






# D5.2 DIGITAL-TWIN ENABLED MULTI-PHYSICS SIMULATION AND MODEL MATCHING

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### ABSTRACT

This deliverable presents a report on the developed actions and results concerning Digital-Twin-enabled multi-physics simulations and model matching. Enabling meaningful simulations within new human-infrastructure interfaces such as Digital twins is paramount. Accessing the power of simulation opens manifold new ways for observation, understanding, analysis and prediction of numerous scenarios to which the asset may be faced. As a result, managers can access countless ways of acquiring synthetic data for eventually taking better, more informed decisions. The tool MatchFEM is conceived as a fundamental part of this endeavour. From a broad perspective, the tool is aimed at contextualizing information between multi-physics simulations and vaster information constructs such as digital twins. 3D geometries, measurements, simulations, and asset management coexist in such information constructs. This report provides guidance for the generation of comprehensive adequate initial conditions of the assets to be used during their life span using a DT basis. From a more specific focus, this deliverable presents a set of exemplary recommendations for the development of DT-enabled load tests of assets in the form of a white paper. The deliverable also belongs to a vaster suit of documents encountered in WP5 of the Ashvin project in which measurements, models and assessments are described thoroughly.

### KEYWORDS

Digital Twin, Simulations, Building Information Modelling, Sensors, Multi-Physics, Finite Element Models

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## ACRONYMS & DEFINITIONS

BIM	Building Information Modelling
FEM	Finite Element Models
V&V	Verification and Validation (Verified and Validated also applies)
SA	Structural Analysis
IoT	Internet of Things
DT	Digital Twin
RDF	Resource Description Framework
URI	Uniform Resource Identifier
RDBMS	Relational Database Management System
CDE	Common Data Environment
IFC	Industry Foundation Classes
XML	Extensible Markup Language
JSON	JavaScript Object Notation
OWL	Web Ontology Language
SQL	Structured Query Language
W3C	World Wide Web Consortium
NoSQL	Not Only SQL
AEC(O)	Architecture, Engineering, Construction, and Operations
URL	Uniform Resource Locator
HTTP	Hypertext Transfer Protocol
LoRaWan	Long Range Wide Area Network
MQTT	Message Queuing Telemetry Transport
CoAP	Constrained Application Protocol
REST API	Representational State Transfer Application Programming Interface
ETA	Estimated Time of Arrival
ETL	Extract, Transform, Load
BREP	Boundary Representation
ADIF	Administración de Infraestructuras Ferroviarias (Spanish Public Company)
LoD	Level of Development
LVDT	Linear Variable Differential Transformer



## ASHVIN PROJECT

ASHVIN aims at enabling the European construction industry to significantly improve its productivity, while reducing cost and ensuring absolutely safe work conditions, by providing a proposal for a European-wide digital twin standard, an open-source digital twin platform integrating IoT and image technologies, and a set of tools and demonstrated procedures to apply the platform and the standard proved to guarantee specified productivity, cost, and safety improvements. The envisioned platform will provide a digital representation of the construction product at hand and allow to collect real-time digital data before, during, and after production of the product to continuously monitor changes in the environment and within the production process. Based on the platform, ASHVIN will develop and demonstrate applications that use the digital twin data. These applications will allow it to fully leverage the potential of the IoT-based digital twin platform to reach the expected impacts (better scheduling forecast by 20%; better allocation of resources and optimization of equipment usage; reduced number of accidents; reduction of construction projects). The ASHVIN solutions will overcome worker protection and privacy issues that come with the tracking of construction activities, provide means to fuse video data and sensor data, integrate geo-monitoring data, provide multi-physics simulation methods for digital representing the behaviour of a product (not only its shape), provide evidence-based engineering methods to design for productivity and safety, provide 4D simulation and visualization methods of construction processes, and develop a lean planning process supported by real-time data. All innovations will be demonstrated on real-world construction projects across Europe. The ASHVIN consortium combines strong R&I players from 9 EU member states with strong expertise in construction and engineering management, digital twin technology, IoT, and data security/privacy.

# TABLE OF CONTENTS

<b>1</b>	<b>GENERAL FRAMEWORK</b>	<b>9</b>
<b>1.1</b>	<b>INTRODUCTION</b>	<b>9</b>
1.1.1	Measurements	10
1.1.2	Simulations, models and prediction	10
1.1.3	The match-the-DT conundrum	11
1.1.4	Objectives of the deliverable, target users and described tasks	13
<b>1.2</b>	<b>SIMULATIONS THROUGHOUT THE LIFE-CYCLE OF ASSETS</b>	<b>15</b>
1.2.1	The design stage	15
1.2.2	The construction stage	17
1.2.3	The maintenance stage	18
<b>1.3</b>	<b>A FRAMEWORK FOR MATCHFEM IN DT PLATFORMS: KNOWLEDGE GRAPHS</b>	<b>20</b>
1.3.1	Gaphs, Ontologies, and Knowledge Graphs: Definitions	20
1.3.2	Knowledge Graphs for DTs in the Built environment	23
1.3.3	KG-DTs and simulations. An ontology for structural simulation.	27
<b>1.4</b>	<b>MATCHFEM WITHIN ASHVIN DT PLATFORM</b>	<b>29</b>
1.4.1	From BIM to the Digital Twin system	31
1.4.2	IoT integration	32
1.4.3	Simulation integration	33
1.4.4	Adding MatchFEM capabilities to the DT Platform	34
<b>1.5</b>	<b>FUNCIONALITIES AND INTEREST OF USE</b>	<b>35</b>
1.5.1	Validation and Verification	37
1.5.2	Plan Maintenance	38
1.5.3	Feed and update models	39
1.5.4	Design monitoring strategies	39
<b>1.6</b>	<b>TESTBEDS FOR MATCHFEM AND MODELS IN THE FRAME OF ASHVIN</b>	<b>40</b>
1.6.1	Material calibration for realistic Initial state	41
1.6.2	concrete maturity - detailed flow from sensor to simulation	44
1.6.3	Geomtrical and material nonlinear analysis with imperfections (GMNIA) derived from geometrical recorded data	48
1.6.4	Laboratory tests - computationally tractable models - computationally expensive data processing (Pointclouds)	57
<b>1.7</b>	<b>DISCUSSION</b>	<b>60</b>
<b>2</b>	<b>RECOMMENDATIONS FOR THE DEVELOPMENT OF DIGITALLY TWINNED LOAD TESTS</b>	<b>61</b>
<b>2.1</b>	<b>INTRODUCTION</b>	<b>61</b>
<b>2.2</b>	<b>TOWARDS DIGITALIZATION OF LOAD TESTS</b>	<b>61</b>
2.2.1	Current practice	61

2.2.2	A digital approach. future challenges.....	66
<b>2.3</b>	<b>LOAD TESTS IN DEMO #1. BRIDGES.....</b>	<b>68</b>
2.3.1	Executed load test plan .....	71
2.3.2	Structural analysis models for results prediction.....	75
2.3.3	Data-collection .....	79
<b>2.4</b>	<b>IDENTIFICATION OF DIGITAL TWIN COMPONENTS .....</b>	<b>80</b>
2.4.1	Virtual Asset.....	81
2.4.2	Data Collection .....	84
2.4.3	Data Processing .....	88
2.4.4	Data Discoveries .....	88
2.4.5	Data for Management .....	91
<b>2.5</b>	<b>EXEMPLARY ACTIONS FOR TARGET USERS. ....</b>	<b>92</b>
2.5.1	Target users .....	92
2.5.2	Designing monitoring strategies.....	93
2.5.3	Verification and validation .....	94
2.5.4	Feed and Update models .....	96
2.5.5	Maintenance plan.....	99
<b>3</b>	<b>CONCLUSIONS .....</b>	<b>103</b>
<b>4</b>	<b>REFERENCES .....</b>	<b>105</b>
<b>5</b>	<b>APPENDIX A .....</b>	<b>110</b>

