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Executive Summary

In 2018 the CEDR Transitional Road Research Programme (funded by Austria, Belgium-Flanders, Denmark, Finland, Germany, Netherlands, Norway and Sweden) commenced a research programme on BIM (Building Information Modelling) with the aim to provide a better understanding of how BIM principles could be practically applied within the European highways industry. The primary research objective was to develop a practical method to support/enhance the data connections between Asset Management Systems (AMS) and BIM platforms. This would make BIM more useful in the operational phase of assets, through the ability to access and use operational data typically available within AMS. AMS would also be able to access and use data from BIM environments so that more efficient and informed decisions can be made when maintaining assets.

To address the aim of the research program, the CoDEC (Connected Data for Effective Collaboration) project has built on previous research, such as AM4INFRA and INTERLINK, to facilitate improved data integration between BIM and AMS via the development of standardised processes – a "Data Dictionary" and a "Data Ontology" – that supports the integration of asset data across key infrastructure assets (Roads, Bridges and Tunnels). Building on this Ontology, CoDEC has also delivered a software application (Application Protocol Interface, API) for implementation of the developed methods and has demonstrated the benefit of the developed data integration processes through three pilot projects located on a tunnel, a bridge and on sections of a road.

By creating a framework that includes data provided by new technologies CoDEC gives NRAs a practical, implementable and future-proofed solution to manage and interpret asset data. Although CoDEC did not cover all road infrastructure assets and data types, it provides a structured and practical framework that can be expanded to include other asset types and data as required in the future - hence CoDEC provides a steppingstone in the transition from traditional Asset Management to operation via BIM, and the exploitation of Digital Twin data.

Based on the findings from the research and the pilot projects, CoDEC has recommended:

- **Collaboration between all stakeholders should be encouraged to share and understand needs**
- **The level of detail within BIM models should be simplified and optimised to accommodate asset data at an appropriate level of detail**
- **Normalisation/standardisation of BIM conventions and nomenclature**
- **Further automation in the data processing/synchronisation between systems**

This Final Report provides a summary of the CoDEC project and its outcomes.

1 Introduction

Building Information Modelling (BIM) has, in recent years, become firmly established in the infrastructure sector. The process is designed so that asset information can be generated, captured, maintained and used effectively throughout the asset lifecycle. To date the application of BIM has tended to focus on information generated during the construction phase of the asset lifecycle and there are still gaps in applying BIM for the operational phase. On the other hand, well-developed Asset Management Systems (AMS) and processes are in place to support the operational management and maintenance of highway infrastructure. These systems hold considerable amounts of asset information in various formats, and many have been in use for decades by National Road Authorities (NRA). To make BIM more useful in the operational phase, BIM systems need to access and use operational data which is typically available within Asset Management Systems (AMS). AMS should also be able to access and use data from BIM environments so that more efficient and informed decisions can be made when maintaining assets.

A significant amount of work has been undertaken to date to define the core requirements for data capture, storage, and maintenance in the BIM environment. Industry Foundation Classes – IFC (ISO 16739-1:2018) have standardised BIM data formats for the BIM Object-Type-Library (OTL) and buildingSMART (buildingSMART, 2020) has defined a “Data Dictionary” for data within BIM. However, these do not provide standardised methods to capture and generate data during the operational phase of an asset, or to integrate data with AMS. Additionally, recent developments in asset data capture technology (e.g., scanning systems, remote sensing, mobile sensors, IoT, etc.) are now generating data to monitor and manage assets which currently is poorly supported in either BIM or AMS platforms. These systems also need future proofing to support the sharing of data provided by new technologies. A key factor sustaining this disparity is the absence of standardised data formats to allow this exchange of information.

In 2018 the CEDR Transitional Road Research Programme (funded by Austria, Belgium-Flanders, Denmark, Finland, Germany, Netherlands, Norway and Sweden) commenced a research programme to address these challenges with the aim “*to free and enrich data coming from various sources expressed in various formats in a contractual situation in a real infrastructure project and visualize the data in a combined environment.”*

To address the aim of this research program, the CoDEC (Connected Data for Effective Collaboration) project proposed to facilitate improved data integration between BIM and AMS through the development of standardised processes – a “Data Dictionary” and a “Data Ontology” – that would support the integration for three key infrastructure assets (Roads, Bridges and Tunnels). Further to this CoDEC also proposed to develop an OpenAPI (Application Protocol Interface) to enable automatic data connection between different systems and demonstrate the benefit of the developed data integration processes through three pilot projects. Ultimately, the CoDEC project aimed to assist Road Authorities make efficient and effective use of data to support asset management.

The purpose of this final report is to provide a summary of the CoDEC project and its deliverables.

2 Overview of CoDEC

The CoDEC project is based around a methodical framework for data (the Data Dictionary), translated into a machine-readable framework (the ontology), to make AMS and BIM data interoperable. This provides a step on the journey to the ultimate goal of making data available seamlessly when and where it is needed across management systems. The AM4INFRA (AM4INFRA,2018) and INTERLINK (INTERLINK, 2018) research projects, funded by CEDR, took the first steps towards a standardised format for data sharing, by developing a European Road Object Type Library (EurOTL), based on the IFC (Industry Foundation Class) standard. CoDEC has built on these to encompass the data used in asset management decision making processes - including data from new technologies such as scanning systems and sensors - to develop standardised methods to automate the data integration process of this wider data.

Figure 1 provides an overview of the CoDEC processes and outcomes. CoDEC undertook literature review, stakeholder engagement and desktop research to understand the as-is situation, the aspirations of NRAs and the challenges they face. This was used to determine the requirements for the CoDEC Data Dictionary and the CoDEC Ontology for three key infrastructure assets: Roads, Bridges and Tunnels. Building on this Ontology CoDEC has produced a software application (Application Protocol Interface, API) for implementation of the developed methods and applications in three demonstration pilot projects.

