. Where it includes link references into the content of documents that do not support standardized querying mechanisms, their resolution may depend on third party interpreters. Alternatively, the link references may be interpreted by the recipient applications or reviewed interactively by the recipient. The format can also be used to deliver multiple versions of the same document with the ability to convey the known differences or priority between them.

Within the scope of this task, a concept for the definition of information containers for data exchange with legacy IAMS is developed. Existing national data formats (e. g., OKSTRA, Interlis2) will be linked with the IFC format. It has to be documented which data is transported via which format (e.g., IFC, OKSTRA, Interlis2), which data is mapped to each other and how, and which consistency checks are necessary. For the creation of information containers according to ISO 21597, a framework developed by RUB is used.

The information containers are defined based on ISO 21597 and can therefore be used or extended easily and without restrictions by other users. Information container specifications are made available in neutral IDD format on the project website without restrictions to the CEDR members and the market. Thus, Information containers can be used when there is a national need for more information and to interact with existing legacy systems. This is a rather practical approach and allows the re-use of existing data formats. Of course, it must be ensured that the different systems can read and interpret the files contained in the container.

Once the IFC file representing the infrastructure asset is handover to the NRA, the data transfer between IFC and IAMS is enabled by means of the information containers. Information Container for linked Document Delivery (ICDD, ISO 21597) is the data structure intended for handling a variety of interrelated documents. The documents in the container are contextualized, and the data is linked according to the ICDD specification. All the information stored in the container is described by means of ontologies, also the part of a container. The generic ICDD consists of four components (see Figure 43):

- index.rdf (description of the container content)
- Ontology resources folder (ontology storage)
- Payload documents folder (documents storage)
- Payload triples folder (links storage)

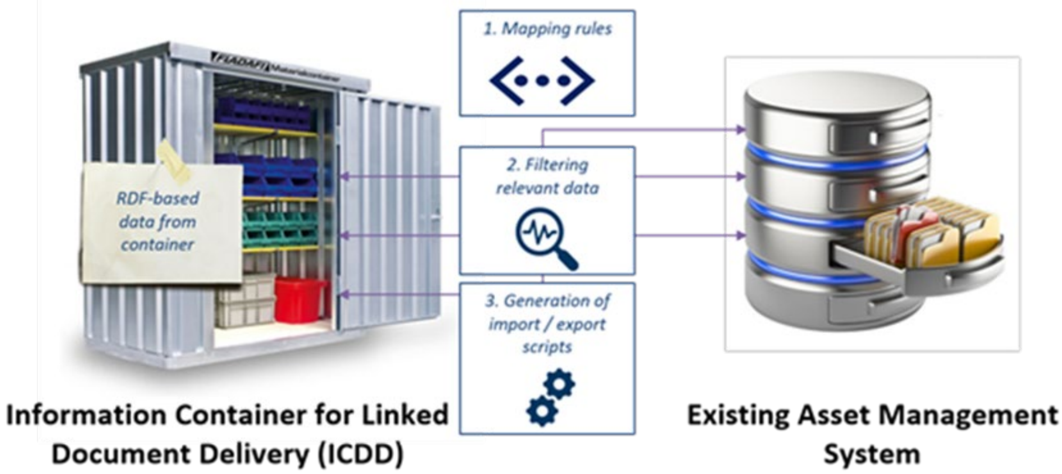


Figure 43 : Graphical representation of the data exchange between ICDD and AMS database

6.2 IFC Property Mapping Example

The functionality of the IFC property mapping was tested based on two examples. Therefore, an IFC model of a bridge and a road section were created and enriched with property sets. Both are described in the following subchapters.

6.2.1 Bridge IFC Model

The bridge model used as an example is a BIM of a 12.5 meter spanned simply supported double girder bridge built in the 1930s. The bridge was modelled using Autodesk Revit. The model complies with the LOD 350. Girders, railings, roadsides, and asphalt cover are modelled as in-place structural framing components. Finally, the model was exported in IFC format. Figure 44shows the modelled IFC model of the bridge.

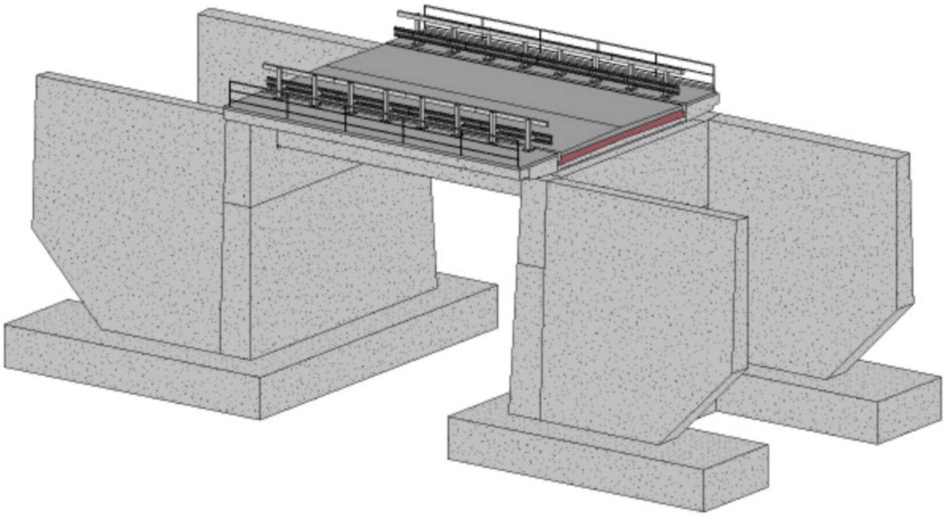


Figure 44: Exemplary BIM model of a bridge (Isailović 2020)

6.2.2 Road IFC Model

The IFC example model of the road is a simple model of a 1 km long straight road section. This is split into two 500 m long construction sections. Furthermore, the section is divided into ten 100 m condition sections. The model consists of pavement surface layer, asphalt binder course, asphalt base layer and the unbound base layer. In addition, the model has a virtual layer to store conditions and measures on the corresponding sections. The model was created with the AutoCAD extension ProVI and exported to IFC format.

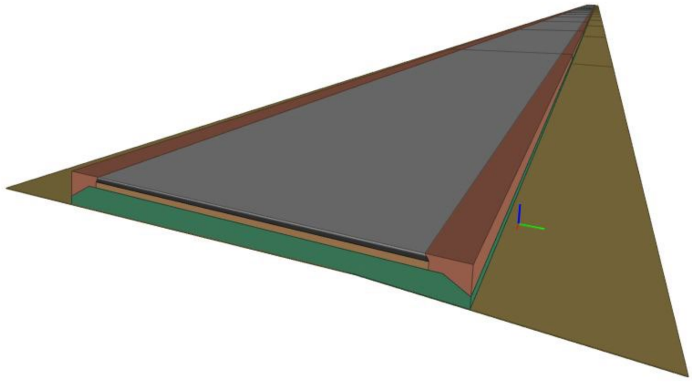


Figure 45: Exemplary BIM model of a road section

6.2.3 Property Extension

Since not all properties are available in the IFC, the properties must be extended in order to link further data with the model. Thus, extended property sets were defined for the condition information, and these can be linked to the corresponding pavement segment and layers of a road model via an ontology authored for this purpose. The external file with the condition information is then only linked to the model and not directly integrated.

The extended property sets are defined and listed in Report D4-2. and are available for download at [http://data.amsfree.eu/.](http://data.amsfree.eu/)

(Login: AMSFree, password: CEDRCall2018!).

7 Prototype Description

7.1 Functional memorandum for of the Prototype

7.1.1 Scope of the Prototype

The prototype can be used to link IFC models and IAMS databases. Containers can be either uploaded to the Information Container Data Delivery (ICDD) Platform, extended or created. The users can then use the containers to link information in the prototype and create relations. In addition, IFC models are displayed in the IFC viewer, in which 3D-shapes can be clicked on to retrieve related information. The prototype can be used to synchronise changes in the IAMS and the BIM database so that reliable consistent data management can be realised.

The application of the prototype, see Figure 46, is intended for the IAMS life cycle of pavement and bridges. This includes asset creation, condition assessment, maintenance planning and as-built models of implemented measures.

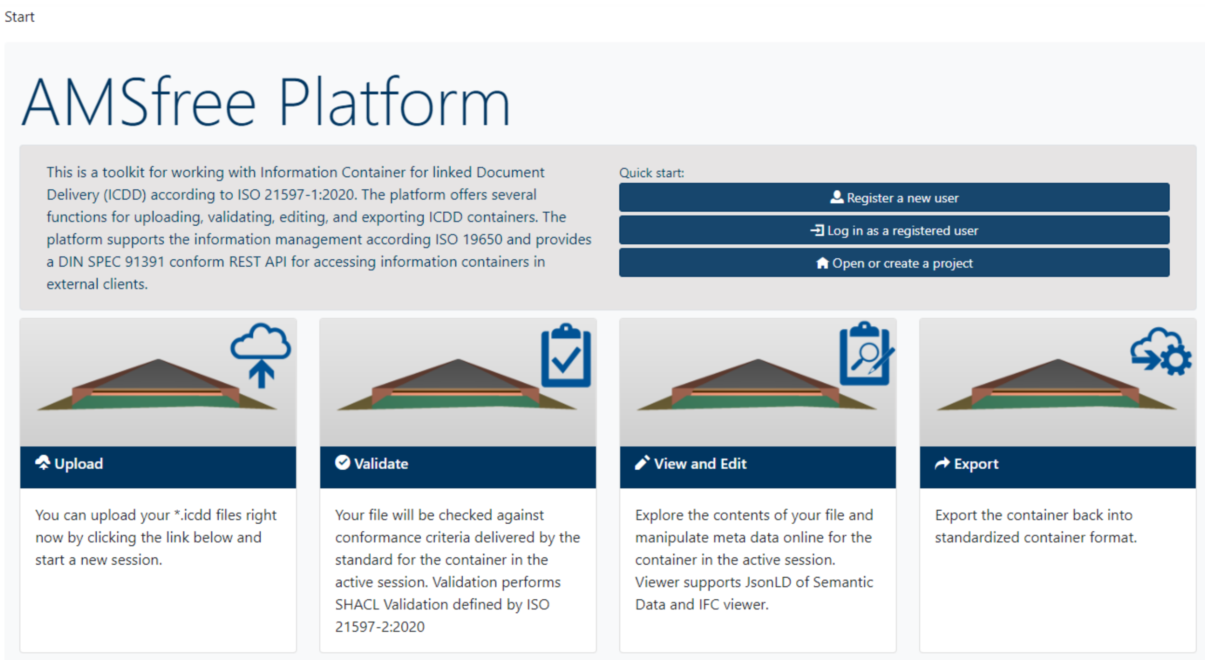


Figure 46: Start screen of the prototype ICDD-Platform [RUB]

7.1.2 System architecture of the Prototype

The system architecture of the prototype to realize ICDD functions can be understood in three parts, shown in Figure 47. The created containers are recorded in the data repository for further use. The business & data access logic part provides the core processors for the functionalities of the ICDD. Furthermore, the data flow from the data repository to the presentation for the user is managed. The container processor provides the functionality to create, edit and delete content in the container. Other processors related to the container processor retrieve or send container-related data. The IFC Processor is processing IFC-files shown within the Web User Interface with the geometry and spatial hierarchy of the IFC model.