## INDEX OF FIGURES

Figure 1.	Conception of MatchFEM.....	14
Figure 2.	Ashvin demo-cases for the implementation of MatchFEM.....	19
Figure 3.	Related nodes on a graph .....	21
Figure 4.	Summary of the proposed ontology .....	29
Figure 5.	Graph databases and Ashvin building blocks .....	31
Figure 6.	Steps of the integration of IoT and BIM in the graph .....	32
Figure 7.	Issues in the knowledge graph.....	33
Figure 8.	Event-driven architecture in the Ashvin platform .....	34
Figure 9.	Ashvin toolkit and MatchFEM functionalities.....	37
Figure 10	Location and overview of La Plata Viaduct .....	42
Figure 11	Longitudinal and cross section of La Plata Viaduct .....	42
Figure 12	Load test of La Plata bridge and a sample of collected sensor data .....	43
Figure 13	Filament frame element (Source: Marí A, 2000).....	43
Figure 14	Parametric fibre-based model of La Plata Viaduct cross section.....	44
Figure 15.	Sensor location and the corresponding filament to match strains .....	44
Figure 16	MILE Ávila office building render and BIM model (Provided by BIS structures) .....	45
Figure 17	Collection of data, sensors location and measures acquired.....	46
Figure 18	Maturity index and compressive strength estimation from temperature data within Grasshopper .....	46
Figure 19	Concrete material properties with estimated compressive strength (Karamba 3D) .....	47
Figure 20	Karamba 3D model assembly for the simulation of deflections .....	47
Figure 21.	Location and general view of PR-04-B015 bridge .....	49

Figure 22. From drawings to IFC accessible geometries.....	50
Figure 23. Final point cloud after the registration process. The position of the scanner and spherical target is highlighted. ....	51
Figure 24. Geometrical model and pointcloud after the registration process.....	51
Figure 25. A: bounding box used to reduce the pointcloud to points contained in the region of study. B: Pointcloud segmentation using oriented bounding boxes of the box girder sub-panels .....	52
Figure 26. Multiple scans (M1 to M4) result in overlaid pointclouds that are associated with the elements of the bridge .....	52
Figure 27. Results of the deviation analysis conducted on the bridge span for all the scans up to date .....	53
Figure 28. Different levels of available as-built information, from full sections to single web sub-panels .....	53
Figure 29. Stability analysis of a longitudinally stiffened partial web.....	54
Figure 30. Eigenvalue analysis of isolated panels. ....	55
Figure 31. Sensitivity of the magnitude of imperfection on the load bearing (pure compression) .....	55
Figure 32. Imperfect contact between ‘as-built’ surfaces derived from the pointcloud measurements and ‘perfect’ stiffeners from the model .....	56
Figure 33. Mesh generated from surfaces fitted to the point cloud measurements.....	56
Figure 34. Full-order GMNIA models based on seasonal imperfections.....	56
Figure 35. Prestressed cable net.....	58
Figure 36. Initial TLS scan of the prestressed cable net mock-up .....	58
Figure 37. a) unloaded (purple) net pointcloud with identified nodes (red) superimposed to a loaded configuration (green) with identified nodes (blue). In b), the derived net configuration (points and lines) after processing the pointclouds. ....	59
Figure 38. Pipeline for updating cable force information from pointcloud measurements. In blue, information snippets that are stored in the ASHVIN platform. In orange, computational processes executed.....	59
Figure 39. Flowchart of the proof load test procedure according to NAP 2-4-2.0.....	63
Figure 40. Measuring vibrations and displacements with a GB-INSAR in a large arched bridge .....	64
Figure 41. Load test data model.....	67
Figure 42. Location of Valdelinares Viaduct.....	69
Figure 43. Valdelinares Viaduct. Drone view .....	69
Figure 44. Location of la Plata Viaduct.....	70
Figure 45. La Plata Viaduct. Drone view .....	70
Figure 46. Valdelinares Viaduct. Cross-section .....	71
Figure 47. La Plata Viaduct. Cross-section .....	71
Figure 48. LVDTs labels and locations for static load test at span 3 .....	72
Figure 49. Locations schema of LVDTs sensor for deflection measurement .....	72
Figure 50. Strain gauges location (plan view) .....	73
Figure 51. Accelerometers location (plan view) .....	75
Figure 52. Accelerometers location (cross-section view).....	75
Figure 53. Static load test structural model .....	76
Figure 54. Dynamic load test structural model.....	78
Figure 55. Vertical displacements at the midspan 3 (static load test).....	79
Figure 56. Accelerations at the midspan 2 (pseudo-static test: 5km/h) .....	79
Figure 57. Accelerations at the midspan 2 (max speed 80km/h).....	79
Figure 58. Vertical displacements at the midspan 1 (max speed 80km/h).....	80
Figure 59. Main components of a Digital Twin .....	80
Figure 60. Pipeline for La Plata Viaduct virtual asset generation.....	83
Figure 61. La Plata viaduct type and locations of sensors for the load test.....	85

Figure 62. IFC relations to add sensors to a BIM model..... 85

Figure 63. Tasks for measures during the load test..... 86

Figure 64. Preparation of accelerometers during testing ..... 86

Figure 65. Sensor data uploaded to the IoT platform..... 87

Figure 66. Sensor data retrieved in the Digital Twin platform ..... 87

Figure 67. Deflection results for load test checking using a python script within Grasshopper ..... 88

Figure 68. IFC-BIM model to Rhino for constructing the structural analysis model topology . 89

Figure 69. Generation of La Plata structural analysis model ..... 90

Figure 70. Bending moment diagram of the simulation of La Plata structural model..... 90

Figure 71. Structural analysis results in the Ashvin Digital Twin platform..... 91

Figure 72. Ashvin vision for planning monitoring strategies at design stages ..... 93

Figure 73. Ashvin vision for validation of load tests ..... 96

Figure 74. Ashvin vision for feeding and updating models..... 98

Figure 75. Feed and Update Models application for Demo 6..... 99

Figure 76. Ashvin vision for planning maintenance..... 101

Figure 77. Plan maintenance example of application for Demo 7..... 102

Figure 78. Ashvin vision for the life cycle of a digitally twinned bridge..... 104

## INDEX OF TABLES

Table 1 Demonstrators, simulation needs, potential measurements ..... 36

Table 2 Results for static tests ..... 65

Table 3 Impact ratio results for dynamic tests..... 65

Table 4 Exemplary peak frequency results table for dynamic tests ..... 65

Table 5 Exemplary damping results table for dynamic tests ..... 65

Table 6 Description of the executed hypotheses for the static load test..... 74

Table 7 Load applied to the model for each hypotheses of the static load test ..... 76

Table 8 Predicted bending moments and deflections for the static load test hypotheses ..... 77

Table 9 Predicted vibration modes for dynamic test analysis ..... 78

# 1 GENERAL FRAMEWORK

## 1.1 INTRODUCTION

Enabling the potential of simulations within new human-infrastructure interfaces such as Digital twins is paramount. Accessing synthetic yet realistic scenarios to which the asset may be faced opens manifold new ways for observation, understanding, analysis and prediction. As a result, managers can multiply the ways of acquiring data for the sake of taking better and more informed decisions. In other words, the co-existence between measurements and simulation in the same information construct opens new ways of dealing with data, its analysis and its visualization. It also opens new challenges related to one conundrum.