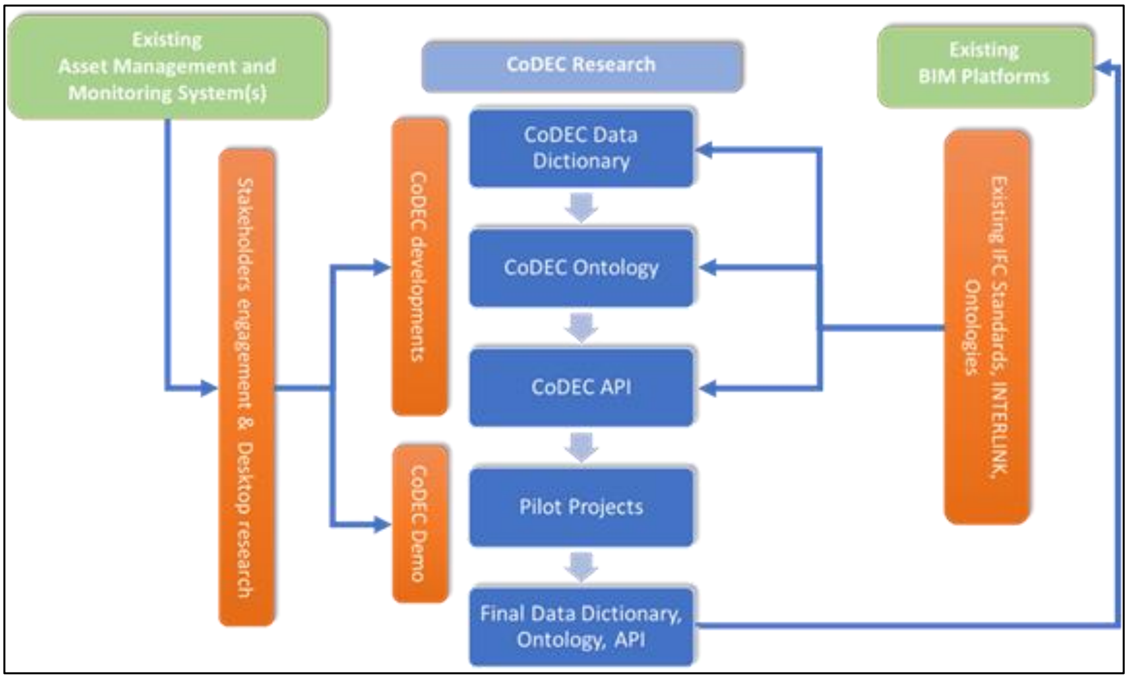


Figure 1: CoDEC Process and Outcomes

The final outcomes of CoDEC are therefore the CoDEC Data Dictionary, the CoDEC Ontology, and an OpenAPI (CoDEC API), all of which are expandable to cater for the needs of individual NRAs, and implementable within their systems and processes.

CoDEC was undertaken as a project of 6 Work Packages and delivered the main outcomes as shown in Table 1.

Table 1: CoDEC Deliverables

Work Package	Description	Deliverables	
WP0	Project Co-ordination	D0.2A-H	Technical Progress Reports
		D0.4	Final Project Report (yet to be published)
WP1	Develop Master Data Dictionary (MDD) for Legacy Data	D1A	Literature Review on Legacy Data and the Data Dictionary
		D1B	CoDEC Data Dictionary
WP2	Develop Master Data Dictionary (MDD) for Sensor/Scanner Data	D2A	Review of sensor technologies and their application
		D2B	CoDEC Data Dictionary
WP3	Applied Research through Pilot Projects	D3A	Pilot projects report and consolidated implementation resources (yet to be published)
WP4	Stakeholder Engagement	D4A	Stakeholder Engagement Report (yet to be published)
WP5	Dissemination	D5A	Dissemination Plan (yet to be published)

This Final Project Report (D0.4) summarises the following main research outcomes from CoDEC's Technical Work Packages (WP 1- 4), as presented in the following sections:

- Section 3: CoDEC Data Dictionary (*Delivered through WP1 and 2*)
- Section 4: CoDEC Data Ontology & API (*Delivered through WP3*)
- Section 0: Demonstrating the developed solution through Pilot Projects (*Delivered through WP3*)
- Section 6: A list of recommendations based on the findings of the research

3 CoDEC Data Dictionary

3.1 Review and Stakeholder Engagement

CoDEC carried out a three-step processes: a literature review was carried out to understand the concept of data management within NRAs (in particular "legacy data" – i.e. data associated with existing asset definition/inventory and its status/condition and "new" data provided by surveys and sensors); this was complemented by an online survey, which was then followed up via direct contact with individuals.

It was found that most NRAs have well-defined processes and existing systems for Asset Management. NRAs are also increasingly using sensors and other technologies for data collection and operational purposes. Many NRAs have also started using BIM during the design and building phase of projects because of the advantages it brings (more efficiency, better planning, better communication, etc.), and may also obtain digital representations of the result in the form of as-built BIM models. However, NRAs do not currently use BIM for long-term asset maintenance management.

The review also found that only some NRAs have developed data dictionaries (England, Lithuania, Norway, Sweden, Germany) and OTL (The Netherlands, Flanders, Finland) for specific projects on roads, bridges and tunnels.

As a further outcome of the stakeholder engagement three NRAs (Belgium, Finland and The Netherlands) were identified to work collaboratively as Implementation Partners for CoDEC in the development phase and to support the practical demonstrations in the Pilot Projects (section 0). All three NRAs provided consultation, information including OTL, asset data and 3D BIM models to help define the Data Dictionary Structure, CoDEC Ontology and the Pilot Projects.

3.2 Data Dictionary Structure and Content

The development of the Data Dictionary focused on its ultimate application in supporting the management of highway assets, which must include the management and reporting of both legacy data and new sensors and sensor data.

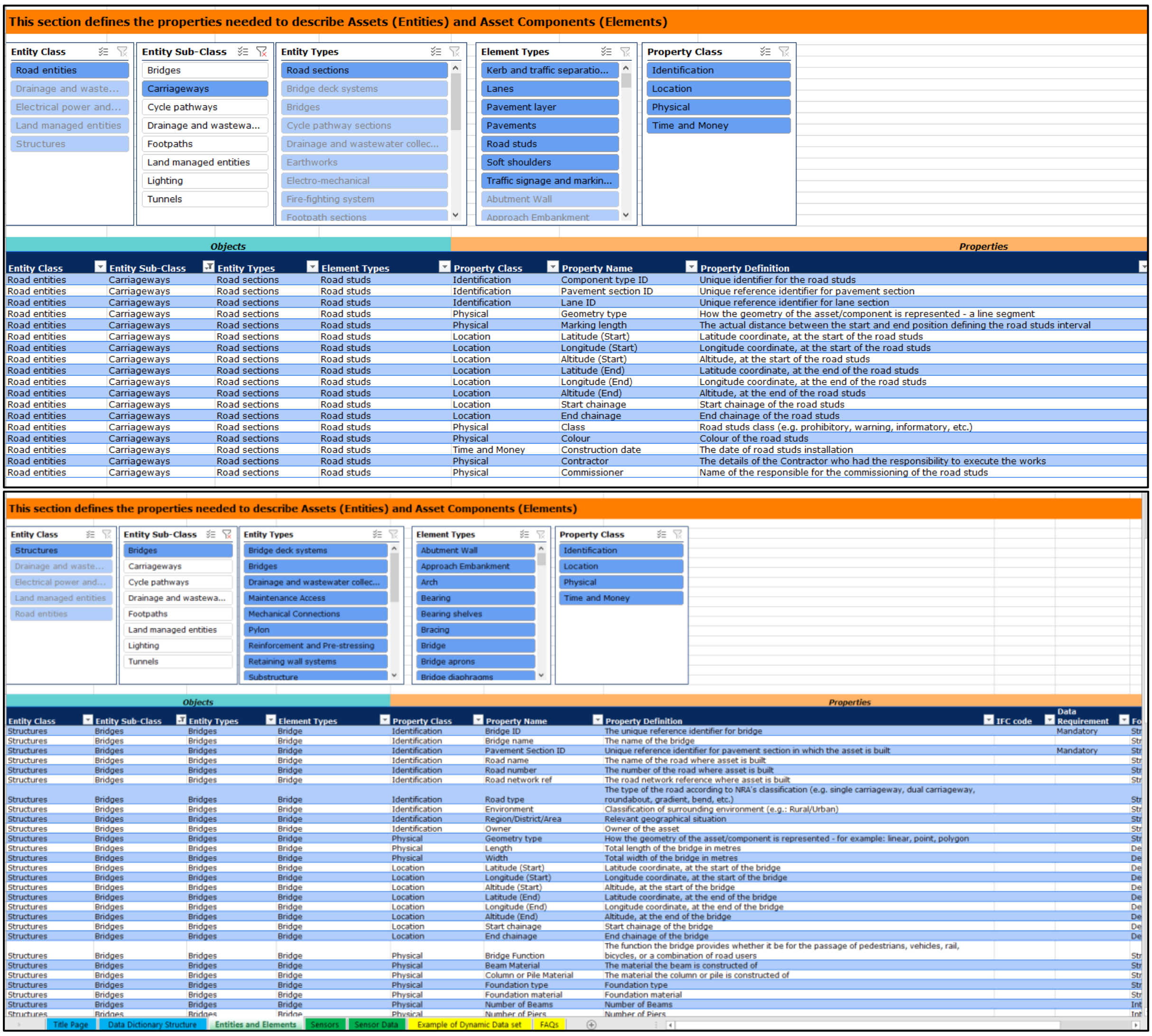
The review identified the previous work undertaken in the development of Data Dictionaries and the existing Dictionaries within NRAs. The development of the dictionary therefore built on the previous work carried out in AM4INFRA (which developed a Data Dictionary for tunnels and bridges (AM4INFRA,2018)), the Highways England UK-ADMM Data Dictionary (Highways England, 2020), the Data Standard for Road Management and Investment in Australia and New Zealand (DSRMI, for tunnels) (Austroads, 2019) and ifcRoad (buildingSMART, 2020). These were combined with the experience and knowledge of the team in infrastructure asset management to identify the technical needs for: (1) what constitutes "an asset" vs the components of that asset, and (2) the level of detail needed to adequately describe that asset for the purposes of asset management. Hence a design for the Data dictionary was proposed for three key highway assets (pavements, bridges and tunnels), including both the legacy data from these Assets and the data emerging from new technologies, such as sensors and scanning lasers. Having established the design, workshops were held in which the Data Dictionary content was presented and discussed with representatives from CEDR NRAs to validate the approach and the content.