Moreover, IFC models can be converted into RDF-based datasets within the platform using the IFCtoLBD converter. The SPARQL and SHACL processors provide to retrieve data of container requested and validate data based on the defined constraints. The R2RML Processor realizes the data integration from the external database into ICDD with predefined mapping rules. The created RDF triples and links are stored in the container. The Web User Interface provides an interface for presenting and interacting with all provided functionalities in the business & data access logic part. Additionally, through the IFC viewer, it is able to create queries related to selected IFC objects in the container with little or no SPARQL expertise.

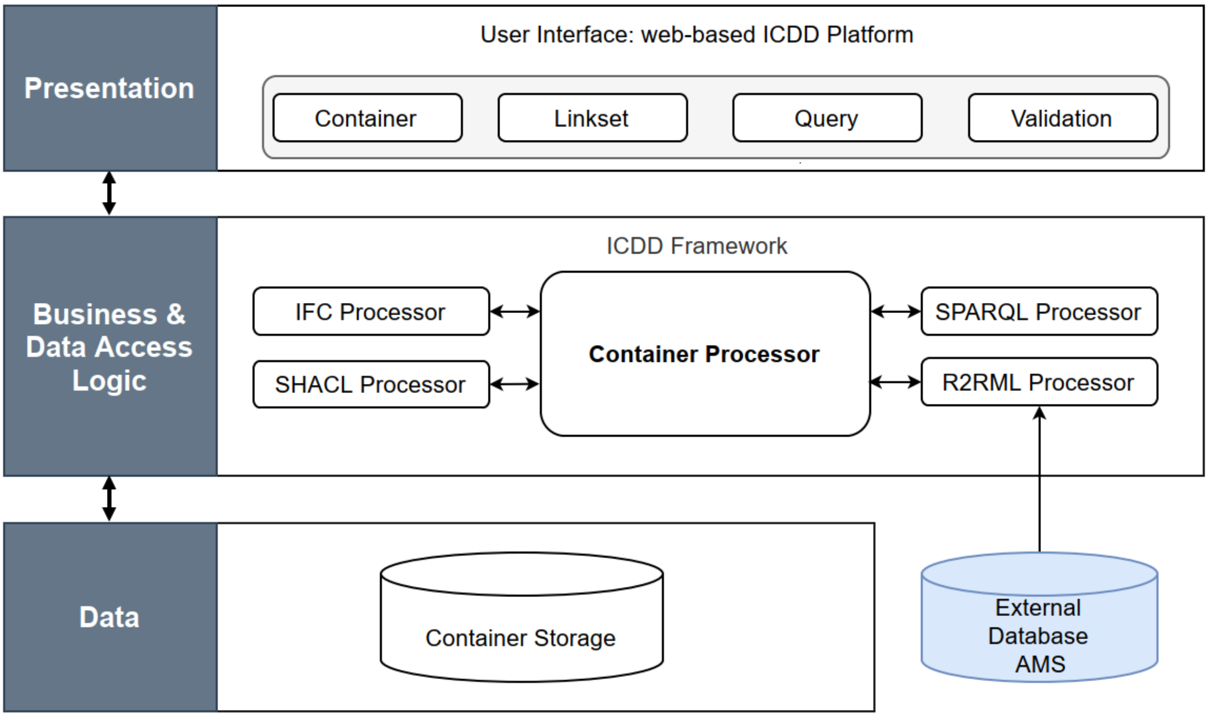


Figure 47: System architecture of the prototype ICDD-Platform – core functionalities with ICDD

7.1.3 Function of the Prototype

7.1.3.1 General

The application and the general interrelationships that are important for the users are described in the guideline report 6.1. The aim of the report is to provide potential users of Building Information Modelling (BIM) from National Road Authorities (NRA) with a guideline to implement approaches developed in the AMSfree project. This document includes a instructions for exchanging linked data between Infrastructure asset management systems (IAMS) and BIM by using information containers, the development of a transformation concept for data exchange between different IAMS systems and a procedure for the systematic integration of existing asset data in different NRA by means of ontologies. This includes the description of the proposed approach, including use cases, the software and data/file formats used as well as an illustrative application of the developed concepts on the example of a road section and a bridge. It gives a detailed explanation of how to proceed as a user in updating the AMS database to mirror physical reality – this will serve as the basis for the engineering application. In the following, the function of the prototype is explained in detail.

The application starts with a login or registration as a user, which must be confirmed by project partner RUB. The login window is shown in Figure 46. The basic functionalities are as follows:

Upload:

The user can easily upload existing ICDD files

Validate:

The uploaded file can be checked against conformance criteria delivered by the standard for the container in the active session. The validation will perform SHACL Validation defined by ISO 21597-2:2020.

View and Edit:

The contents of the file can be explored, and meta data can be manipulated online for the container in the active session. The Viewer supports JsonLD of Semantic Data and IFC Viewer.

Export:

The container can be exported back into the standardized container format.

7.1.3.2 Project Management

Create Project

First, a project must be created on the ICDD Platform. This can be found in the "Project List" (see Figure 48). By clicking on the name, the project is opened. Several information containers can be created in a project, either directly on the website or by uploading them. Templates for Asset Management Maintenance and Inspection are stored on the website and can be selected when creating the project.

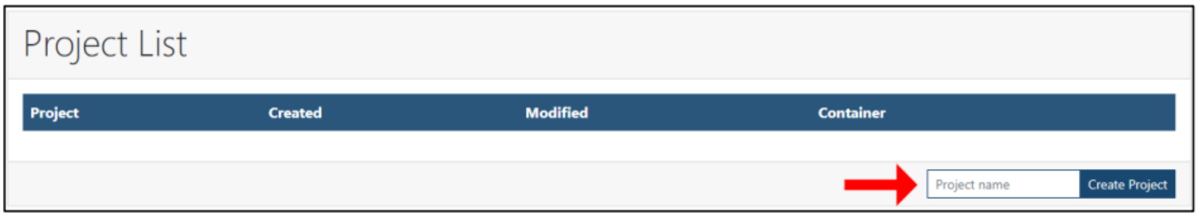


Figure 48: Create project

Edit Project

To open a project and therefore be able to edit it, one can either click on the name of the project or the magnifying glass icon (see Figure 49). The following screen will show the project properties and its containers (see Figure 50).

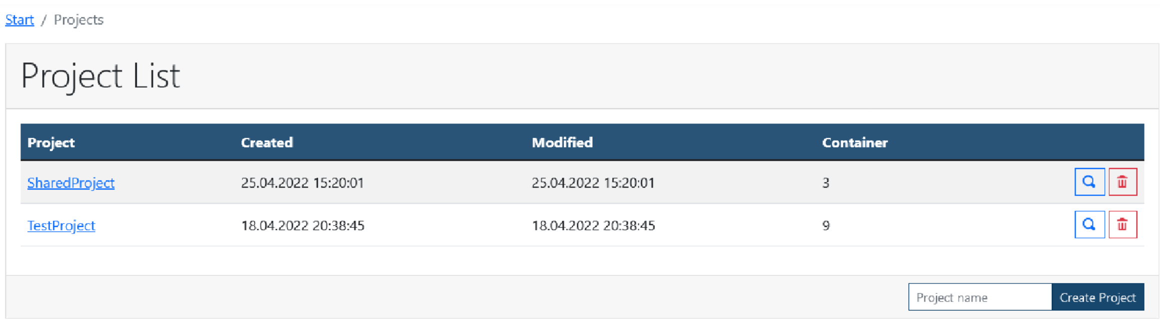


Figure 49: Project list

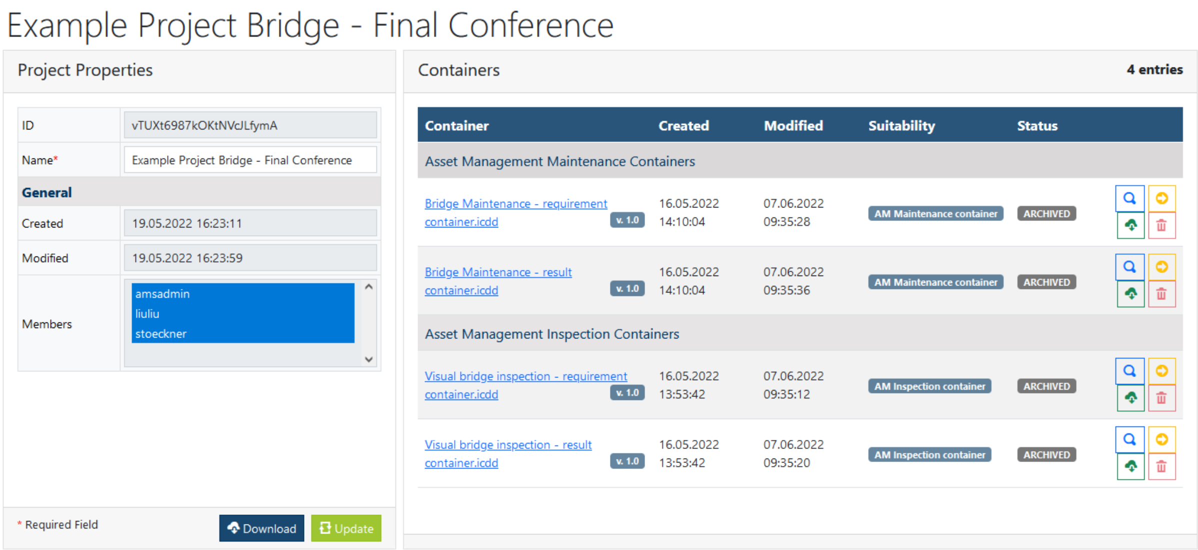


Figure 50: Project details

Delete Project

To delete a project, one can click on the red trash icon (see Figure 51). Another page will open, asking to delete the chosen project. Click on the “Delete”-Button (see Figure 51) to delete the project. The project and all its containers including their contents will be permanently deleted. This action cannot be undone.