***How many sources of data can be dealt with simultaneously?***

The answer to this question is ignited in the predecessor deliverable to this suite (D5.1 Casas et al, 2022) in which layers of information come from the physical realm. MatchFEM is a set of tools aimed at matching synthetic information from the virtual realm with many other types of information layers. This deliverable, which is divided into three parts, presents a report on the developed actions and results concerning the task “Digital-Twin enabled multi-physics simulations and model matching”.

- Part 1 is presented as a general framework. On the one hand, its objective is to present the potential of knowledge graphs as enablers for the semantic connection of multiple information layers (3D geometries, measurements, simulations, asset management...) within the Ashvin DT platform. Then, functionalities conceived for MatchFEM are described. Finally, several applications in many Ashvin demo sites are described. This represents the actions developed in task 5.2 of WP5. The conception of the aforementioned functionalities is directly linked to these demonstrators and these actions.
- Part 2 is presented with a more specific focus, i.e., a set of recommendations for the development of DT-enabled load tests of assets. This part is presented in the form of a white paper. For this purpose, an exemplary demonstrator of the project is analysed thoroughly. Actions taken in this demo for enabling the connection between simulations, measurements and other layers of the DT are described. Presently, load tests on bridges are performed routinely worldwide. Measurements are taken and then compared to predictions coming from simulations. This is ideal for producing a bridge’s DT for maintenance purposes with validated models.
- A concise discussion of the results is presented in Part 3.

### 1.1.1 MEASUREMENTS

Measuring magnitudes from the physical realm allow understanding, comparing and even predicting the behavior of the corresponding phenomena. Measuring has always been part of civilizations. The earliest recorded systems of weights and measures originate back to millennia. Records from the earliest civilizations needing measurement for purposes of agriculture, construction and trade are available. Early standard units represented communal agreements that might only have applied to a single community or small region. Independently, every area developed their own standards for lengths, areas, volumes, and masses. For centuries, the evolution and sophistication of measurement and metrology fundamentals have resulted in considerable advances in sensors, measurement instruments, measurement and estimation techniques, measurement data processing, fusion algorithms, and evaluation procedures for performance analysis of measurement systems or distributed measurement systems in a connected world.

The construction sector has always required insightful knowledge about both the surrounding natural and built environments. Today, a considerably vast array of sensors, the opportunities provided by computer vision and the ability to deploy remote sensing techniques are unforeseen. All these technologies are, and will be feeding the construction sector with data that require proper digestion. Recognizably, extracting value from this information is still a big challenge in AEC.

On the other hand, measuring techniques become more ubiquitous, more accessible (both technically and economically) and more connected. The number of sensors that will be embedded in infrastructure systems will grow considerably in the years to come. As a result, centralized platforms and hubs of information will become a much more fundamental part of these infrastructure systems. The digital twin of these systems represents an information construct in which many layers of information can be aggregated. Accordingly, sensor-, image- and remote sensor-based data need to be meaningfully collected and embedded within DT platforms of various kinds. The reader is referred to the first document of the suit of this work package (Casas et al. (2022)) for a comprehensive description of measuring techniques used in the realm of infrastructure systems.

***Accordingly, sensor-, image- and remote sensor-based data need to be meaningfully collected and embedded within DT platforms of various kinds.***

### 1.1.2 SIMULATIONS, MODELS AND PREDICTION

A simulation is a synthetic operation that mimics a behavior, a process, a system or a phenomenon. They require the use of validated theoretical models, which represent key aspects and characteristics of the observed asset. Simulations may also require

numerical methods, based on certain assumptions and considerable discretization of geometries. Alternatively, predictions can be based on empirical data that feed different kinds of learning techniques. Decades of research on simulation in practically all areas of engineering provide an incredibly huge source of information that may feed digital twins with valuable layers of information. As a result, Verifiable and Validated (V&V) synthetic data becomes a very valuable key component within the vaster DT information construct. The predictive capabilities of DT boost when this layer of information is added. Consequently, Verification and Validation become paramount for future generations of DT when dealing with numerous predictive models generated by potentially different stakeholders.

On the other hand, the computing capacity doubles in increasingly shorter periods of time. The number of operations per unit of time boosts and simulations are becoming more and more sophisticated. In practically all areas of engineering, simulations are becoming closer to reality when models become coupled, more complex and with less designer-assumed conditions. A symbiosis appears clearly. On the one hand, simulations feed DT constructs with V&V data for decision-making in one direction of the data pipeline. On the other hand, data from the real world updates the validity of these simulations in the other direction of the same pipeline. The tandem becomes a trustful source of increasingly enhanced data.

**Verification and Validation (V&V) become paramount for future generations of DT when dealing with numerous predictive models generated by potentially different stakeholders.**

The DT is an information construct in which many layers of information are aggregated. The DT enabled with simulations is a version that becomes an enriched assistant to owners, managers, designers and other stakeholders. On such a basis, data coming from theoretical models, numerical models and/or learning techniques need to be seamlessly connected to a varied set of geometrical entities that belong to the BIM ecosystem and DT platforms of various kinds. As a result, synthetic data becomes useful and interoperable. The reader is referred to deliverables of the project related to ontologies (Khan R., 2022) and interoperability (Hartmann T., 2022) for a deeper understanding of the conceptual design of the data flow.

### 1.1.3 THE MATCH-THE-DT CONUNDRUM

Going back to the definition of the symbiotic relationship between DT and simulations. On the one hand, simulation feeds DT constructs with V&V data for decision-making. On the other hand, data from the real world updates the validity of these simulations. To maintain and improve such symbiosis, a vast-scoped perspective of the information construct is required. Layers of information need to magnetically matched. For instance, a given DT of a bridge, or a building is represented by a three-dimensional geometrical virtual model. In one specific element of such virtual model, for instance,



a portion of a beam, there might be a sensor. It would then be interesting to have a geometrical representation of the portion of that beam that facilitates the virtual location of **this** sensor in **that** corresponding element. Likewise, it would be interesting to have a geometry that facilitates the development of a simulation on that portion of the beam as well. Matching both layers of information is incredibly beneficial for the decision-making process. If both pieces of data information models (beam from simulation, beam from BIM) can be magnetically integrated, then the Match happens.

The model-based simulations are mostly defined by properly connected nodes and elements in forms of meshes. These virtual geometries carry an “information load” organized in, for instance, nodes within volumes (3D solids), in nodes within areas (plates and shells) or in nodes within lines (beam or trusses). Depending on the needs of the simulation, numerical modelers choose the degree of realism. On the one hand, dense meshes tend to give more information and coarse meshes tend to provide reduced yet key information. On the other hand, models can be single-purposed or coupled between manifold phenomena. In either case, simulations should always be Verified & Validated but also, computationally tractable. Efficiency and meaning are also key principles to maintain. An excessive realism in simulations may also result in a waste of resources that neither enhance their validity nor their purpose.