3.3 Future Proofing the Data Dictionary

CoDEC had a particular objective to address sensors and the data they provide, as these are increasingly used to support infrastructure asset management. Sensors were not considered as 'Assets' in themselves, but rather as separate objects. The property sets which would apply in general to sensors were identified and included in the Dictionary. CoDEC considered it necessary to develop different property sets for sensors that have fixed locations and those that are mobile. This addresses differences in the approach taken to referencing the location of fixed and mobile sensors. In addition, there can be differences in how sensors are defined

- for example, one can consider an array (or network) of multiple fixed-location sensors but this does not apply to mobile sensors. Therefore, CoDEC has placed sensors in their own dedicated section of the Data Dictionary, separate from asset entities and elements. Hence the CoDEC Data Dictionary is future-proofed to remain useful in a wide variety of use cases as new sensors and their data are implemented.

Figure 2 shows the content of the CoDEC Data Dictionary for Roads and Bridges and Figure 3 shows the content for sensor data (the figures are truncated to fit, and as such does not show all fields). The Data Dictionary is published in Microsoft Excel spreadsheet format so that it is easy to expand further and include data from other assets.



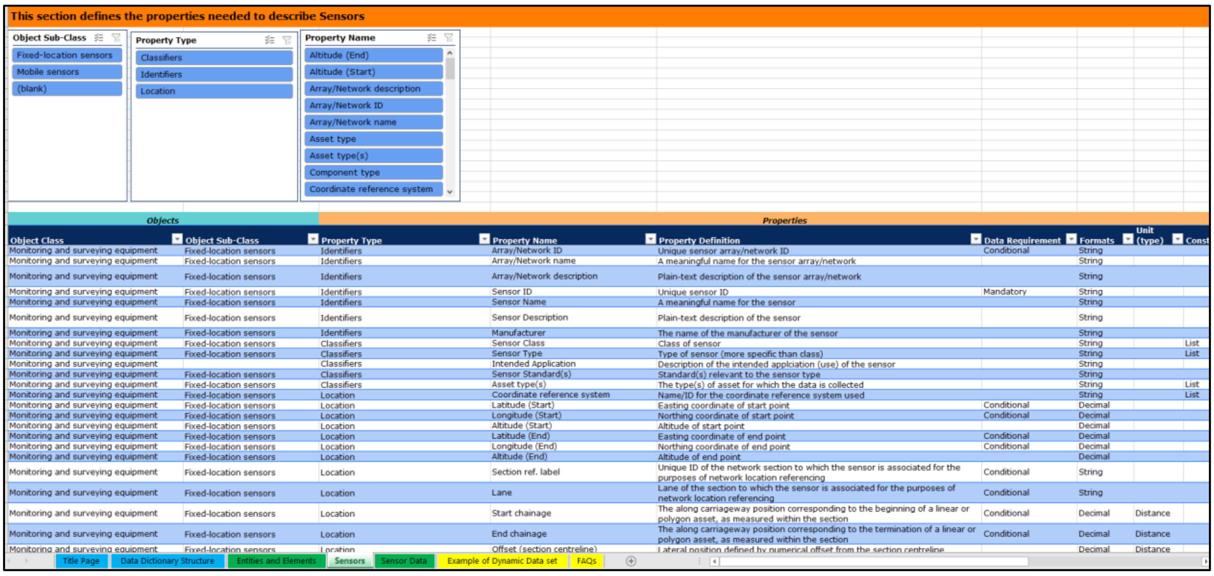
This section defines the properties needed to describe Assets (Entities) and Asset Components (Elements)

Entity Class	Entity Sub-Class	Entity Types	Element Types	Property Class	Property Name	Property Definition
Road entities	Carriageways	Road sections	Road studs	Identification	Component type ID	Unique identifier for the road studs
Road entities	Carriageways	Road sections	Road studs	Identification	Pavement section ID	Unique reference identifier for pavement section
Road entities	Carriageways	Road sections	Road studs	Identification	Lane ID	Unique reference identifier for lane section
Road entities	Carriageways	Road sections	Road studs	Physical	Geometry type	How the geometry of the asset/component is represented - a line segment
Road entities	Carriageways	Road sections	Road studs	Physical	Marking length	The actual distance between the start and end position defining the road studs interval
Road entities	Carriageways	Road sections	Road studs	Location	Latitude (Start)	Latitude coordinate, at the start of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	Longitude (Start)	Longitude coordinate, at the start of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	Altitude (Start)	Altitude, at the start of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	Latitude (End)	Latitude coordinate, at the end of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	Longitude (End)	Longitude coordinate, at the end of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	Altitude (End)	Altitude, at the end of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	Start chainage	Start chainage of the road studs
Road entities	Carriageways	Road sections	Road studs	Location	End chainage	End chainage of the road studs
Road entities	Carriageways	Road sections	Road studs	Physical	Class	Road studs class (e.g. prohibitory, warning, informatory, etc.)
Road entities	Carriageways	Road sections	Road studs	Physical	Colour	Colour of the road studs
Road entities	Carriageways	Road sections	Road studs	Time and Money	Construction date	The date of road studs installation
Road entities	Carriageways	Road sections	Road studs	Physical	Contractor	The details of the Contractor who had the responsibility to execute the works
Road entities	Carriageways	Road sections	Road studs	Physical	Commissioner	Name of the responsible for the commissioning of the road studs

This section defines the properties needed to describe Assets (Entities) and Asset Components (Elements)