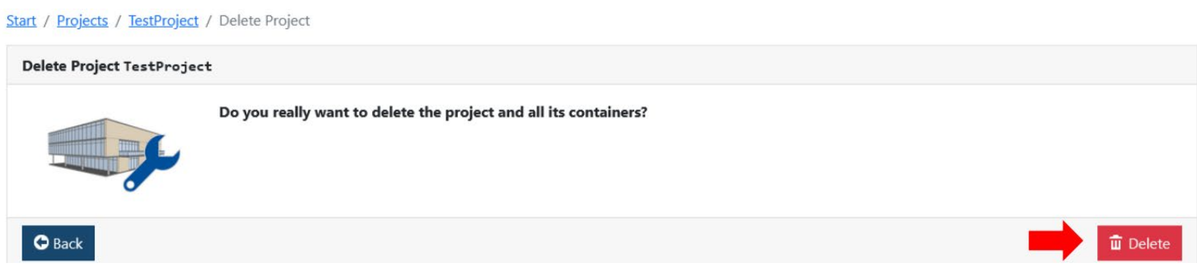


Figure 51: Delete project [RUB]

7.1.3.3 Container Management

After creating a project, the information container can now be generated, uploaded and modified. For that, the container must be opened. The structure of the container can be found in the area of user interface called explorer. The content window contains the content of the files and the container dashboard with information about the container. In addition, it offers five options for editing the container content, including uploading. With “Participants”, contributors can be added who are working on the container. An ontology or a payload triple can be added to ontologies by entering a web URL or uploading a file. The documents field offers the possibility to add internal documents, external documents, database connections and folders. With “Add Linkset” a new linkset can be created in the payload triples folder; only a name has to be entered. This linkset can be extended in the Payload triples folder. A SPARQL query can be written under “Query”. The properties contain the metadata of the container, which was specified when the container was created, and further information. The metadata can be changed and updated here. In addition to the properties that are displayed within the container, there is also the IFC viewer. The IFC viewer displays the models.

Create a Container

There are two ways to create a container (see Figure 52Figure 52):

- Upload a Container (A)
- Create new Container (B).

To open a container either click on the name or the magnifying glass. To create a new version of a pre-existing container, use the yellow arrow icon. To download a container, click on the cloud icon. To delete a container from the list of containers, the trash button can be used.

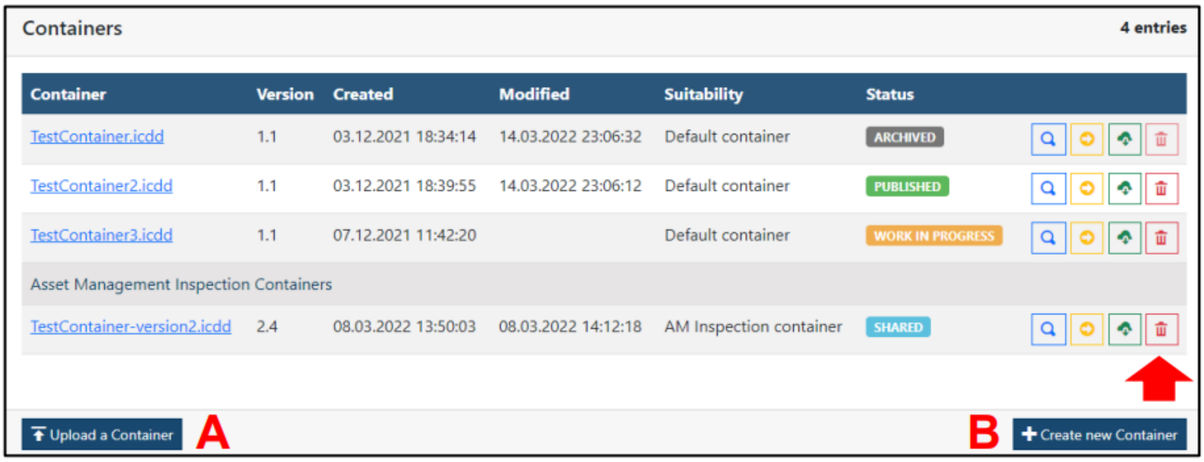


Figure 52: Container list [RUB]

To upload a container a file, a suitability and a status must be chosen (see Figure 53). To create a new container in addition to choosing the suitability and status (see Table 5), a name, description, and revision must be chosen.

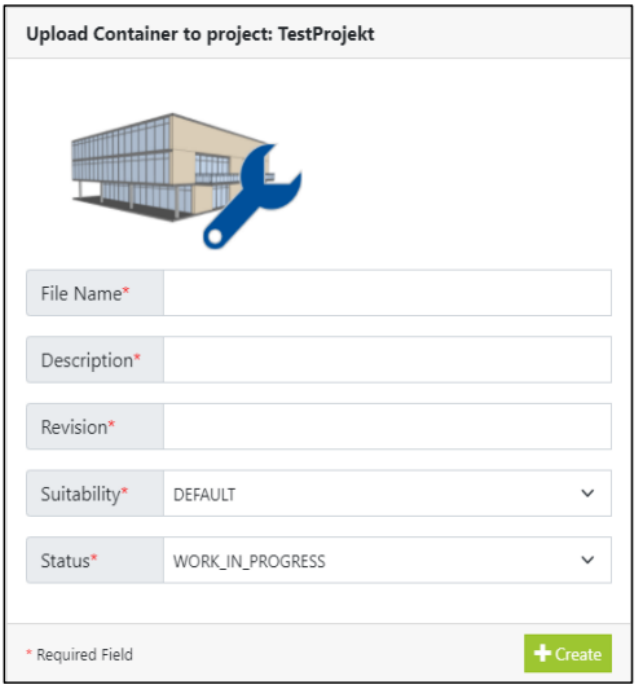


Figure 53: User interface while uploading a container file

Table 5: Suitability and status codes

Suitability	**Status**
- Default	- Work in Progress
- Suitable for Coordination	- Shared
- Suitable for Information	- Published
- Suitable for Internal Review and Comment	- Archived*
- Suitable for Construction Approval	
- Suitable for Manufacture	
- Suitable for PIM Authorization	
- Suitable for AIM Authorization	
- Suitable for Costing	
- Suitable for Tender	
- Suitable for Contractor Design	
- Suitable for Manufacture Procurement	
- Suitable for Construction	
- Suitable for AM inspection	
- Suitable for AM Maintenance	
- Suitable for Requirements	

Note *: Once the status “Archived” is chosen the container cannot be edited anymore and the status cannot be changed again

Delete and Export Containers

There are two different ways to delete and export a container

- in the container list of an open project (see Figure 54)
- under the explorer in an open container using ”Remove“ or “Export“ (see Figure 55)

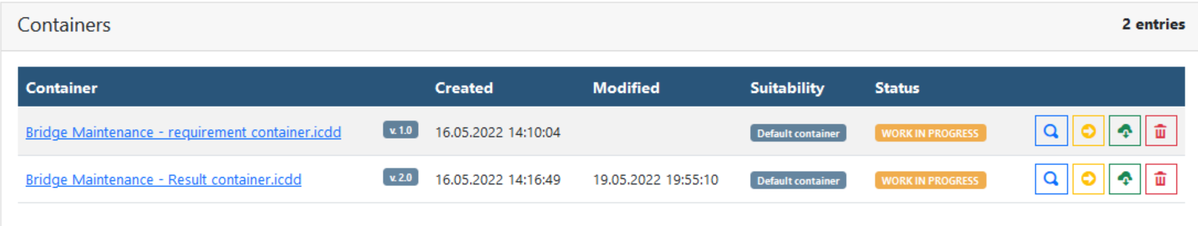


Figure 54: Container list with the icons to remove (red icon “Delete”) and export (green icon “Download”) containers

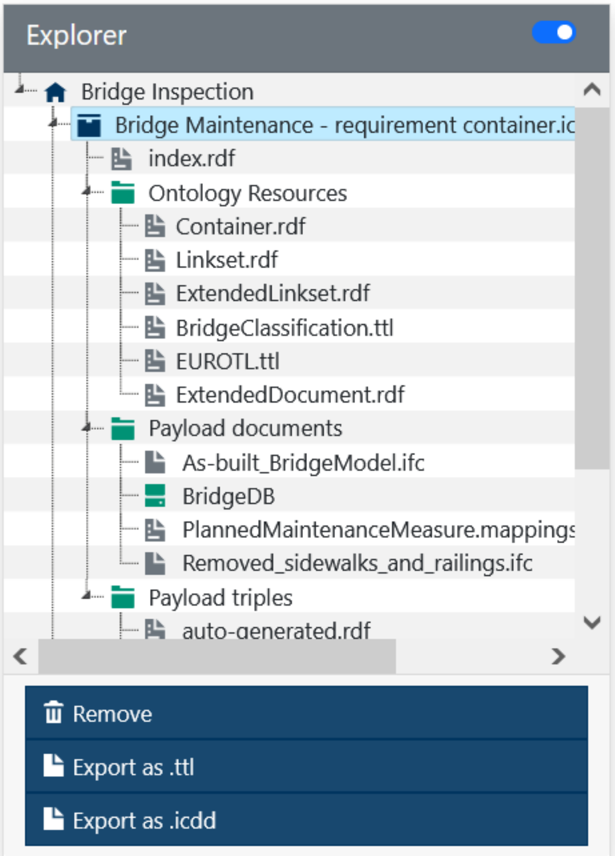


Figure 55: Explorer with the options to remove and export containers

Add new Container Version

To add a new version to a container, click on the yellow arrow icon of the chosen container (see Figure 73). The container and its contents will be duplicated, and the resulting new container will be added to the container list. Its container version will be increased by one.

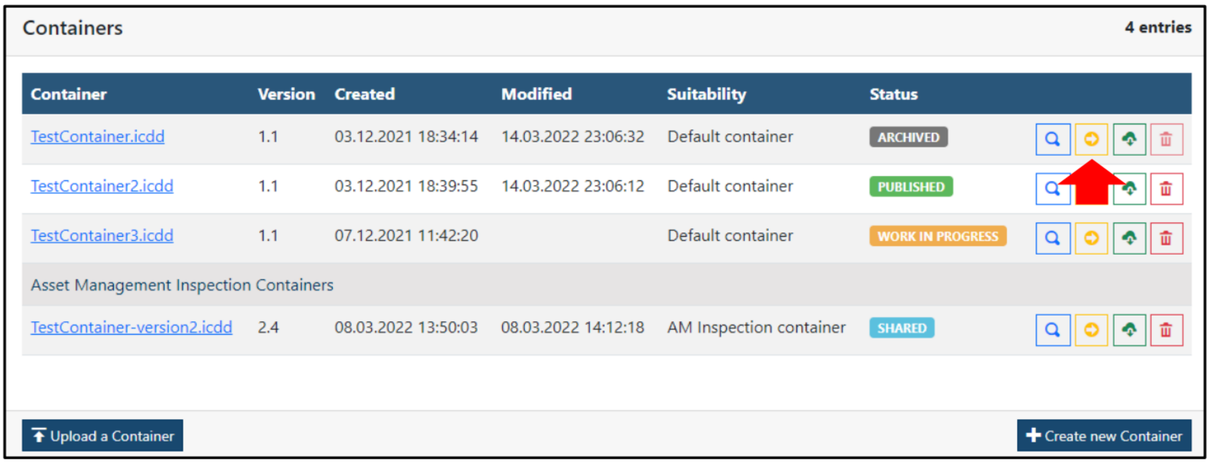


Figure 56: New container version [RUB]

Edit Container

In the container tab details of the container can be edited. The container details are divided into three sections.

- Explorer (left)
- Content (center)
- Properties / IFC Viewer (right)

<u>Explorer:</u>

The explorer gives an overview of the structure of the container with its three folders Ontology Resources, Payload documents and Payload triples and each of its contents. The explorer can be hidden or unhidden with the controller in the far-right corner (see Figure 57). To get back to the dashboard click on the name of the container. At the bottom of the currently open container, other containers that belong to the same project are listed. To switch to one of those, click on the name.