DTs include virtual representations of the data that are either software-dependent or more interestingly, software-independent. Standard representations of the information and data-exchange between stakeholders of the BIM ecosystem are available (ISO, 2020). As a result, designers and developers of Structural Systems, MEP, HVAC and landscape architecture can seamlessly share information without dependency of a specific Proprietary License Software. For instance, Industry Foundation Classes (IFC) (ISO, 2018) represent a standardized information schema that enables data exchange in manifold forms. Molds of information of “beam for the BIM” are already known within the sector.

**Many conundrums arise: What is the most optimal way of fusing meshes and IFC geometries? How can simulation models insert meaningful data to DT dashboards? How are IFC models connected to sensors? Can these embedded sensors provide meaningful data to feed and update models? What if measurements are performed with point clouds? What if images are the source of information?**

All answers to these questions contribute to the definition of multiple pipelines of information. MatchFEM is conceived to be embedded within existing information standards. From a broad perspective, the tool is aimed at contextualizing information between simulations and the corresponding DT. In such information construct, 3D geometries, sensors and measurements, simulations and asset management can magnetically match and coexist symbiotically.

#### 1.1.4 OBJECTIVES OF THE DELIVERABLE, TARGET USERS AND DESCRIBED TASKS

This deliverable describes the conception of MatchFEM and its background. The report provides guidance for the generation of adequate initial conditions of the assets to be used during their life span using a DT basis.

The report is targeted to design engineers and infrastructure managers that intend to develop simulations within digital twin systems for structural analysis, be it general digital twin platforms or specific management tools to make use of digital twin data.

Additionally, the report is targeted towards IT managers and R&I professionals that plan to implement specific digital twin systems and solutions for specific maintenance & operation purposes.

In part one of this deliverable, applications on testbeds are described. Laboratory tests on structural elements, detailed flows from sensor to simulations, computationally tractable reduced-order methods, full-order methods, and model calibration actions are described taking inspiration from demo sites one, six, seven and nine from the Ashvin project. The reader is referred to deliverable 7.1 from the Ashvin project for details on those sites (Łukaszewska 2021).

Subsequently, in part two, one of the applications that is largely described in this deliverable is related to load tests of assets. Load tests provide an ideal scenario for the development of V&V simulations of the structural behavior of infrastructure systems. With sufficient layers, the information construct DT developed at this stage can be deemed as being an initial digital birth of the studied bridges. All efforts devoted to the development of a series of load tests on real bridges by owners, managers, construction firms and academia are put together to generate an archaic yet complete information construct. It is considered that in today's standards, even archaic versions of digital births of bridges developed will provide meaningful data for owners, managers, construction firms and academia in the years to come. In the near future, systems will be much more developed, but data gathered in former generations will be key for validation. In today's standards, there is still a lack of consensus about what is the minimum number of layers to define digital birth.

Moreover, again as a very important point, it is mentioned that these V&V simulations require embeddedness into vaster information constructs. Consequently, MatchFEM is conceived as set of tools that provide simulation capabilities to digital twins using standard data-exchange models and targeted simulations based primarily on meshes. The connection is actually conceived as a set of multiple connectors between geometries, sensors, mesh entities, tasks, schedules and very importantly, simulated results. For demonstration purposes, developments are presented as part of Ashvin DT platform and as a set of developments in Grasshopper. The development of MatchFEM is conceived by three aspects:

- An encompassing vision of geometrical entities that enable embeddedness between real and synthetic data.
- The nature of data exchanges with the ASHVIN DT platform.
- The open vision to other potential services that can be coupled by third-parties to enlarge the DT information construct.

The first version of MatchFEM is implemented in several demonstrators. Applications and needs are framed to the realism provided by Demo 1 (Bridges), Demo 6 (Building), Demo 7 (Bridges) and Demo 9 (Classified as industrial building). Several lines for information are established with the following objectives.

- To conceive the instances of these simulations with high degree of embeddedness within vaster DT information constructs.
- To verify and validate (V&V) these simulations with real-world data.
- To feed DT with synthetic data for end-user visualization purposes and for end-user development of “what if” scenarios.
- To conceive the structural design of new assets with a DT paradigm.
- To connect to existing third-party AI engines tools also embedded into DTs.

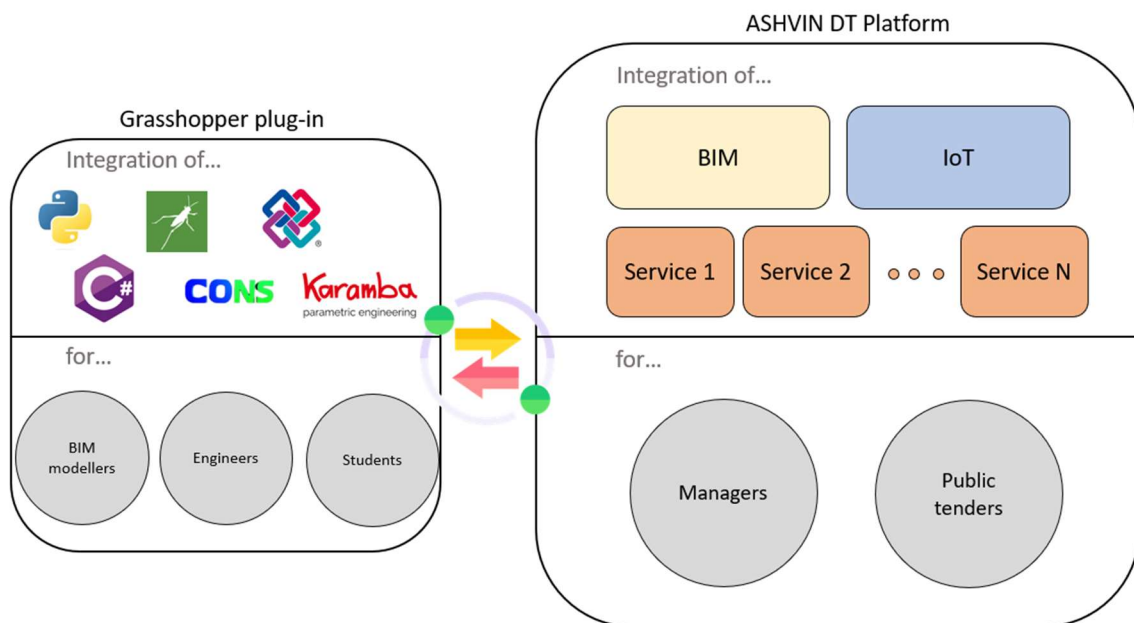


Figure 1. Conception of MatchFEM

## 1.2 SIMULATIONS THROUGHOUT THE LIFE-CYCLE OF ASSETS

Simulations of various kinds are needed to simulate and predict the performance of structures and phenomena during their lifecycle. All these simulations respond to specific needs of the asset at specific moments of the life cycle. From conceptual design to operations, simulations play nowadays a vital role for the development of data-informed decisions. Consequently, there is a continuous development of models in the market for a wide variety of needs.