Entity Class	Entity Sub-Class	Entity Types	Element Types	Property Class	Property Name	Property Definition	IFC code	Data Requirement	Fo
Structures	Bridges	Bridges	Bridge	Identification	Bridge ID	The unique reference identifier for bridge		Mandatory	Str
Structures	Bridges	Bridges	Bridge	Identification	Bridge name	The name of the bridge			Str
Structures	Bridges	Bridges	Bridge	Identification	Pavement Section ID	Unique reference identifier for pavement section in which the asset is built		Mandatory	Str
Structures	Bridges	Bridges	Bridge	Identification	Road name	The name of the road where asset is built			Str
Structures	Bridges	Bridges	Bridge	Identification	Road number	The number of the road where asset is built			Str
Structures	Bridges	Bridges	Bridge	Identification	Road network ref	The road network reference where asset is built			Str
Structures	Bridges	Bridges	Bridge	Identification	Road type	The type of the road according to NRA's classification (e.g. single carriageway, dual carriageway, roundabout, gradient, bend, etc.)			Str
Structures	Bridges	Bridges	Bridge	Identification	Environment	Classification of surrounding environment (e.g.: Rural/Urban)			Str
Structures	Bridges	Bridges	Bridge	Identification	Region/District/Area	Relevant geographical situation			Str
Structures	Bridges	Bridges	Bridge	Identification	Owner	Owner of the asset			Str
Structures	Bridges	Bridges	Bridge	Physical	Geometry type	How the geometry of the asset/component is represented - for example: linear, point, polygon			Str
Structures	Bridges	Bridges	Bridge	Physical	Length	Total length of the bridge in metres			De
Structures	Bridges	Bridges	Bridge	Physical	Width	Total width of the bridge in metres			De
Structures	Bridges	Bridges	Bridge	Location	Latitude (Start)	Latitude coordinate, at the start of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	Longitude (Start)	Longitude coordinate, at the start of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	Altitude (Start)	Altitude, at the start of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	Latitude (End)	Latitude coordinate, at the end of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	Longitude (End)	Longitude coordinate, at the end of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	Altitude (End)	Altitude, at the end of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	Start chainage	Start chainage of the bridge			De
Structures	Bridges	Bridges	Bridge	Location	End chainage	End chainage of the bridge			De
Structures	Bridges	Bridges	Bridge	Physical	Bridge Function	The function the bridge provides whether it be for the passage of pedestrians, vehicles, rail, bicycles, or a combination of road users			Str
Structures	Bridges	Bridges	Bridge	Physical	Beam Material	The material the beam is constructed of			Str
Structures	Bridges	Bridges	Bridge	Physical	Column or Pile Material	The material the column or pile is constructed of			Str
Structures	Bridges	Bridges	Bridge	Physical	Foundation type	Foundation type			Str
Structures	Bridges	Bridges	Bridge	Physical	Foundation material	Foundation material			Str
Structures	Bridges	Bridges	Bridge	Physical	Number of Beams	Number of Beams			Int
Structures	Bridges	Bridges	Bridge	Physical	Number of Piers	Number of Piers			Int

Figure 2: Data Dictionary showing Roads and Bridge Assets Data



This section defines the properties needed to describe Sensors

Object Sub-Class: Fixed-location sensors; Mobile sensors; (blank)

Property Type: Classifiers; Identifiers; Location

Property Name: Altitude (End); Altitude (Start); Array/Network description; Array/Network ID; Array/Network name; Asset type; Asset type(s); Component type; Coordinate reference system

Objects		Properties						
Object Class	Object Sub-Class	Property Type	Property Name	Property Definition	Data Requirement	Formats	Unit (type)	Const
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Array/Network ID	Unique sensor array/network ID	Conditional	String		
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Array/Network name	A meaningful name for the sensor array/network		String		
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Array/Network description	Plain-text description of the sensor array/network		String		
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Sensor ID	Unique sensor ID	Mandatory	String		
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Sensor Name	A meaningful name for the sensor		String		
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Sensor Description	Plain-text description of the sensor		String		
Monitoring and surveying equipment	Fixed-location sensors	Identifiers	Manufacturer	The name of the manufacturer of the sensor		String		
Monitoring and surveying equipment	Fixed-location sensors	Classifiers	Sensor Class	Class of sensor		String		List
Monitoring and surveying equipment	Fixed-location sensors	Classifiers	Sensor Type	Type of sensor (more specific than class)		String		List
Monitoring and surveying equipment		Classifiers	Intended Application	Description of the intended applciation (use) of the sensor		String		
Monitoring and surveying equipment	Fixed-location sensors	Classifiers	Sensor Standard(s)	Standard(s) relevant to the sensor type		String		
Monitoring and surveying equipment	Fixed-location sensors	Classifiers	Asset type(s)	The type(s) of asset for which the data is collected		String		List
Monitoring and surveying equipment	Fixed-location sensors	Location	Coordinate reference system	Name/ID for the coordinate reference system used		String		List
Monitoring and surveying equipment	Fixed-location sensors	Location	Latitude (Start)	Easting coordinate of start point	Conditional	Decimal		
Monitoring and surveying equipment	Fixed-location sensors	Location	Longitude (Start)	Northing coordinate of start point	Conditional	Decimal		
Monitoring and surveying equipment	Fixed-location sensors	Location	Altitude (Start)	Altitude of start point		Decimal		
Monitoring and surveying equipment	Fixed-location sensors	Location	Latitude (End)	Easting coordinate of end point	Conditional	Decimal		
Monitoring and surveying equipment	Fixed-location sensors	Location	Longitude (End)	Northing coordinate of end point	Conditional	Decimal		
Monitoring and surveying equipment	Fixed-location sensors	Location	Altitude (End)	Altitude of end point		Decimal		
Monitoring and surveying equipment	Fixed-location sensors	Location	Section ref. label	Unique ID of the network section to which the sensor is associated for the purposes of network location referencing	Conditional	String		
Monitoring and surveying equipment	Fixed-location sensors	Location	Lane	Lane of the section to which the sensor is associated for the purposes of network location referencing	Conditional	String		
Monitoring and surveying equipment	Fixed-location sensors	Location	Start chainage	The along carriageway position corresponding to the beginning of a linear or polygon asset, as measured within the section	Conditional	Decimal	Distance	
Monitoring and surveying equipment	Fixed-location sensors	Location	End chainage	The along carriageway position corresponding to the termination of a linear or polygon asset, as measured within the section	Conditional	Decimal	Distance	
Monitoring and surveying equipment	Fixed-location sensors	Location	Offset (section centreline)	Lateral position defined by numerical offset from the section centreline		Decimal	Distance	

Title Page | Data Dictionary Structure | Entities and Elements | Sensors | Sensor Data | Example of Dynamic Data set | FAQs

Figure 3: Data Dictionary showing Sensor Data

4 CoDEC Ontology, API and Architecture

An Ontology is a framework to describe the interconnectivities between asset data and metadata in a shareable and reusable format. An ontology can be defined as a "*formal, explicit specification of a shared conceptualization*" (Studer et al., 1998), meaning that concepts, their constraints, and their relationships are encoded in a way that is systematically structured, explicit and machine-readable. This allows ontologies to be used to integrate and retrieve information, obtain semantically enhanced content, and to support knowledge management. However, ontologies are often created in a format which is not easily understandable by the asset managers who work with asset data.

Therefore, whilst the CoDEC Data Dictionary provides a method for creating a domain specific ontology in plain English that is understandable by asset managers, the CoDEC Ontology translates the content to machine readable Ontology Web Language.