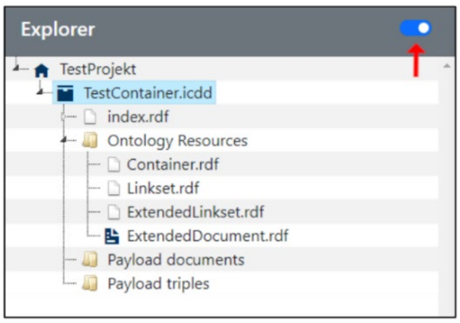


Figure 57: Explorer and Controller [RUB]

<u>Content:</u>

Within the content window are the contents of the files and the container dashboard with information about the container. The container dashboard offers 5 ways to edit the container contents (see Figure 58).

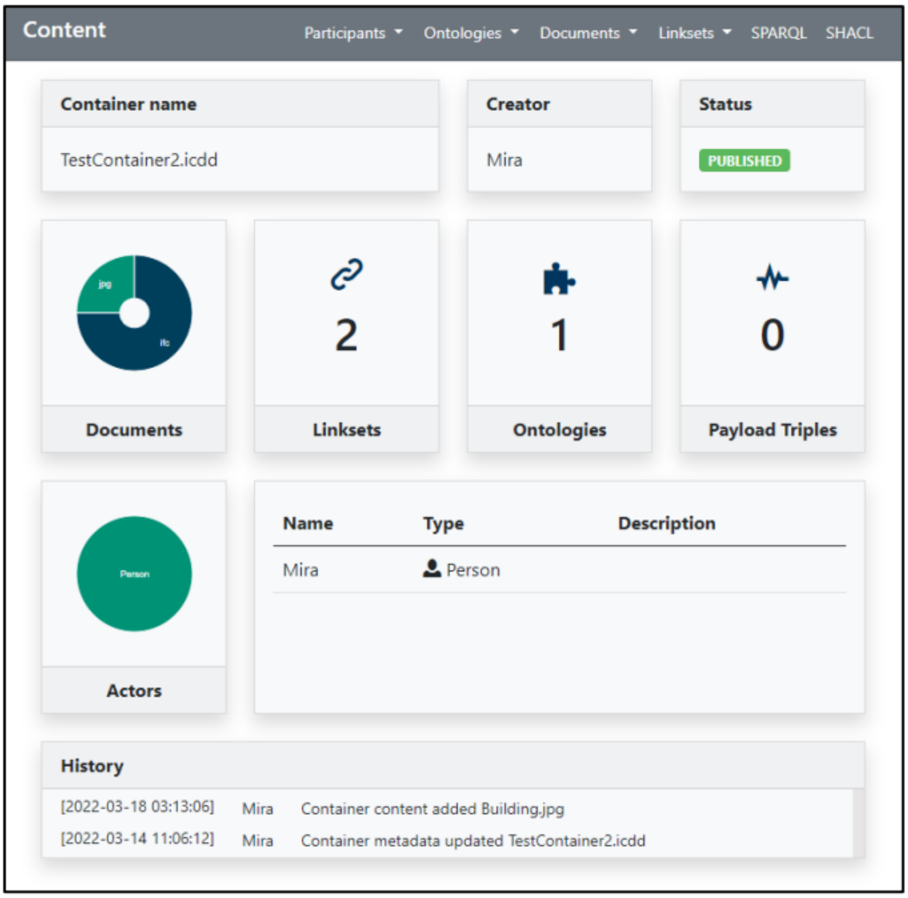


Figure 58: Container dashboard [RUB]

Properties:

The metadata of the container (selected when creating the container) and further information can be found in Properties. In Properties the metadata can be changed and updated.

IFC-Viewer:

Additionally, to the properties, the IFC-Viewer can be found in “Properties” in the upper right corner (see Figure 59). The IFC-Viewer shows the IFC models in the container, the label and GUID of selected Elements. The models can be activated and deactivated with the “Visibility” controller. To make the model transparent, use the “Transparency mode” Button, and the Button “Reset viewer” resets the model to its original point of *view.*

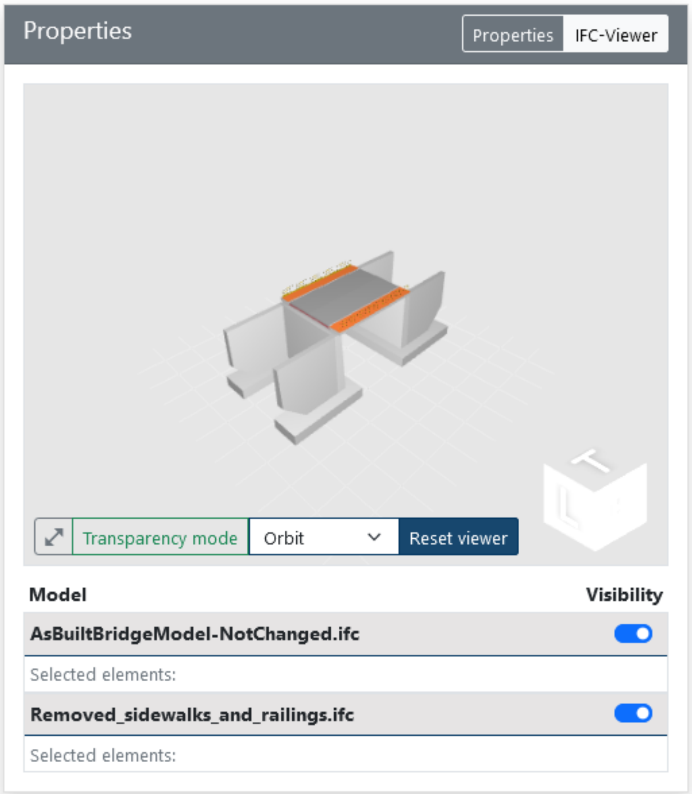


Figure 59: IFC viewer [RUB]

The operating instructions of the mouse functions in the IFC viewer are the following:

Rotate model:	Cube or hold left mouse key
Move entire model:	Right mouse key
Zoom in and out:	Mouse wheel
Activate/deactivate:	Visibility controller
Select model element:	Click on it with left mouse key
Back to starting position:	Button “Reset viewer”

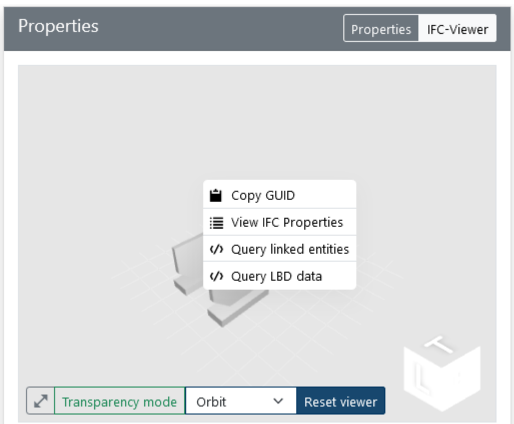


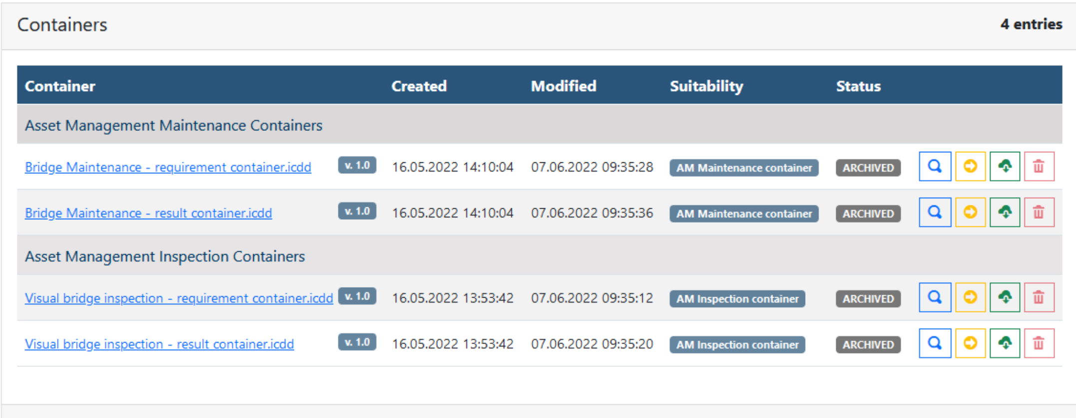
Figure 60: Pop-up menu IFC viewer

To open the pop-up menu for an element, click on the element in the IFC-Viewer using a right mouse click. The option “Copy GUID” copies the Guid of the chosen IFC element. “View IFC Properties" directs one to the specific element in the .ifc file. Using “Query linked entities" or “Query LBD data”, the SPAQRL query feature opens up with a query to find linked entities or LBD data.

7.2 Examples and Use Cases

7.2.1 Pavement

In the beginning, the user selects which use case or which data is to be considered. This selection is made by clicking on the corresponding container in the container list (see Figure 61). This selects the corresponding ontology and loads the IFC model.



Containers — 4 entries

Container		Created	Modified	Suitability	Status
Asset Management Maintenance Containers					
Bridge Maintenance - requirement container.icdd	v. 1.0	16.05.2022 14:10:04	07.06.2022 09:35:28	AM Maintenance container	ARCHIVED
Bridge Maintenance - result container.icdd	v. 1.0	16.05.2022 14:10:04	07.06.2022 09:35:36	AM Maintenance container	ARCHIVED
Asset Management Inspection Containers					
Visual bridge inspection - requirement container.icdd	v. 1.0	16.05.2022 13:53:42	07.06.2022 09:35:12	AM Inspection container	ARCHIVED
Visual bridge inspection - result container.icdd	v. 1.0	16.05.2022 13:53:42	07.06.2022 09:35:20	AM Inspection container	ARCHIVED

Figure 61 : Container list / Pavement

An overview page is displayed, which is divided into three windows (see Figure 62); the explorer, the content window and the properties window, in which it is possible to switch between properties and the IFC viewer.

The explorer window displays the stored files and their folder structure. Files can be selected here for closer observation. It is also possible to switch between the various containers for different use cases.

In the content window, an overview of the containers is displayed at the beginning, with the number of linksets, ontologies and payload triples contained. When a file is selected in the explorer window, the metadata of the file and its structure are displayed in the content window.

An IFC model exists for the roadway, which was loaded onto the platform. In addition, the platform provides containers for condition assessment, maintenance planning and modification of the as-built model. All containers receive a roadway model, a container RDF, a linkset RDF and an object-type library.

Figure 62: Overview page for example "pavement"

7.2.1.1 View S&A

The aim of this use case is to query and display the results of the condition survey and assessment (S&A) of road sections.

Workflow

The user selects the survey file in the explorer window. The information is now displayed in the content window. The list in the content window contains road sections that are surveyed and the results of drill cores.

Now the user can select a section. The IFC viewer opens, and the selected section is displayed as a marker in the IFC model (see Figure 63). Below the IFC viewer, the status information of the selected road section is displayed in tabular form.