As a matter of fact, simulations and models can be very simple (depicting one specific behavior) or can be very complex, including manifold layers of information dealing with coupled phenomena. Simulations are, however, computationally expensive. Even with cheaper and larger data-storage facilities, sizes, calculation times and storage need escalate rather quickly. As a result, the compromise between realism and accuracy, the available resources, and the tractability of the generated data dictates the nature of the performed simulation. When developing models that mimic behaviors, processes or what-if scenarios, the level of complexity is adjusted according to those needs. At design stages, simulations are mostly defined as a series of what-if scenarios for predicting the behavior of the asset facing such case. At this stage, the asset is not built at all. During the construction stage, simulations are often needed to recalculate the asset due to unexpected modifications of the original design or to calculate specific scenarios under temporary conditions. During the operations and maintenance stage, simulations are often needed for verification of the asset whose integrity is under scrutiny. For each stage, the needed level of complexity of the simulation may vary.

**Simulations and models can be very simple (depicting one specific behavior) or can be very complex, including manifold layers of information dealing with coupled phenomena. Simulations are, however, computationally expensive.**

Therefore, it is important to define the scope of the tool as well as its usefulness for each case. As a versatile set of tools, MatchFEM is conceived for the generation of easy-to-embed simulations for applications at all stages. In the following section, the underlying ideas behind this conception is presented for Design, Construction and Maintenance life-cycle stages.

### 1.2.1 THE DESIGN STAGE

Let us circumscribe the use of simulations at design stages for the exemplary cases of various types of buildings and bridges. Structural analysis is arguably the most usual type of modeling at this stage. Actions are collected and combined according to guidelines. Geometrical models are loaded with those actions and from these needs, materials and dimensions of the structure are found. At this stage, the asset is only virtual. What-if scenarios under a considerable number of assumptions can be

developed. Scenarios in which actions are combined for mimicking the routine state of the asset or scenarios in which actions are combined for mimicking extreme events of the asset are routinely created in design offices nowadays.

Today's technology readiness proves that many connectors between Structural Analysis (SA) and BIM platforms exist. Design Software are increasingly coupled with BIM platforms at design stages. BIM modelers seamlessly communicate with structural modelers and files are exchanged between specific Software and vaster information constructs quite fluidly. Vaster information constructs developed in BIM platforms connect to varied sets of platforms. Parametric design and computational geometry tools such as Grasshopper and/or Dynamo represent to date, ideal scenarios for such connections.

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However, these connections are seldom conceived to be used in higher information constructs belonging not only to the virtual realm. Presently, routine design is not developed under the assumption that a vast array of sensors will be present during construction and/or maintenance. Let alone thinking that designers expect the physical realm provides real feedback to their virtual models about their own designs.

Even though sensors can provide a considerably high level of phenomenological insight to the designers about their own assumptions, their job often ends once the project is delivered. Once the design is finalized, there is seldom feedback to design offices in which the actual behavior of the asset is depicted. In a future in which measurements of all kinds are ubiquitous, this would represent a waste of valuable information that may feed new designs with trustful information. In Today's new designs, Simulation- and BIM models are often uncoupled from any other action performed at construction and maintenance stages.

In order to contribute to the whole life cycle of assets with a potential use of their corresponding digital twin, the conception of MatchFEM as a set of useful tools at design stages is addressed. From the very beginning of the generation of the virtual asset, it is expected that designers conceive it in a way that BIM models, future measurements and simulations are put together on a common data environment. The key question to try to answer for designers is:

**Can we foresee future scenarios of a given asset that can be simulated, measured and compared between the physical and the virtual realms?.**

The exemplary Demonstrator 1 within the Ashvin project provides an ideal testbed in the realm of bridge design and is used for seeking answers to this question.

## 1.2.2 THE CONSTRUCTION STAGE

Subsequently, let us circumscribe the use of simulations at construction stages for the exemplary cases of various types of buildings and bridges. Construction of such assets lasts months. Simulations performed at the design stage may or not include all sequential construction temporary scenarios. Design may be based under certain construction conditions or technologies that the construction company may change at this stage.

Today, construction materials of buildings and bridges structures are dominated by concrete and steel. Casting concrete is arguably the most used construction technique worldwide. Steel structures erection also represents a considerable proportion of assets construction. In either case, sequential construction techniques must be studied in advance. Most design projects include what-if scenarios of the construction process. Construction methods must guarantee that materials and structures perform at least, as expected at design stages. During construction, the asset becomes real. Theoretical predictions of how concrete hardens or how welding generates structural imperfections in steel structures face thus reality checks. Are materials and structures behaving as expected during construction? Can we rely on those theoretical predictions performed in office months or years ago?

During the construction stage, sensors, images or remote sensing techniques become first-hand observers (or observation-enablers) of the construction process. Timely comparison between measurements and sequential construction predictions become a very interesting source of information for owners, construction managers and other stakeholders. Safety, efficiency and timely scheduling can be enhanced based on data-informed decisions.

In order to contribute to the whole life-cycle of assets with a potential use of their corresponding digital twin, the conception of MatchFEM as a set of tools useful at construction stages is addressed as well. In new constructions, BIM models are expected to exist. Construction measurements and simulations are expected to track the quality and the efficiency of the construction procedure. All these layers of information are also put together on the same common data environment. The key question to answer is:

**Can we track the material and the structure behaviors during construction? Can simulations include temporary aspects of the material and of the structure such as rheology or changes in structural configurations? Can we feed models with measured real data for increasing realism and minimizing assumptions?**

In this context, the exemplary demonstrator 6 within the Ashvin project provides a testbed in the realm of building structures under construction. In addition, real

scenarios of load tests of democase 1 (bridges) are depicted as an exemplary application of MatchFEM during the end of the construction of the asset.

### 1.2.3 THE MAINTENANCE STAGE

Finally, let us circumscribe the use of simulations at operations and maintenance stages for the exemplary cases of various types of buildings and infrastructure, e.g., bridges. This stage may last dozens of years. Throughout this stage, built assets accomplish their design goals. These assets are faced to random conditions of use together with random and unknown potentially hazardous events. Even under mild scenarios, all assets are prone to deterioration (either gradual or abrupt). In all cases, owners and managers require to decide on the adequate maintenance and reparation deployments that specific asset requires. Providing meaningful data to owners and managers improve the decision-making process and thus, safety, money and resource efficiency.

Presently, infrastructure owners and managers have a considerable palette of monitoring techniques for acquiring meaningful information about their asset. A vast array of sensing techniques is available for measuring a considerable amount of potential asset pathologies. Deploying such techniques is, however, costly. Information about the nature, the quantity and the scope of the measurements generate much better-informed decisions to all stakeholders. In order to increase resource efficiency and more targeted and precise deployments, a combination of simulations and measurements put together in the same common data environment represents a beneficial feature. Since most infrastructure systems are presently maintained with resources given by taxpayers, an optimal use of such resources is paramount. The potential aid of specific simulation Software for understanding the behavior of the asset is very powerful. In today's standard though, specific software may not be conceived for its proper integration within vaster information constructs. For integrating such variety of options, the design of the MatchFEM is based on requirements of modularity, interoperability, etc. (Pawels 2022).