4.1 Ontology

The CoDEC Ontology was built on the EUROTL[1] framework (INTERLINK, 2018) using "Linked Data" and "Semantic Web" technologies. The Semantic Web helps link datasets so that they are understandable not only to humans but also to machines, and "Linked Data" makes these

[1] INTERLINK, INformation managemenT for European Roads using LINKed data is a previous CEDR project with the objective of defining, link, and manage infra-asset information for roads using Linked Data approach and Semantic. The main deliverable of this project was the European Road Object Type Library (EUROTL). The EurOTL framework covers highly reusable definitions such as provenance, quantities and units, temporal and spatial locations, transport networks, basic support for asset lifecycle and also main asset types and properties as needed for sharing asset lifecycle data. More information about the project can be found in https://www.roadotl.eu/ .

links possible. In other words, Linked Data is a set of design principles for sharing machine-readable interlinked data on the Web. The CoDEC Ontology was developed using the Resource Description Framework (RDF) Schema and the Ontology Web Language (OWL) which were developed by the World Wide Web Consortium (W3C).

As a first step, each Data dictionary entity was mapped to an existing class or property in EUROTL, as shown in Table 2. Properties are defined either as an object property or data property, meaning a semantic relation between object classes, or between the class and data (e.g. strings or numbers). CoDEC created a new class or property where mapping was not present in the EUROTL. The ontology was developed using Stanford's Protégé[2] (*Musen, 2015*). As an example, the Bridge concept already exists in the EUROTL Framework (*AM4INFRA 2018).* However, the concept of a Structural Element (or equivalent) of the bridge is not found in EUROTL. Hence, a new Structural Element class was created in the CoDEC ontology, as a sub-class of the already existing EUROTL concept EurOTL:PhysicalObject.

Table 2: Example of Data Dictionary to ontology mapping

CoDEC Data Dictionary				**CoDEC Ontology**		
Property	**Description**	**Format**		**Domain**	**Object/Data Property**	**Range**
Bridge ID	The unique reference identifier for bridge	String		bridgeID	is-a	Bridge
Bridge name	The name of the bridge	String		bridgeID	rdfs:label	xsd:string
Environment	Classification of surrounding environment (e.g. Rural/Urban)	String	➡	bridgeID	inEnvironment	xsd:string
Region/ District/Area	Relevant geographical situation	String		bridgeID	prov:atLocation	eurotl:LocationByIdentifier

4.2 Application Protocol Interface (CoDEC API)

The last step in the process to link data between different systems was to develop an Open Application Protocol Interface (CoDEC API). Application Programming Interfaces (APIs) are a "set of clearly defined methods of communication subroutine definitions, communication protocols" to support querying data to and from various sources using linked data/semantic web technology. By providing an API, CoDEC provides a practical and systematic approach that can be implemented by NRAs to connect their Asset Data with their BIM Platforms, and vice-versa. The concept of this API is shown in Figure 4.

[2] Stanford University's Protégé is a free, open-source platform that provides a suite of tools to construct domain models and knowledge-based applications with ontologies. More information can be found in https://protege.stanford.edu/ .

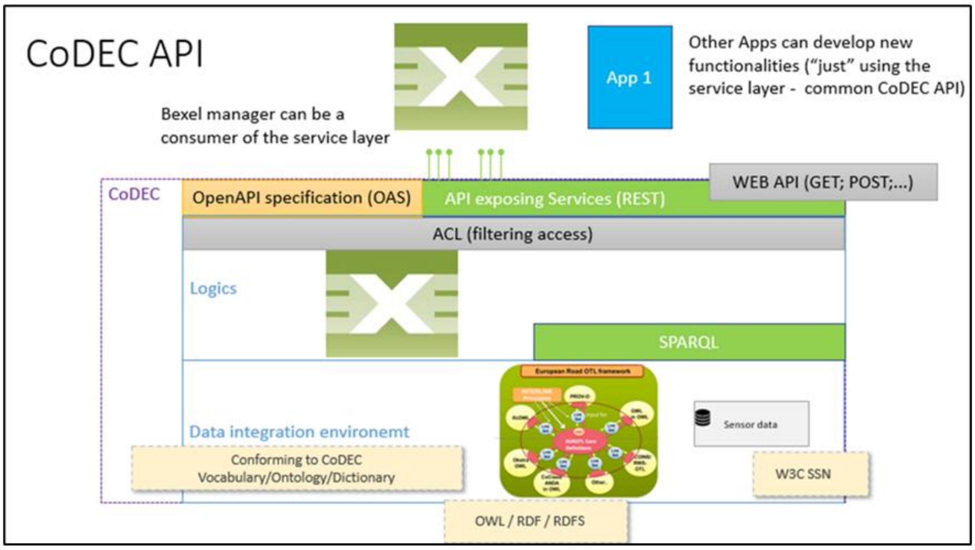


Figure 4: CoDEC API overview

The CoDEC API is a critical component of the technical solution. It creates

- a layer of abstraction and independence between the data and logical levels,
- allows any technological solution to access the linked data environment,
- eliminates any technical dependency to access the linked data environment,
- allows the ontology to evolve without changing the applications that access it through the API and
- allows the complexity of the data to be isolated

The API can be used by any application without needing to know the details of the implementation for faster development and it simplifies the entire process of testing and validation. Finally, visualisation and data management tools allow access to the API to manipulate and access data in the linked data environment. For the end user, the only interface required with the CoDEC solution is the visualisation / data management tool, hiding all the complexity of the linked data environment.

4.3 Technical Architecture

To manage the complexity of the linked data environment and create a "separate layer" that can be used without interfering with other "layers", CoDEC employed a set of services (REST Web services and Python services). These services are responsible for communicating with the linked data environment, typically through a set of SPARQL queries and can be used by any application, as long as it has permission to access both services and data. This layered approach has several advantages, the most critical one being that the separation provided by multiple layers allows modification of the linked data structures without affecting the normal behaviour of external applications, as they just need to know how to call the services (their inputs and outputs). CoDEC has delivered the OpenAPI specification, i.e., description and documentation detailing how services can be called, ensuring this can be used by all NRAs.

Figure 5 visualises the high-level architecture. The first layer highlights the existing information on which the technical solution was developed - namely, the Road OTL ontology of the Interlink project, making it possible to implement the CoDEC ontology from the Road

OTL implementations, and the CoDEC Data Dictionary. The ontology instances are stored in a Linked Data Environment, so they can be accessed to meet the requirements of the different pilot projects.