Furthermore, it is possible for the user to select the route sections in the IFC viewer. The information is also displayed in a table under the IFC viewer of the selected road section. In addition, the selected road section is highlighted and displayed in the content window.

Requirements

What data is accessed? → A result file of the condition data from S&A campaign.

Which feature groups are updated / exchanged?

- General information on the S&A campaign, e.g. time of implementation, person who recorded the data, scope of recording:
  - Campaign
  - Subproject
- Results of the survey, i.e. standardised condition values:
  - Asphalt condition values
  - Concrete condition values
  - Partial and aggregate values

Which data format is available?

- For providing the general information and results of the survey
  - IFC – digital model
  - PFD, image format (e.g. JPG) – paper-based documents
  - XML, CSV – semantic information
  - RDF, TTL – semantic information (retrievable with SPARQL)
- For exporting the selected data of result with SPARQL:
  - CSV

The results of the condition recording are attached to a virtual layer by means of property groups and properties. The location of the areas must be done by specifying the start and end points. The width and length of the surface elements are to be calculated from the geometry of the profile or the grid length of the condition survey.

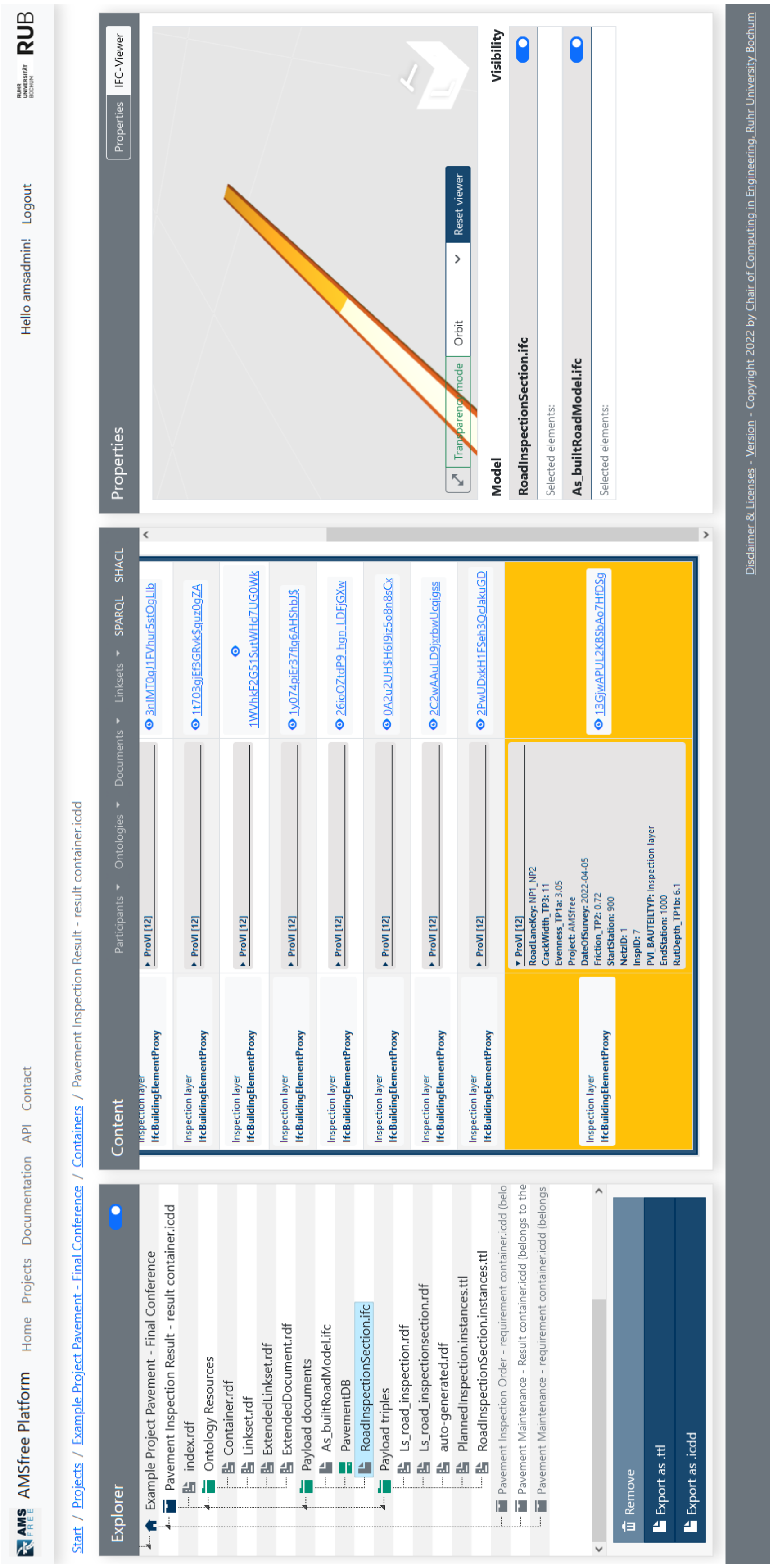


Figure 63: Example of a selected road section in survey

7.2.1.2 View Maintenance Plan

The purpose of the use case is to query and graphically display the results of maintenance planning. The planned maintenance sections, including information on the type of measure, costs and time, which were previously generated with a PMS, will be displayed.

Workflow

The user selects a specific road section for analysis via the content window. The related model is then loaded and displayed in the IFC viewer and the properties of the section and the maintenance planning are displayed in the properties window under the IFC viewer (see Figure 64).

The maintenance planning is colour-coded according to the type of measure in the IFC viewer. The user can identify directly whether it is maintenance or replacement.

The user can see further maintenance sections via the IFC viewer and click on them to obtain more detailed information. The information (condition data) attached to this surface layer is displayed in the properties window under the IFC viewer.

Requirements

The results are collected using ICDD. The maintenance units are linked to the output of the PMS calculations. The results ICDD are saved by the asset owner separately.

- What data is accessed? Output from PMS calculations, i.e. list of measures.
- Which groups of characteristics are updated / exchanged?
    - Type of measure
    - Cost of the measure
    - Year of measure
    - Explanation of reason/trigger of measure
- Which data format is available?
    - For providing the general information and the results
        - IFC – digital model
        - PFD, image format (e.g. JPG) – paper-based documents
        - XML, CSV – semantic information
        - RDF, TTL – semantic information (retrievable with SPARQL)
    - For exporting the selected data of result with SPARQL:
        - CSV

The information to be represented by means of property groups and properties is attached to a virtual layer in the IFC model.

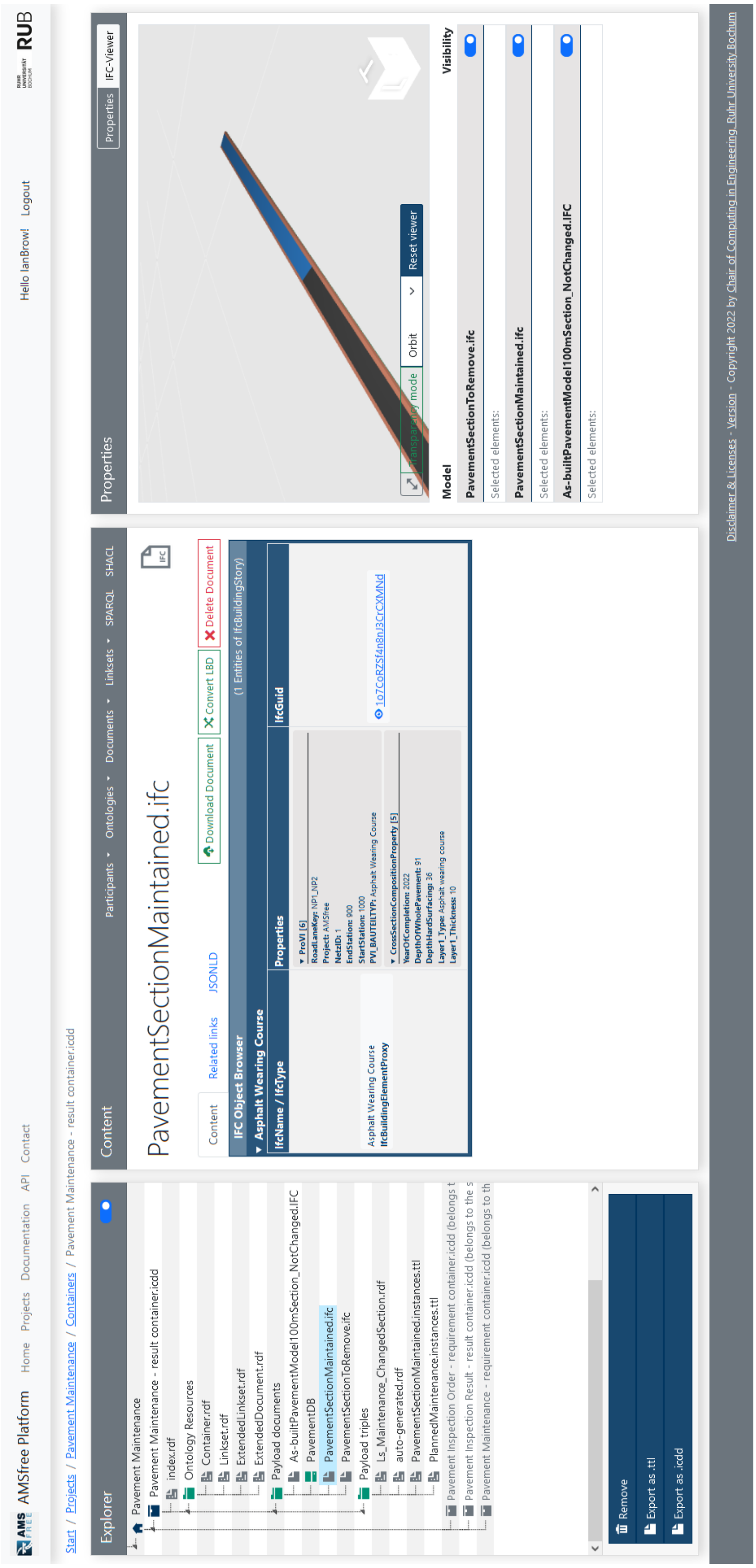


Figure 64: Maintenance plan for a selected road section

7.2.1.3 As-built View

The purpose of this use case is to import as built data from the construction phase and to query and graphically display this information. Here, the following two features are of particular relevance:

- Changes in the geometry of the structure (e.g., changes in the layout).
- Location of individual drill cores
- Display of information on material properties on drill cores.

Workflow

The user has to select an element by clicking on it. Then, the information attached to the element is displayed.

The position of the individual drill cores is displayed to the user in the IFC viewer. To locate the drill cores, they must be located by reference.

The user can get information about the drill core in a new window by clicking on the marked drill core locations. When selecting the drill cores, the information obtained from the material inspections (acceptance test) should be displayed. The model element is highlighted in the IFC viewer.