Today, operations and maintenance of existing assets often rely on scheduled plans for inspection. Too much or too little inspection is detrimental when deploying plans. Technologies and procedures for condition monitoring are tending towards predictive maintenance plans based on more comprehensive information. In order to contribute to the whole life cycle of assets with a potential use of their corresponding digital twin, the conception of MatchFEM as a set of tools useful at maintenance stages closes the suite. In existing constructions, manifold types of measurements and varied specific simulations are expected. All these layers of information are also put together on the same common data environment (CDE). The key question to answer is:

**Can we predict remaining life of an asset carrying existing pathologies?  
Can simulations help designing maintenance strategies.**



In this context, the exemplary demonstration cases 7 and 9 within the Ashvin project provide a testbed in the realm of existing bridges and industrial buildings.

Fig. 2 shows a visual illustration about the developed actions in task 5.2 of Work Package 5. The corresponding testbed demo sites are also illustrated. More details about simulations on those sites are described in section 1.6.

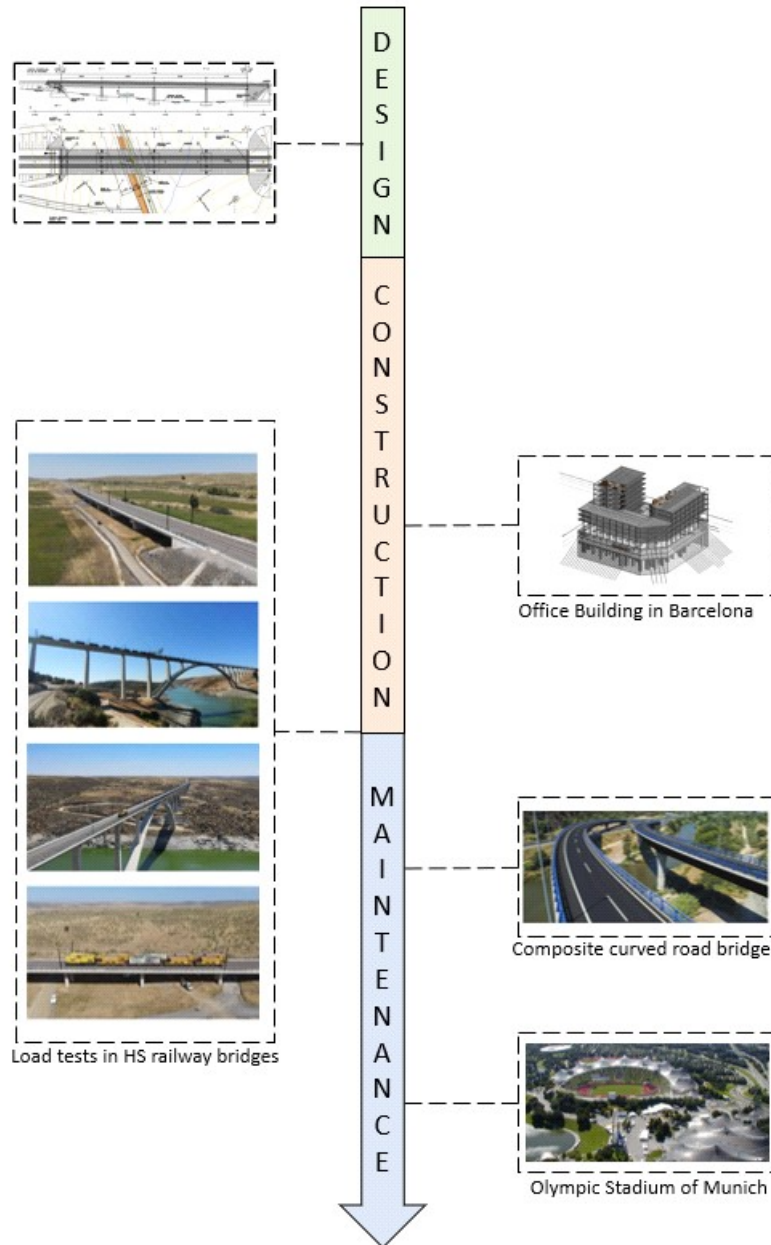


Figure 2. Ashvin demo-cases for the implementation of MatchFEM



## 1.3 A FRAMEWORK FOR MATCHFEM IN DT PLATFORMS: KNOWLEDGE GRAPHS

Digital twins must provide a generalized framework for sharing information between stakeholders. When conceived as virtual assistants that enable informed decision-making to their users, one must bear in mind that contextualized information about a specific asset whose status flows dynamically. To achieve this, digital twins need to integrate asset information models from different domains within the built environment (Architectural, structural, HVAC, MEP, etc.) together with different types of data, i.e., time-series, images, videos, point clouds and documents, that may be produced by unrelated stakeholders and stored in disparate dedicated systems. The information constructs that form digital twins need to be available to a set of computational agents that extract, transform, and load back new abstracted data into the digital twin system. Moreover, this system must continuously adapt to the industry's needs and be flexible enough to cope with its dynamics as new information and services are added or modified.

**DT systems must continuously adapt to the industry's needs and be flexible enough to cope with its dynamics as new information and services are added or modified.**

This way of conceiving digital twins presents some difficulties when designing their system architecture. Knowledge graphs are emerging as a solution to integrate and contextualize information from multiple disconnected systems into a unified and semantically rich model, with an intuitive and flexible structure that fit the digital twin paradigm requirements.

To conceive MatchFEM, the integration of multi-physics models, external simulation engines, and simulated data within digital twins is needed. Integrating such entities will enable services that enhance maintenance planning, verify and validate models against real-world data, configure alert systems based on continuous monitoring of physical parameters, or aid the design process of assets using simulated information. To that purpose, we investigate the use of knowledge graphs as the base information core of digital twin systems that enable aggregating simulation capabilities.

### 1.3.1 GAPHS, ONTOLOGIES, AND KNOWLEDGE GRAPHS: DEFINITIONS

#### 1.3.1.1 *Graphs and graph data models*

A **graph** is a data model represented by a collection of nodes, or vertices, that are connected by relationships, or edges (Fig. 3). Nodes normally represent entities in a specific domain while relationships explicitly define how entities interrelate. Graphs can be directed or undirected. Directed graphs have a one-way relation between node A to node B, while in undirected graphs the relation is two-way. This structure provides

a simple yet powerful general-purpose data modelling tool to represent complex relations between entities and how they relate to the world.

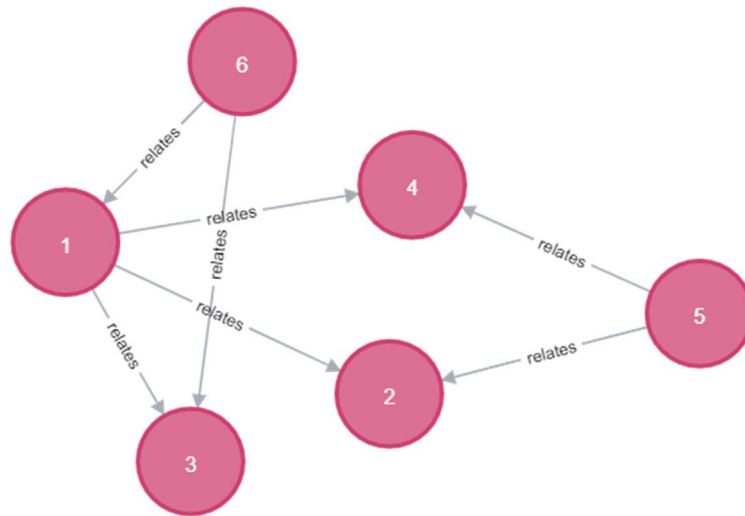


Figure 3. Related nodes on a graph

Nowadays, there are two popular graph models: The **property graph model** and the **Triple-based model**:

The triple-based model is a model for directed graphs in which nodes are connected using three-part statements called triples. Each triple is formed by a subject, a predicate, and an object, where the predicate establishes a relation from the subject to the object. The triple-based graph is based on the Resource Description Framework (RDF) schema (Corby et al., 2000) which is the underpinning standard developed by the W3C standardization group for sharing data on the semantic web, where each entity in the graph is referenced over the web using a Unique Resource Identifier (URI), which allows linking data as a graph over the internet. The use of this standardized schema allows sharing and exchanging of data among systems and applications, enabling graph data interoperability. Several technologies allow the manipulation of RDF graphs. They are stored in specialized RDBMS-based systems called semantic-stores and the information can be queried using SPARQL, a standardized query language. Moreover, RDF-based data can be serialized using multiple syntaxes such as RDF/XML, N-Triples, Turtle, or JSON-LD.