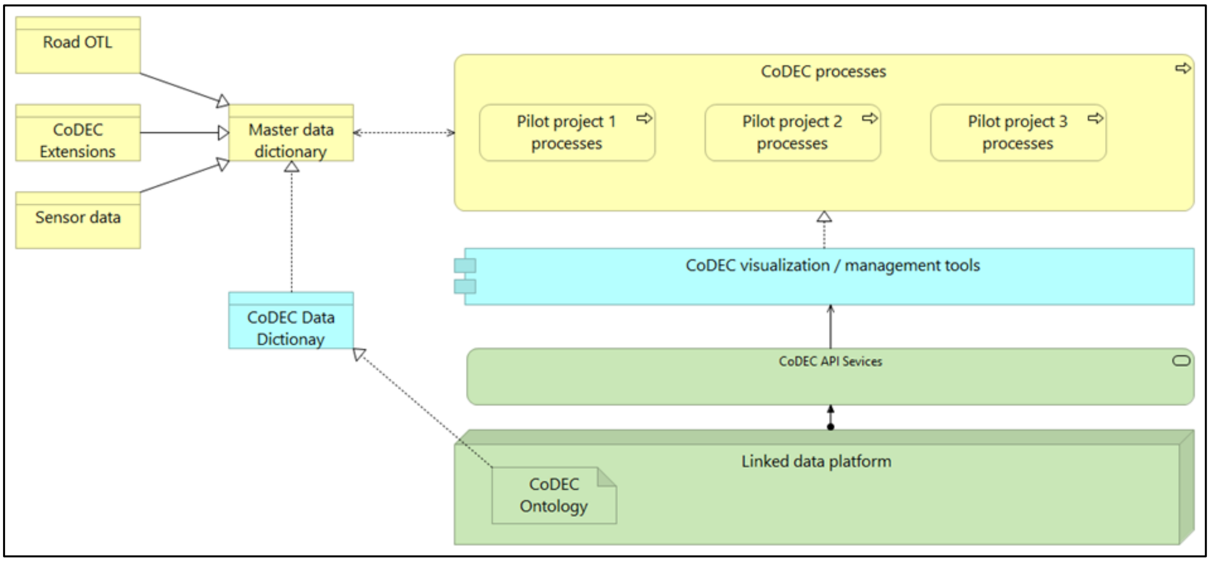


Figure 5: CoDEC Technical Architecture

5 Demonstrating the developed solution through Pilot Projects

5.1 Overview

As an initial proof-of-concept CoDEC developed a demonstrator using linked data from the INTERLINK project and a BIM model containing light posts. To implement this demonstration, CoDEC used Bexel Manager as the BIM environment[3]. Following this successful proof of concept the method was taken forward to the Pilot Projects. Three pilot projects were undertaken with three implementation partners (CEDR NRAs) covering three different asset types. The objectives of the pilot projects were to show that the CoDEC solution can be successfully implemented for different Asset Types and demonstrate how integration of different data sets in one system can improve and help NRA decision making. The three pilot projects were:

- Pilot Project 1: Integration and 3D visualisation of monitoring data within a BIM Model of a Tunnel
- Pilot Project 2: Linking and visualizing condition data with a Bridge BIM model
- Pilot Project 3: Enhancing legacy data by linking the BIM model of a Road to a GIS

[3] Bexel Manager is a BIM project management platform that provides a single solution and enables construction professionals to digitalize key workflows through advanced integrated and flexible system. BEXEL Manger fully supports BIM Open Interoperability standards and formats such as IFC and BCF file formats. Open API allows users to create fully customized BEXEL Manager tools or add-ins which can automatically execute various analyses and processes. More information about Bexel Manager can be found in: https://bexelmanager.com/

5.2 Pilot project 1: Integration and 3D visualisation of monitoring data within a BIM Model

Pilot Project 1 was carried out with Agentschap Wegen & Verkeer (AWV), the Belgian (Flemish) NRA, using BIM model provided by them. This Pilot Project demonstrated the use of the CoDEC approach to integrate sensor data within a Tunnel BIM Model. The model included a broad range of categories, families and element types for the Tunnel, and data was provided from monitoring sensors (CO, NO2, temperature, sight distance) installed in the tunnel (data collected over a period of one month).

A summary of how Pilot Project 1 applied the CoDEC approach is shown in Figure 6. The BIM model was imported to Bexel Manager and the sensor data was linked to the corresponding sensors in the 3D BIM model using the CoDEC Ontology and API. This mapping enabled an automatic, bi-directional relationship between the BIM elements and their related sensor data. The enriched BIM model can be exported using open standard formats such as IFC to other BIM applications that support open standards.

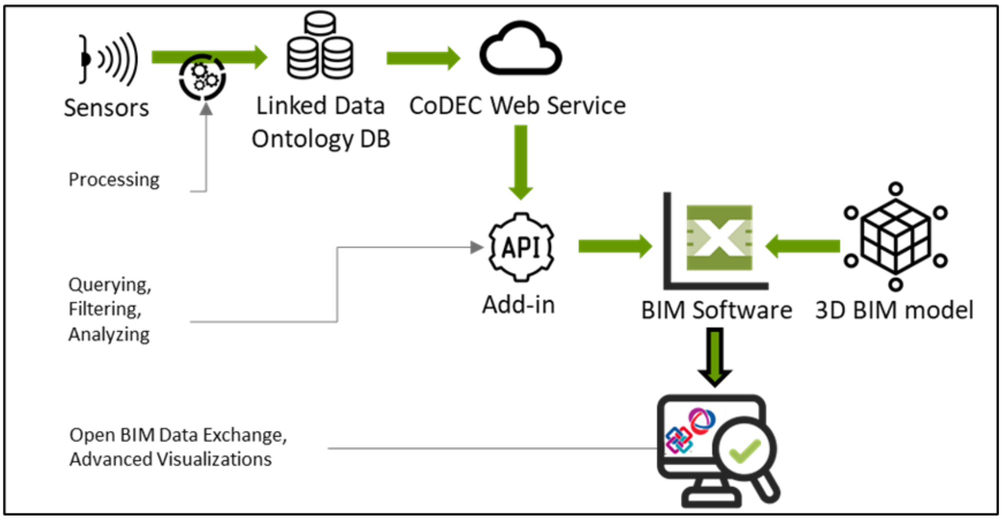


Figure 6: Methodology for Tunnel Pilot Project

Pilot Project 1 also considered the challenges of visualising distributes dynamic data within the BIM model – something that is not typically undertaken in BIM. Environmental sensors are themselves small elements of the tunnel located at point locations distributed along the length of the tunnel. The imported sensor cannot be shown in the BIM model just at the source point as it would not be informative. Hence, it was a challenge to find an ideal way to visualise imported data. In this case, the wall panel elements distributed along the tunnel were used to visualise the sensor values. Automating the sensor values to align with specific wall panels was one of the key workflows addressed in the pilot. Ultimately, sensor readings could be imported into the BIM environment and applied to specific 3D BIM model elements and wall panels to deliver visualisation of the environmental conditions. Figure 7 shows the 3D visualization of the sensor data in the BIM Model using Bexel Manager's 3D colour-coded view, with the sensors' values shown in different colours.

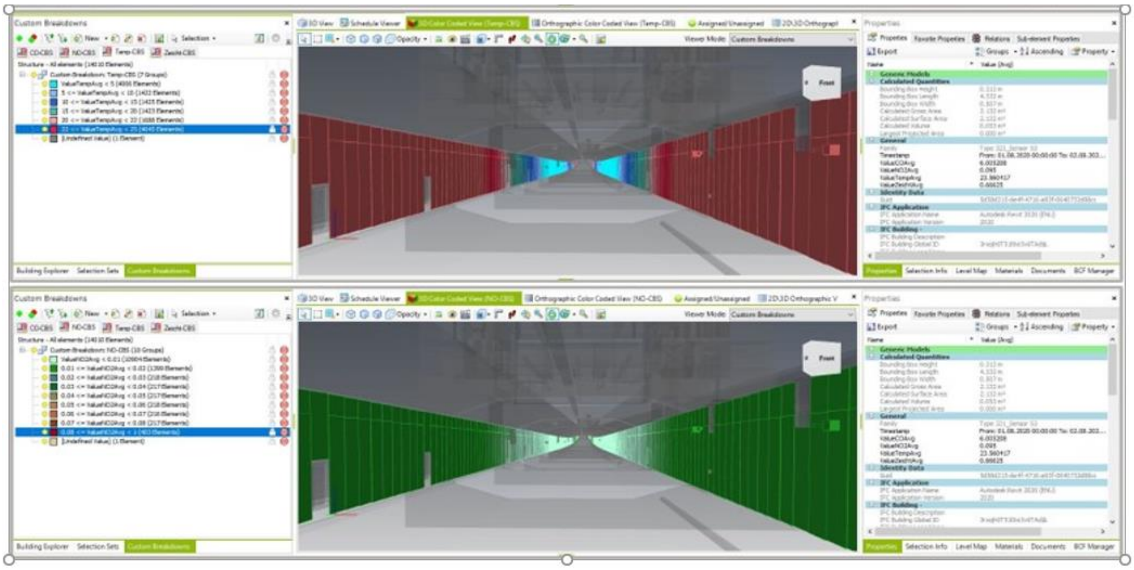


Figure 7: Visualisation of point sensor data in a BIM Model by colour coding wall panel elements of the tunnel