Requirements

- What data is accessed? → Planning documents, reports of the acceptance tests.
- Which groups of characteristics are updated / exchanged?
  - Layer general
  - aggregate control test
  - Binder control test
  - Asphalt mix control test
  - Concrete mix control test
  - Asphalt surface layer control test
  - Concrete surface layer control test
  - Asphalt binder layer control test
  - Pavement bound Control test
  - Pavement unbound Control test
  - Paving conditions
  - Photo of the drill core
- Which data format is available?
  - For providing the general information and the results
    - IFC – digital model
    - PFD, image format (e.g. JPG) – paper-based documents
    - XML, CSV – semantic information
    - RDF, TTL – semantic information (retrievable with SPARQL)
  - For exporting the selected data of result with SPARQL:
    - CSV

The information to be presented based on property groups and properties is attached directly to the drill core location in the results. For updating the model (as-built model), the corresponding information is attached to the individual layers and the geometry is adjusted if necessary.

Changes in the geometry

Example: Replacement of a surface layer

In Example 1, a surface layer of the same thickness is replaced as part of a maintenance measure. The individual layer thicknesses remain the same, so that only the feature groups need to be updated. Therefore, no changes in geometry are necessary.

The geometric changes must also be adjusted in the geometry of the model. For this purpose, existing elements are removed and replaced by new geometric elements. The as-built properties are attributed to the new elements. The properties of the previous element are linked to the new element for reproducibility.

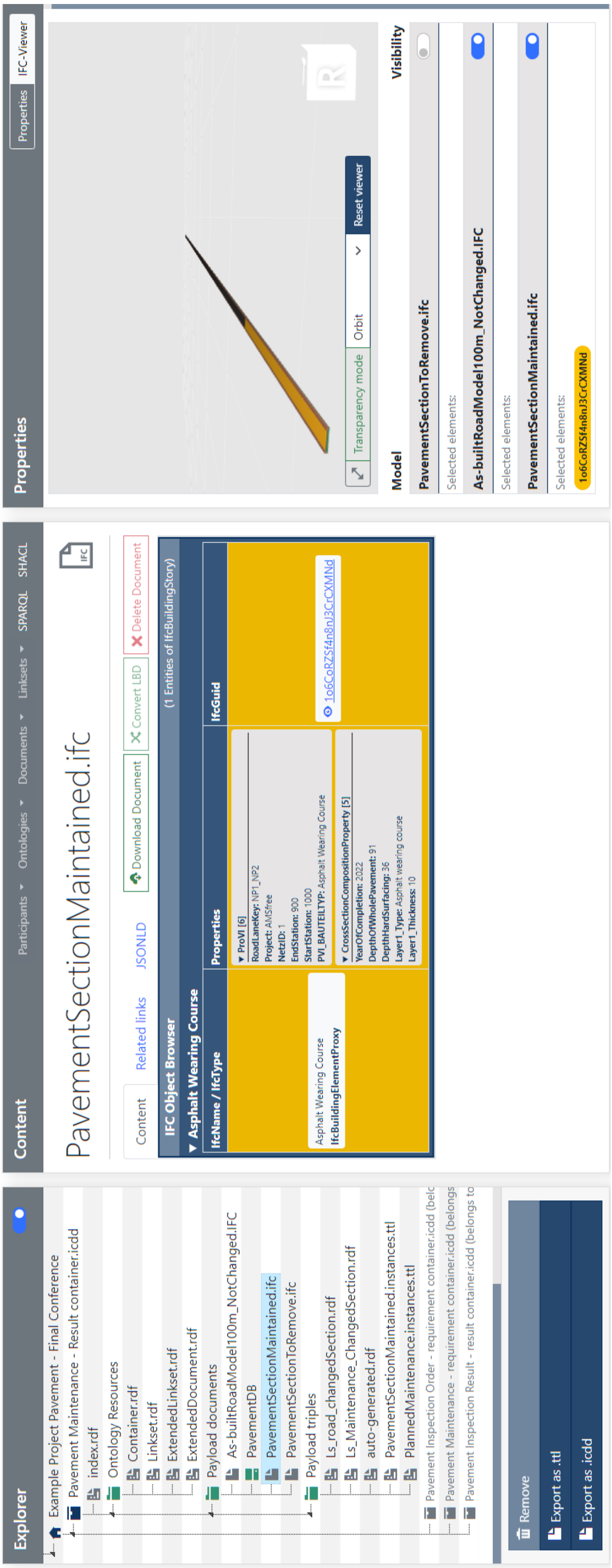


Figure 65: Maintenance with the road section replaced by the work

7.2.2 Bridge

The prototype includes the following three use cases; condition assessment, maintenance plan, and as-built view.

Workflow to start the described use cases:

1. In the prototype, all structures are listed for selection.
2. The user selects a structure for further information display.
3. After selecting the structure, the user can choose between "view condition assessment", "view maintenance plan" and "as-built view".
4. After selecting the use case, the procedures are described accordingly.

7.2.2.1 View Inspection

Purpose

The user wants to view the condition of a specific structure.

Workflow

The user selects the structure and the as-built model is loaded into the embedded IFC viewer of the prototype and displayed.

The existing inspections with meta-information (year, inspector, elements of the structure) are to be read from the database and displayed in the prototype for the year selected.

The meta-information of the latest inspection is displayed as the default information. The user can select the inspection according to the year of execution.

By clicking on the button "Show detail", the inspection data of all bridge elements of the selected year are read from the database and displayed as a table in the Prototype.

When clicking on an element in the IFC-Viewer, the corresponding element information is highlighted in the table.

The same behaviour applies when clicking a row in the table, the element is highlighted in the IFC Viewer.

If images are available for a component, a "bracket" symbol is displayed in the table. It is highlighted at the beginning of each element and table row.

When clicking on the "bracket" symbol, the damage image from the data storage is read out and displayed (see Figure 66). The element and the location of the image are highlighted in the IFC Viewer.

Requirements

1. The mapping between IFC element and bridge element from database should be available as ontology. (IFC element ID ↔ ID bridge element).
2. An ontology for the relevant inspection data from database shall be predefined.
3. The location of the damage photo

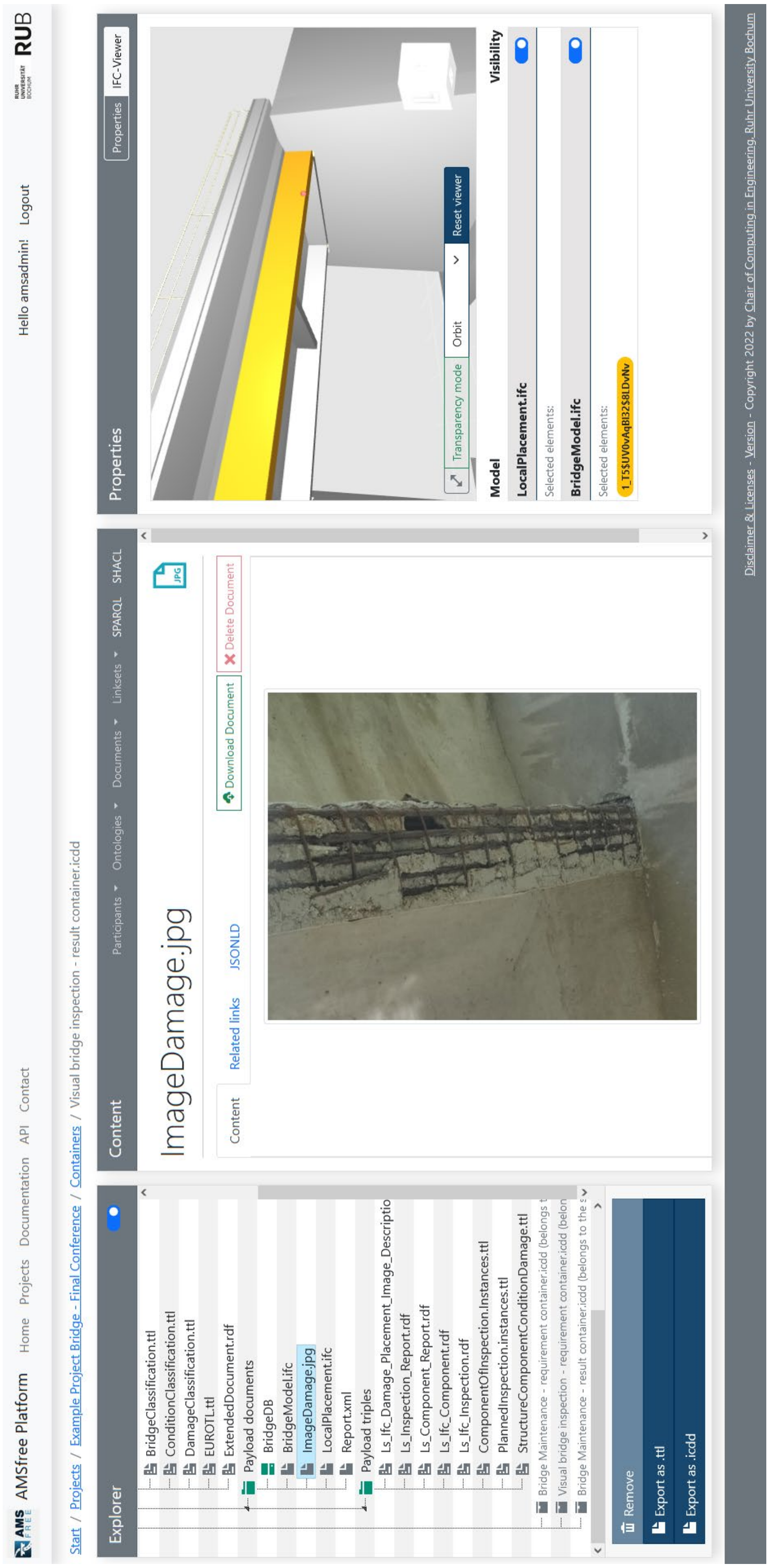


Figure 66: Image of a damage from a selected structure element

7.2.2.2 View Maintenance Plan

Purpose

The user wants to view the maintenance plan of a structure from a specific inspection year.

Workflow

The user selects the structure and the as-built structure model is loaded and displayed in the embedded IFC viewer of the prototype.

The year of construction is preselected as the default value. The meta-information of the structure is displayed in Prototype.

The user can select or change the maintenance year.

The information of the measures is read from the database and displayed in Prototype for selecting the year.

The maintenance model / partial model of the selected maintenance year is uploaded to IFC-Viewer at the same time as the as-built model. The maintenance information is displayed in Prototype (see Figure 67).

Requirements

The meta / construction information of the building is read from the database. In the corresponding predefined ontology, this data should be imported as entities.

The maintenance information of the building should be read from the database and imported into the corresponding predefined ontology.

For each measure a model of the maintained structure elements should be created and stored.

A geometric change is not taken into account during the measure.