On the other hand, the property graph model provides nodes and relationships with an internal structure. To nodes can be assigned multiple *labels* that normally declare a category and the nodes' purpose within the graph. Relationships are assigned with a *type*, which semantically defines how entities interrelate. Additionally, both nodes and relationships can have *properties*, stored as key-value pairs. Property graphs are gaining popularity as they are the preferred model used in popular native graph databases such as Neo4j (Neo4j, 2023) which have proven increased efficiency for operating with graph data (Robinson et. al., 2015).

The property graph's structure allows modelling data more naturally and flexibly (since they are not bonded to any standard), and its dedicated graph databases are better suited for systems where the driver is to provide efficient transactions of information (Robinson et al, 2015) . On the other hand, RDF graphs are conceived for knowledge sharing and interoperability between graph-based applications. The use of mappings between both, RDF graphs and property graphs, has become essential to combine operational efficiency and interoperability(Angles et al., 2020; Barrasa & Cowley, 2023.)

### 1.3.1.2 Ontologies and Taxonomies

An ontology is defined as '*a formal, explicit specification of a shared conceptualization*' (Studer et al., 1998), where '*formal*' refers to a 'machine-readable', '*shared*' refers to 'agreed upon a group' and '*conceptualization*' refers to an 'abstract model describing a particular field of knowledge'. In other words, they are data models (conventions) that through a set of relationships and rules describe what entities 'mean' in the scope in which they are used. Taxonomies are a simplified version of an ontology, in which relations only express a hierarchical classification of entities in a domain.

The most popular ontology language used in practice is the Ontology Web Language (OWL) which is recommended by W3C and based on the RDF schema, and thus, compatible with RDF graphs. When nodes and edges in graph data are mapped to entities and relations in ontologies, graphs can be shared and interpreted according to domain-specific knowledge. Additionally, through semantic axioms and inference rules, reasoning engines use ontologies to derive new knowledge from data.

Ontologies' popularity is increasing. They can be openly published on the web to underpin interoperability among graph-based applications or be created as information assets that enable cross-enterprise data management. In this sense, they have become essential graph data (meta)models that allow the creation of graphs containing elements from different domains, which result especially useful in the conception of knowledge graphs.

### 1.3.1.3 Knowledge graphs

Knowledge graphs are graphs with an emphasis on contextual understanding of data. They are sets of interlinked metadata that capture knowledge in application scenarios that involve integrating, managing, and extracting value from diverse data sources at a large scale (Barrasa et al., 2021). The use of knowledge graphs presents clear advantages for structuring, modelling, managing, and analysing heterogeneous data with complex relations and a dynamic structure (Hogan et al., 2021). They allow the modelling of complex abstractions of knowledge in a specific domain, that can be easily linked to shared entities in other domains. In contrast to relational or NoSQL models, data in knowledge graphs can evolve flexibly since there is no need for a-priori schema definitions. Knowledge graphs can be interoperable when their entities are mapped to existing ontologies. Additionally, semantic rules provided by ontologies can be used to

enable reasoning about the terms used in the graph. Furthermore, modern graph analytics allow gaining additional insight into the domains being described in the graph. In practice, the implementation of knowledge graphs is usually encapsulated exclusively within the semantic web paradigm and related to RDF and the semantic web technology stack due to the large amount of open-access knowledge graphs that have been built upon open ontologies and published on the web in RDF-related formats. Some examples are DBpedia (DBpedia Association, 2023), Wikidata (Wikidata, 2023), BabelNet (BabelNet, 2023.) and YAGO (Hoffart et al., 2013). However, the concept of a knowledge graph is independent of the technology stack. In fact, the property graph model and graph databases are being increasingly used to store and manage enterprise knowledge graphs (Barrasa et al., 2021), where transactional efficiency is key and data owners' privacy policies are a major concern.

### 1.3.2 KNOWLEDGE GRAPHS FOR DTS IN THE BUILT ENVIRONMENT

To understand how knowledge graphs, benefit digital twins, we need to understand the requirements imposed by our industry for their implementation, which, as we will see, align with the effort that the BIM paradigm is doing to improve collaboration and information management in the industry. Once the utilization of the knowledge graph is proven to be a solution to cope with the needs of construction digital twins, MatchFEM can be naturally defined as an extension to those information systems.

**Knowledge graphs are very powerful and versatile tools to model domain data, but how do they benefit digital twins in the construction industry? And how does MatchFEM fit in all of this?**

#### 1.3.2.1 Digital twin requirements for the built environment

The built environment is a complex system of systems, where economic infrastructure, social infrastructure and natural environment co-exist and interact with each other and their users, providing a network of services that become essential for the proper functioning of society. This environment is dynamic; the architecture, engineering, construction, and operation industry (AECO) continuously copes with the design, construction, operation, and decommissioning of the assets that form it. The AECO industry is known for its decentralized organization. Projects executed during the life of an asset are powered by the cooperation of myriad stakeholders, while each stakeholder manages multiple projects simultaneously, on different sites, with independent collaborators, and in variate contexts. Thus, the industry is a complex network that consumes, produces and exchanges a vast amount of data with different levels of detail and in multiple formats. In this context, the generation of digital twins for the built environment has some particularities when compared with other industries. Digital twins were originally generated focusing on specific products, where long-term, fixed and tailor-made monitoring systems fed high-fidelity predefined simulations within

controlled industrial facilities. This contrasts with the constraints imposed by the nature of the construction sector. Projects need to account for information produced at different scales, i.e., at the product level, at building levels and at infrastructure and city levels, that are virtualized using variate modelling techniques. Built assets cannot be easily monitored, generally resulting in human-in-the-loop processes that modify the digital twin information dynamics, moving from 'real-time' to 'right-time' synchronicity. Additionally, physical parameters gathered by sensor systems need to traverse several contextual layers of abstraction to provide useful information to support informed decisions.