5.3 Pilot project 2: Linking and visualizing condition data with a Bridge BIM model

Pilot Project 2 was carried out on in consultation with the Netherland NRA, who also provided the BIM model. This pilot project demonstrated the potential to use a BIM platform as a framework to store information and provide a visual interface that integrates condition data with bridge components in a BIM model. A summary of how the pilot applied the CoDEC approach is shown in Figure 8. The model, which was imported into Bexel Manager in IFC open BIM format, contained 496 elements of four different IFC Classes. A list of attributes was added to each BIM element to support association with condition data provided by inspections, including access to data such as photos.

Pilot Project 2 demonstrated visualisation and risk analysis of condition data directly in a BIM model by deploying the CoDEC approach. After opening the BIM model in Bexel Manager, all the typical functionality of the Bexel BIM tool was available. However, once the linked data add-in was installed, the user could also access the list of inspections associated with the structure and the risk and condition data associated with that inspection. Figure 9 shows the 3D visualisation of the condition indicator index that could be shown in the BIM Model (assigning different colours to the elements of the structure, according to the condition level determined for each element in the selected inspection). The same functionality was explored for other values associated with that inspection, namely, the qualitative assessment of the condition state of the elements, the deadline for the next inspection and the type of the next inspection.

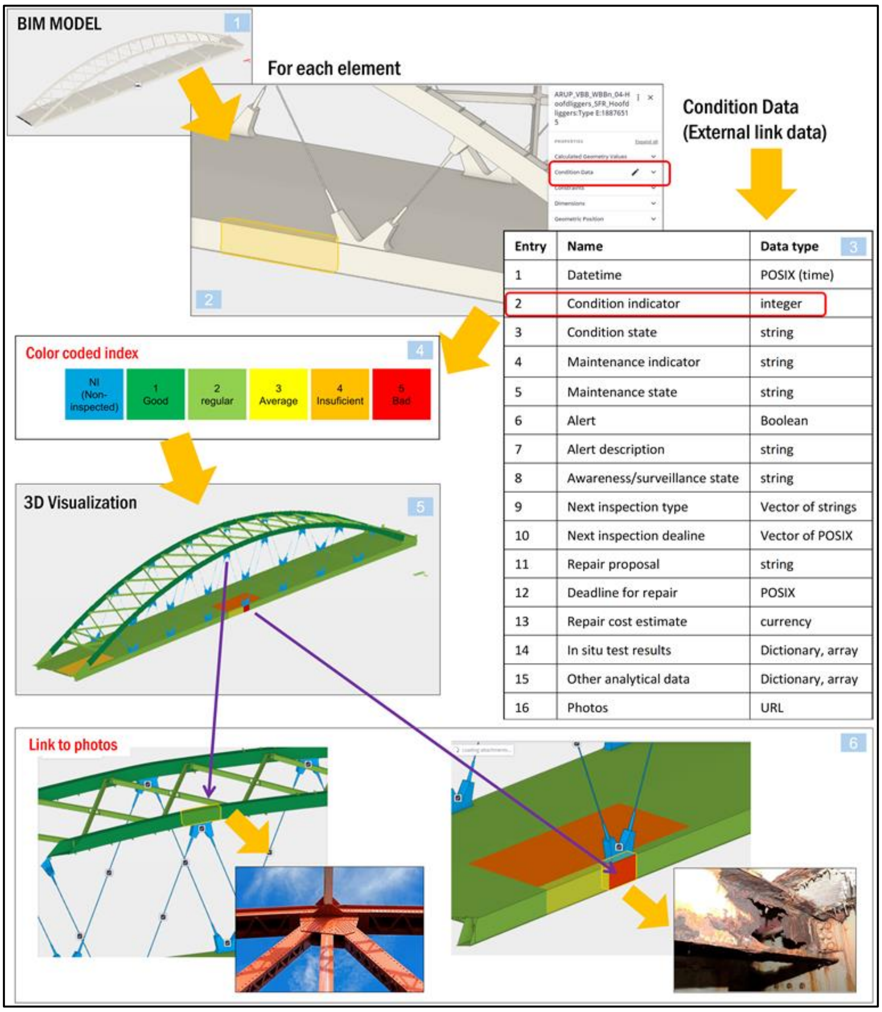


Figure 8 : Process of Connecting Sensor Data to Bridge BIM Model

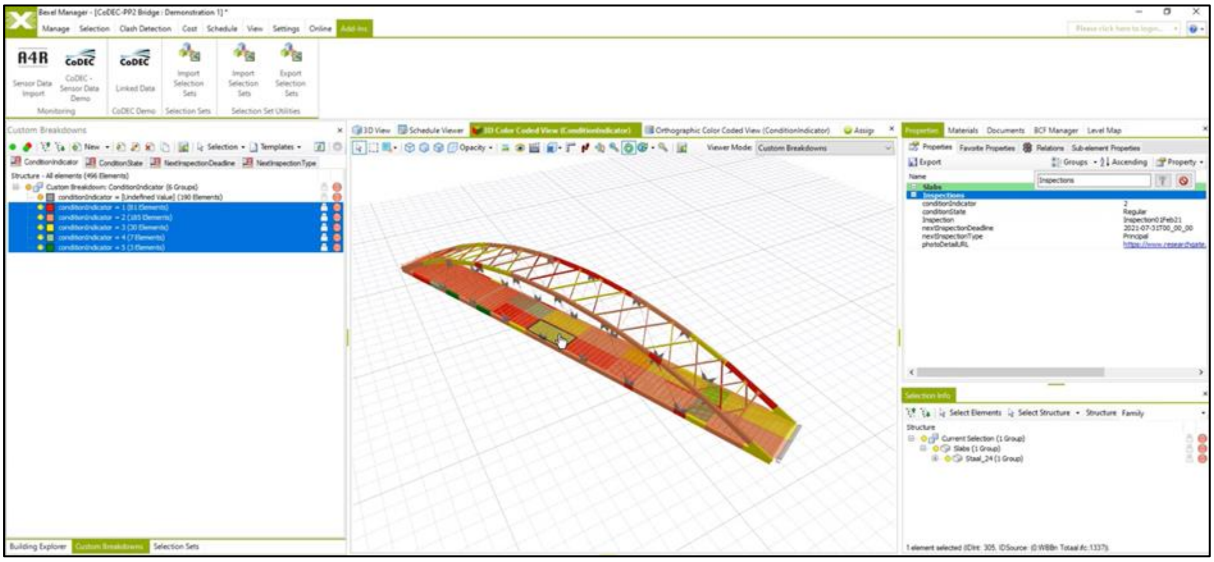


Figure 9 BIM Model showing coloured by condition indicator index

5.4 Pilot project 3: Enhancing legacy data by linking BIM models with GIS-based systems

Pilot Project 3 demonstrated that CoDEC methods can also be used to deliver data from BIM to other systems (whilst the opposite was demonstrated in the other two pilots). This pilot was developed in consultation with FTIA (Finnish NRA). However, the data and BIM model was provided by the Smart Mobility Living Lab, located in the London Borough of Greenwich, UK.