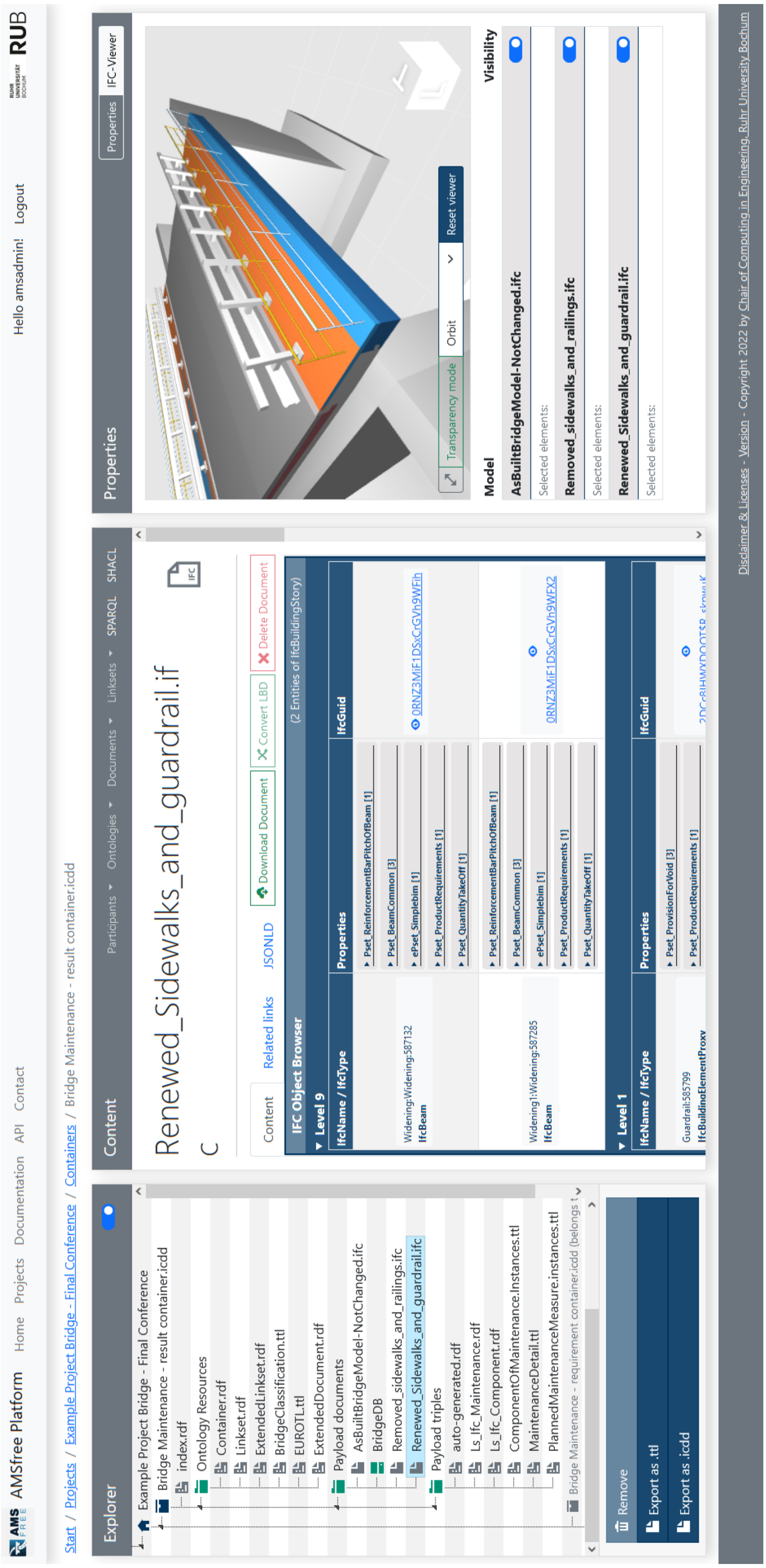


Figure 67: The maintenance information in the content list and color-coded IFC model

7.2.2.3 As-built View

Purpose

The purpose of this use case is to import structure material data from the construction process and to query and graphically display this information. Here, the following two features are of particular relevance:

- Display of information on material properties
- Changes in the geometry of the structure (e.g., extension of the width).

Workflow

The user needs to select an element by clicking on it. The information attached to the element is then displayed.

The model element is highlighted in the IFC viewer (see Figure 68).

When the element is selected, the information obtained from the material tests (acceptance test) is displayed.

Requirements

What data is accessed? → Planning documents, reports of acceptance tests.
Which groups of properties are updated / exchanged?
Mixed material_concrete_inspection test
Substrate _Control test
Construction conditions
Images of the structure
Which data format is available? → PDFs

Changes in the geometry

The geometric changes must be adjusted in the geometry of the model. For this purpose, existing elements are removed and replaced by new geometric elements. The as-built properties are attributed to the new elements. The previous elements can be linked to the new element for reproducibility.

The information to be displayed based on property groups and properties is attached directly to the element in the results. For updating the model (as-built model), the corresponding information is attached to the individual elements and the geometry is adjusted if necessary.

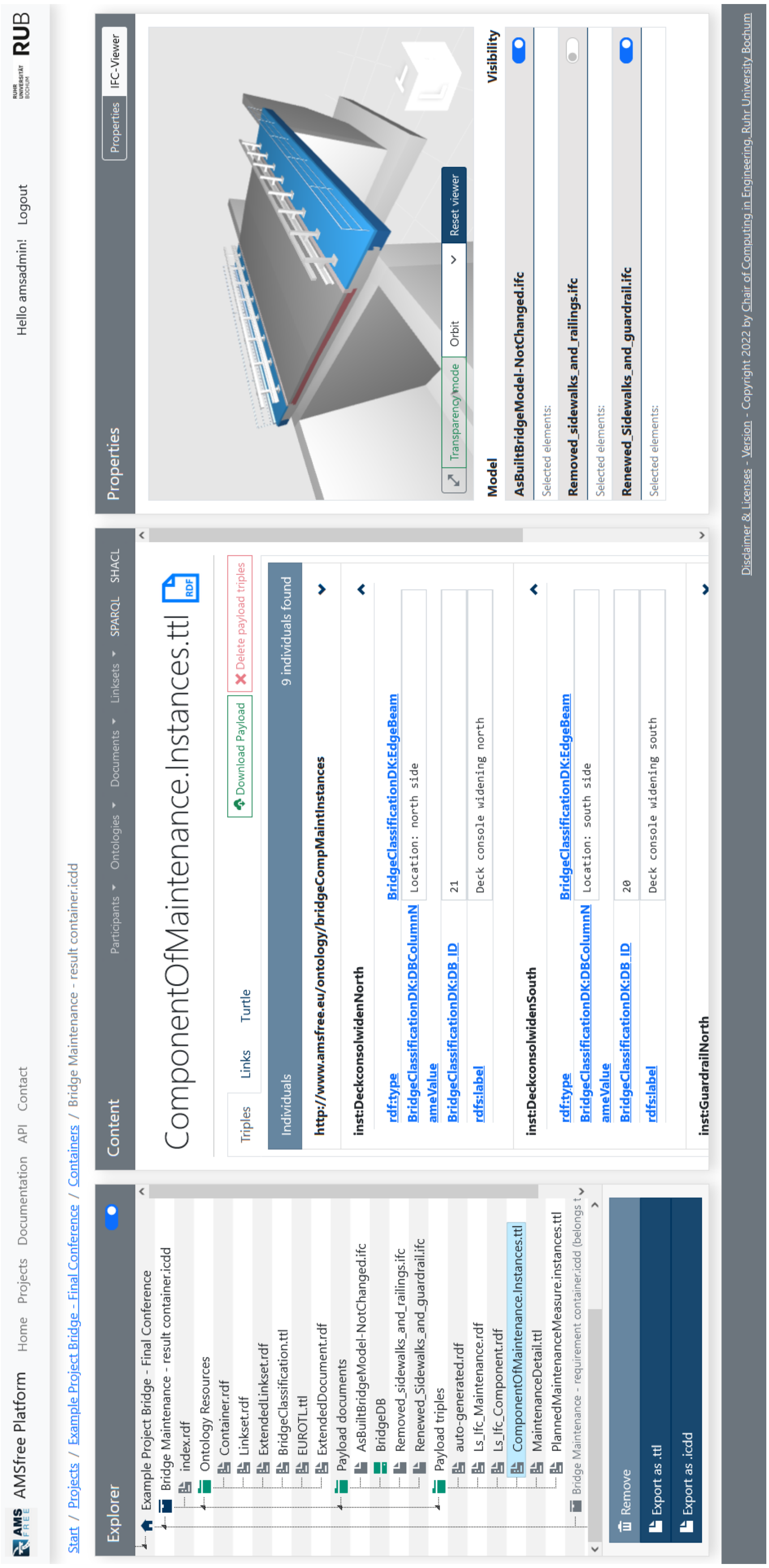


Figure 68: The as-built model after a measure

7.3 Reference to Web Application

The prototype described above can be reached at the following link:

https://icdd.vm.rub.de/amsfree/

A user account with simple containers for viewing and downloading is provided as following:

Login: amsadmin

password: I0&X6B(K

For testing and using the platform, the user should register with an own account.

7.4 Short Description of Prototype

A brief description and overview of the prototype was presented on a summary poster (see Figure 69). The poster can be downloaded from the following link:

http://www.amsfree.eu/documents

Three use cases were described for the prototype. These were also summarised in a poster (see Figure 70 to Figure 72), which can be downloaded from the following link:

http://www.amsfree.eu/documents

Figure 69: Summary poster of the prototype

Figure 70: Poster for the description of the use case inspection

Figure 71: Poster for the description of the use case maintenance plan

Figure 72: Poster for the description of the use case maintenance measures

7.5 Mapping Software Architecture

For creation of customized property sets as templates and adding the defined property sets to the entities of an IFC model, a mapping tool can be developed with consideration for the services shown in the software architecture in Figure 73.

The tool must contain three major components to realize the creation and mapping of properties within IFC schema:

- Templating: generate the property set template
- 3D Viewer: view the geometry and interact with IFC model
- Model Content: view the structure and properties of the IFC model and select the IFC object.

In each component, the necessary functionalities are introduced as following:

Templating includes the three functions. The user can create property set template with a human readable form provided by the user interface. The input data for the property set will be converted into IFC schema. The generated property set templates can be exported in xml or other common data types for further use in model design and view applications. With the existing property set templates, the data of the properties can be added to the IFC model object. In the same way, the user can import the property set template in the supported datatype and add them to the IFC model in this tool. To attach the properties to an IFC model, the tool must enable the user to view and interact with the IFC model. The functions are realised through the components of “IFC Apstex Toolbox Framework”.

3D Viewer and **Model Content** are components performed based on IFC visualisation tool. There are various visualisation tools, e.g., Xbim-Toolkit (https://docs.xbim.net/) which enables an integration of the 3D viewer into a self-developed system. In the introduced system, we prefer to use the IFC Apstex Toolbox Framework. In **3D Viewer**, the core function is the visualization of geometry and the interaction with the 3D object. The structure and the semantic data of the IFC model, such as properties, can be listed in the user interface by functions of **Model Content**. The filtering of IFC objects can be realised by selecting IFC Entities using a structure list.