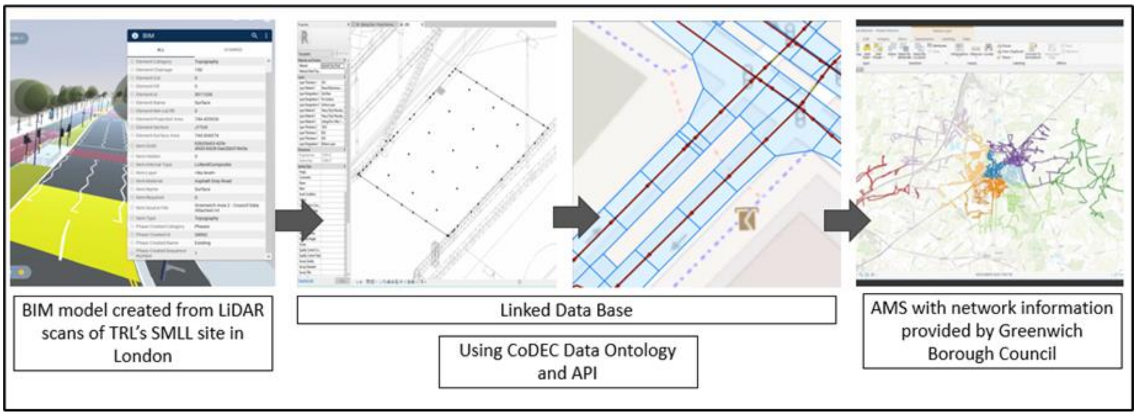


Figure 10: Linking data from the BIM model to GIS

BIM models are often created for the design/construct phase of Road assets, whilst roads are managed during the operational phase using GIS-based Asset Management Systems. Hence the BIM model often holds information useful for asset management, which could be used to enrich (and/or complement) the data held within AMS, However, this information is typically not made available to the AMS. Pilot Project 3 aimed to demonstrate this link. Figure 10 shows the process.

The method of linking data from a BIM model to a GIS based AMS has three main elements:

1. Linking asset data from BIM to Linked Database
2. Linked Data Base to GIS and
3. GIS to Linked Data Base

Before asset data can be linked from the BIM model to the AMS, it is necessary to assign parameters from the detailed geometric representation in the 3D BIM model to the 2D line representation of the road network typically deployed in an AMS. 2D Network models are simple by design because they are used to provide insights on network performance as a quick and clear overview. Conversely, 3D BIM models provide a more detailed representation of the network. Converting these complex geometries to simple lines will result in loss of information. In the pilot project, CoDEC defined the pavement as a set of "slabs" (rectangular units) that together form the road network and intersected each of them with the lines defining the route of the road. The positions of the slabs were stored as linked data using the ISO 19148:2021 Linear Referencing ontology, used in the European Road OTL. This ontology provides a means to locate objects (assets) along elements of a network, alignments, or other linear elements. In this case the linear element was an individual slab within the road network. For each slab, the start and end position on the network was determined, by measuring the start and end distance relative to the start of the entire polyline, using tools in the ArcGIS[4] system. Finally, these linear elements were uploaded back into the CoDEC repository using the CoDEC API. This approach enriched the road network model with information from the BIM model using linked data technology and international standards.

This Pilot project demonstrated the use of the CoDEC ontology for successfully linking data between BIM and GIS, which could provide benefits to NRAs including: Providing a single source of truth for highway assets; Having the required data available in the system where assets are primarily managed; and future-proofing such that data from new technologies (e.g. sensors, digital twins etc) can be supported within the AMS. The pilot also provided experience in the practicality of applying the CoDEC approach and its implications for further implementation. For example, pavements are linear features but will need to be modelled in small segments in BIM to accommodate condition data (which may be associated with specific locations or parts (e.g., layers) of the pavement). There will be a need to determine the optimum size for such segments, and there are many factors influencing the decision – for example, the granularity of the data available to be attached to each segment, the road layout (curvature, length between junctions, complexity etc), and maybe even constraints on model size.

6 Conclusions and Recommendations

Data is vitally important to asset managers and supports decisions throughout the asset lifecycle. Although there has been progress integrating BIM into the operational phase of Assets, CoDEC is one of the first projects to consider this from the Asset Management side - creating practical methods to enrich data, data systems, and change our way of working.

Building on previous research projects, such as AM4INFRA and INTERLINK, CoDEC applied a methodical approach to develop a framework for data (the data dictionary) and translate this into a machine-readable framework (the ontology) to make AMS and BIM data interoperable. This provides a step on the journey to making data seamlessly available when and where it is needed across data management systems and supports the first steps in the transition from traditional Asset Management to operation via the Digital Twin.

CoDEC has aimed to provide practical and implementable outcomes to NRAs that are also future-proof, by creating a framework that includes data provided by new technologies. Although, Codec did not cover all road infrastructure assets and data types, it provides a structured and practical framework that can be expanded to include other asset types and data as required in the future - hence catering for Road Authorities' future needs.

Although CODEC has successfully developed applications to integrate data from different systems, there is substantial work still to be done in this area. One of key findings from the CoDEC Stakeholder engagement was that there is a lack of collaboration and common

[4] ArcGIS Pro is a commercial GIS application developed by Esri. ArcGIS is the industry standard for working with desktop GIS. In the pilot project is used for data visualization, data management and spatial analysis. Information about this application can be found here: https://www.esri.com/en-us/arcgis/products/arcgis-pro/

understanding of the data requirement across the stakeholders. The pilot projects have also helped to understand the limitations of current systems and identify the need for developments that could help the future exploitation of the CoDEC approach.

Based on the challenges and findings from this research, the CoDEC recommendations are:

- **Encourage collaboration** between asset owners (such as NRAs), standardisation bodies (such as ISO and IFC) and the software technology industry to understand the practical needs of asset managers/owners when it comes to data integration, and to build on the outcomes of this project to deliver the tools that will meet these needs.
- **Simplify level of detail within BIM models**: To simplify the discretisation of the visualisation components, it is recommended that BIM model designers develop elements with the appropriate level of detail for visualisation - i.e., that visualisation needs are considered when developing BIM models.
- **Normalisation and standardisation of conventions and nomenclature:** The mapping between the BIM elements and the elements present in the ontology is a critical aspect in the development of the integration. It is recommended that BIM solution manufacturers provide advanced filtering mechanisms for generating ifcOWL from BIM models.
- **Automation**: Whilst the current solution is adequate, it requires effort in data instantiation and synchronization with distinct data sources that limits a fully automated method. Automating all steps in the process would increase the ability to exploit the results of the CoDEC project - allowing a real-time approach.

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