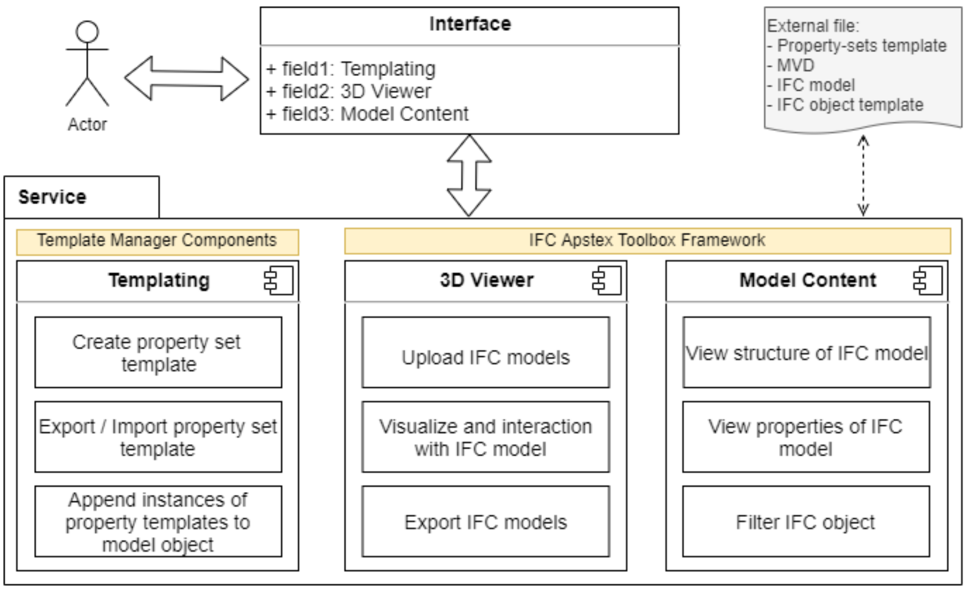


Figure 73: System Architecture of a Mapping Tool for the IFC Property Template

8 Summary

8.1 Task of the project

The AMSfree project analysed the architecture of Infrastructure Asset Management Systems (IAMSs) used by National Road Authorities (NRAs), as well as the asset information content in current IAMSs in order to establish detailed technical requirements for linking IAMS and Building Information Models (BIMs) as infrastructure asset databases on a macro and micro level. The analysis is performed on a range of BIM models utilized by designers and contractors, so the level of development (LOD) for the common infrastructure asset BIM can be agreed on. To allow full utilization of state-of-the-art data acquisition techniques (sensors and drones etc.), requirements for existing condition assessment techniques are established and documented in information delivery manual (IDM) for the condition assessment of assets. Based on the the processes of national asset management system a generic IAMS-Process approach was developed and a related IAMS-oriented IDM was established. Extensions of existing IFC schema were developed and for linking national data formats (e.g., OKSTRA, Interlis2) information containers according to ISO 21597 were used. Based on these results a prototype for linking legacy databases with IFC were developed and tested with three differ-ent use cases for pavements and bridges.

8.2 Approach in the project

The aim of the AMSfree project was to develop and implement approaches to combine asset management systems with BIM. This includes concepts for exchanging linked data between Infrastructure asset management systems (IAMS) and BIM by using information containers. It includes the development of a transformation concept for data exchange between different legacy systems and a procedure for the systematic integration of existing asset data in different NRA by means of ontologies. The research approach conducted the following steps:

- Comparative analysis of IAMS and common BIM's in Europe: Within this step a detail analysis of technical requirements for linking IAMS and BIM as infrastructure databases was conducted. As well the content of common infrastructure asset BIM and the level of Development could regard.
- Digital Condition Assessment: An overview about existing and current condition assessment techniques is given. An IDM for condition assessment should be developed and possibilities for an IFC Extension could be examined.
- Data fusion and semantic transformations: First, the definition of an AM reference process model according to the systems of the different NRA could be established. Regarding the reference model data exchange based on Information Containers for the relevant data exchange points in AMS is described.
- Development of a referenced vendor-free IFC based data structure: Takin into consideration the Information container an IAMS-oriented IDM should be provided as well as a linking guide of European Road OTL and national Classifications.
- Data Exchange to legacy Systems: A Prototype for different use case should be developed and examples, software architecture should be described in a guideline for IFC property mapping.
- Development of a Prototype: This last step contains the testing with different use cases connected with the tasks of an IAMS, functional memorandum and the short de-scription of the prototype.

8.3 Summary of essential project results

Based on the previously described potential to combine AMS with BIM, concepts for the integration of data from AMSs into BIM are introduced. First, the stakeholders within the context of asset management and its processes are described by using a process map. Three relevant update steps were defined on which an asset manager interacts with external contractors such as a inspector, a tender preparation team and a construction team. Based on the process analysis, the related data that needs to be exchanged at each update step and the national data formats are analysed. The approach involves linking and transferring different data sources, models, or formats. This challenge cannot be solved in a universally valid way. The SWT is used to define ontologies for the description of domain-specific semantic information and link data from different data sources. It is shown how existing national data formats for managing road assets during the whole life span are linked with the IFC format. The approach was tested and validated in the context of use cases.

A prototype was developed to evaluate the proposed concepts of sharing, exchanging and visualization of data between the asset manager and external contractors by using information containers. The ICDD provides an environment for capturing and linking data from different formats. File-based documents can be linked in this information container. Figure 2 shows the idea of using standardized information containers for the data exchange between an asset manager and external contractors. In detail, the project contains the following results:

- The AMSFree project analysed the architecture of Infrastructure Asset Management Systems (IAMSs) used by National Road Authorities (NRAs), as well as the asset information content in current IAMSs in order to establish detailed technical requirements for linking IAMS and Building Information Models (BIMs) as infrastructure asset databases on a macro and micro level.

- The use and maturity of BIM in Europe and the existing IFC Model were analysed and described, which content of common IAMS BIM can be handed over from planers and contractors to asset managers.

- An overview of current and new survey and assessment technologies were provided and demonstrated how they can be used in the context if BIM-based IAMS. The technologies firstly comprise the assessment of roads and bridges and secondly new technologies and examples of their application.

- Based on these results an Information Delivery Manual (IDM) for condition assessment was developed as well as the IFC using for visualizing condition assessment or inspection result.

- A generic reference process model was developed and characteristic data updates were defined. For this model, data demands for pavements and bridges were defined, according to the requirements of national AMS. This includes the data drop points and requirements within the IAMS Process.

- Information Containers for Pavements and Bridges were created, as well as the ontologies and the payload documents. This leads to the development of a referenced vendor-free based data structure.

- An IAMS oriented IDM is provided as well as IAMS-oriented application and extension of the IFC Standard.

- A prototype for the data exchange to legacy systems was developed using information containers. The web-based application was tested based on a project-related database with different use cases according to the relevant updates within the IAMS Process for bridges and pavements.

- The prototype application is described in a guideline for IFC Property Mapping, in a functional memorandum and the description of different use cases.

8.4 Evaluation of the project results and further procedure

From the project AMSfree the following conclusions are given:

- The process, data handover from as-built model to operation model and the data demand for the operation period is clearly described. Property sets and properties can be extended related to national demands.

- Relevant data updates regarding needs of IAMS during the operation period are defined.

- IDM for condition assessment / inspection regarding also new assessment methods are given.

- A linked data concept and prototype for using legacy data bases based on information containers is given and tested with different use cases. The method and workflow is given, so that the approach is scalable.

- The approach allows asset managers to keep their working routines, legacy databases (incl. valuable data), and software applications. The ICDD contains all relevant data and information referred to one geometric model.

- The approach is tested as “lab-application”, the next step should be system demonstration in the real operational environment of a road authority.

Important in the overall result is that the presented method does not presume the existence of a certain software but can be integrated independently into different software- and data environments. As a final goal, the method should significantly facilitate the data handover from the construction period to the operation period as well as the data handover between different process within the operation method. Therefore, the engineering process in asst management don’t need to be changed, because the developed method follows these processes an is able to manage all information parts.

The method is now ready for use in a real working environment, so the next step should be a project related application. Within this test, the following points seems useful:

- Extension to the national class model regarding IFC

- Adaption to the national property sets and properties

- Update and adaptation of national process descriptions

- Site tests

- Improvements and implementation plan

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10 Appendix

10.1 Overview of the sub reports

WP 1 Project Management and Dissemination

- Half time Report
- Final Report

WP 2 Comparative Analysis of IAMS in and common BIM#s in Europe

- Report D2.1 IAMS and BIM in Europe

WP 3 Digital Condition Assessment

- Report D3.1 Report outlining current assessment techniques and identifying opportunities how to incorporate new data streams in condition assessment
- Report D3.2 Information Delivery Manual (IDM) for condition assessment

WP 4 Data Fusion and Semantic Transformations

- Report D4.1 Definition of an Asset Management Reference Process
- Report D4.2/4.3 Information Container for Road Maintenance Planning and Bridge Condition Assessment

WP 5 Development of a refenced vendor-free IFC based data structure

- Report D5: Development of a refenced vendor-free IFC based data structure
  D5.1 IAMS-oriented Information Delivery Manual
  D5.2 IAMS-oriented Application and Extension of the IFC Standard
  D5.3: Linking Guide of European Road OTL and National Classifications

WP 6 Data Exchange to Legacy Systems

- Report D 6 Data Exchange to Legacy Systems
  D6.1 Guideline IFC Property Mapping
  D6.2 IFC Property Mapping Examples
  D6.3 IFC Mapping Software Architecture
  D6.4 Guideline Exchange of Linked Data using In-formation Containers

WP 7 Development of a Prototype

- Report D 7 Development of a Prototype
  D7.1 Functional Memorandum of Prototype
  D7.2 Link to Current State of Prototype
  D7.3 Short Description of Prototype

10.2 Project Publications and Dissemination

Liu, L., Hagedorn, P., & König, M. (2022). **”BIM-based organization of inspection data using semantic web technology for infrastructure asset management”**. In C. Pellegrino, F. Faleschini, M. A. Zanini, J. C. Matos, J. R. Casas, & A. Strauss (Hrsg.), Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures (Verlagsversion, Bd. 200, S. 1117–1126). Springer International Publishing. https://doi.org/10.1007/978-3-030-91877-4_127

Liu, L., König, M., Hajdin, R., Stoeckner, M., & Großauer, K (2022). **“Integration and Provision of BIM-Based Information Containers for the Asset Management of Roads and**

Bridges”. In ASCE International Conference on Computing in Civil Engineering 2021 (pp. 771-778). http://dx.doi.org/10.1061/9780784483893.095

Hagedorn, P., Liu, L., König, M., Hajdin, R., Blumenfeld, T., Stöckner, M., Billmaier, M., Grossauer, K., & Gavin, K. Forthcoming. **“ BIM-ENABLED INFRASTRUCTURE ASSET MANAGEMENT USING INFORMATION CONTAINERS AND SEMANTIC WEB“**, ASCE's Journal of Computing in Civil Engineering. DOI: 10.1061/(ASCE)CP.1943-5487.0001051

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