The life span and the level of integration between the life-cycle stages of physical assets also have important implications in the digital twin design rationale. In the manufacturing and aerospace industries, physical assets generally experience a shorter life, and their lifecycle stages are well integrated under the supervision of an immutable set of stakeholders. Benefiting from industrialized in-mass production, digital twins provide valuable insight derived from statistical information over the whole product lifecycle, generating new knowledge for an immutable set of stakeholders and improving future product generations. Conversely, built assets are unique. There are different information needs for the design, construction, and operation stages, and they are managed by different stakeholder settings, resulting in disaggregated information storage and information loss during the handover between stages. Moreover, their lifespan overly exceeds that of assets in other industries, people, and enterprises, positioning them within an ever-changing social, economic and technological environment. This leads to significant challenges in developing and implementing digital twins:

- (1) Digital twins need to host a **single source of interrelated cross-domain virtual representations** across life-cycle stages that can be generated and accessed by a changing set of stakeholders while preserving the interoperability of information resources. In this context, the use of cloud technologies and shared semantics is essential.
- (2) Digital twins need to cope with a **vast variety of types of data**, that is, time-series data, images, videos, point clouds, geometry files, etc. These data need to be contextualized within federated virtual representations. For that purpose, multiple dedicated storage systems need to be used and integrated. Furthermore, data is **produced as a service by third-party vendors, or by different stakeholders** that might be interested in retaining control over their storage and access. Accessibility varies ranging from heavily restricted access to sensitive data to radically open access to other types of data.
- (3) Digital twins need to be **extendable and flexible to modify their structure** on-demand and as needed to cope with new incoming use cases and adapt to stakeholders' needs. This **requires a high degree of modularity** in all of its building blocks, from data sources to virtual representations, computational agents and services.

- (4) Digital twins need to be able to share information with higher-level digital twins, thus generating a **versatile ecosystem able to encompass the multiple scales of the built environment**. Ideally, from fundamental elementary levels to broad perspectives of cities and nations.

For the last decade, the use of digital tools and innovation in information management in the built environment have been framed within Building Information Modelling (BIM). It has been stated that digital twins in the construction industry are a consequence of the evolution of BIM (Deng et al., 2021) and that the development of a digital twin departs from a BIM model, to which IoT, simulations and AI capabilities are added. This integration remains a challenge in the industry. However, recent approaches within BIM interestingly align with the needs of the digital twin era.

### 1.3.2.2 BIM and data sharing in the built environment

According to the BIM Dictionary (2023), BIM is “*a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a facility in virtual space*”. The recently published standard ISO 19650 (ISO, 2020) defines BIM as “*the use of a digital representation of a built asset to facilitate design, construction and operation processes from a reliable basis for decisions*”. Although slight variations in BIM definitions can be found, it is clear that this view of a shared virtual environment where collaboration is essential poses the interoperability of digital assets as a major requirement.

The release of open BIM standards such as Industry Foundation Classes offered a shared semantic specification across domains in the built environment, enabling interoperability among BIM applications. Originally managed and maintained in EXPRESS language, it established a system of information exchange based on file transactions. Nowadays, IFC is the most complete data schema that describes the built environment. Its scope is vast, covering the definition of 3D geometry, Infrastructure, construction processes and various taxonomies of products across domains.

Recently, the arrival of advanced cloud and web technologies is shifting BIM towards centralising project-related information in web data platforms, known as Common Data Environments (CDEs). In this context, it is envisioned that BIM files are substituted by databases and file-based information exchanges among applications are turned into data-based transactions made through web APIs, allowing stakeholders access to the right data in a more granular and flexible way.

In this context, the use of IFC is being scrutinized for its complexity and its lack of modularity, extendibility and flexibility. To adapt to the cloud paradigm, the IFC schema is now being maintained and managed using the Unified Modelling Language (UML), a more generic modelling language from which IFC models can be expressed in more convenient transactional data structures, such as XML or JSON (Pauwels et al., 2022).



The JSON format is currently present in almost every web-based application. Its simplicity and human-readable format make it the preferred option for web developers to perform flexible information exchanges with web servers and among microservices.

Another approach advocates for BIM interoperability based on ontologies, enabling the exchange of information in the form of RDF graphs using semantic web technologies. The first approach was translating the IFC schema to its OWL version, specified in the ifcOWL ontology (Pauwels & Terkaj, 2015), however, ifcOWL graphs result in very large and verbose models due to the built-in complexity of IFC. As an alternative, the Linked Building Data (LBD) group has developed a set of ontologies conceived to be combined and extended with third-party ontologies that help to generate a more flexible description of the built environment that adjusts to each use case needs (Mavrokapnidis et al., 2021). Some of the ontologies used are listed below:

- Building Topology Ontology (Janowicz, 2021)
- Building Element Ontology (Pauwels, 2020)
- Ontology for distribution elements (Pauwels, 2019)
- Damage monitoring Ontology (Hamdan et al, 2019)
- Bridge topology Ontology (Hamdan & Scherer, 2020)
- Building Product Ontology (Wagner et al., 2019)
- Ontology for Managing Properties (Ramussen et al., 2018)
- Ontology for Managing Geometry (Wagner et al., 2019)
- File ontology for geometry formats (Wagner et al., 2019)

These advances open the door to new ways of modelling and sharing data in the built environment. Graph data models postulate as promising candidates for their ability to represent the complex interconnections usually found in BIM models. Enabling interoperability of graph data models by combining multiple modular ontologies that complement each other cross-pollinates the formal virtualization of the built environment, allowing it to be extended to adapt to the dynamics affecting industry semantics.

### **1.3.2.3 Knowledge graphs as DT enablers for the built environment**

As a result, in order to create a more complete digital twins of a built asset, its corresponding BIM virtual construct needs to be extended with physical that comes from IoT systems, AI agents and simulation agents at the same time. It then encompasses and contextualizes data of different natures. Due to this fact, knowledge graphs emerge as enablers for digital twins in construction for their capability to cope with the requirements imposed by the industry:

- (1) Knowledge graphs are able to describe and manage federated BIM models, enabling granular access to their information via database queries as well as managing their dynamic interrelations.

- (2) Knowledge graphs enable data to be stored using a distributed system architecture, where geometry, properties, time-series data from sensors, process information and files will be 'linked' to the graph, providing an effective manner of discovering and querying data across multiple dedicated storage systems.
- (3) Knowledge graphs can integrate metadata of internal and external computational agents that consume and produce data within the digital twin ecosystem, to provide a contextualized use of them and be able to automate pipelines that require their capabilities.
- (4) Additionally, the flexibility of knowledge graphs allows on-demand knowledge extension, and their semantic richness provides DTs with capabilities such as inferring missing information about physical assets, detecting inconsistencies in data, performing semantic queries across models and data, and providing support for decision-making processes suggesting actions based on contextual information.

In this report, we focus on the creation of MatchFEM, which involves a set of computational agents, information models and conceptualizations that allow digital twins to integrate simulations and enable a set of processes that use them together with other information resources for multiple purposes. In the next section, we elaborate further on how simulation could be integrated using a knowledge graph-based digital twin.

### 1.3.3 KG-DTS AND SIMULATIONS. AN ONTOLOGY FOR STRUCTURAL SIMULATION.

As mentioned in previous sections, simulations are present during the whole life cycle of assets in many forms. While during the design stages the simulations are part of an exploratory endeavour, during the construction and operation stages simulations are triggered in very specific contexts, that dictate their nature and level of complexity. In this section, we focus on the application of simulations conducted for structural analysis and how they could be integrated within digital twins that are based on a knowledge graph.

Nowadays, most structural simulation software is offered by private vendors which, generally, provide packages composed of pre-processing modules (i.e., modules for creating the model), numerical methods to compute the simulation results (solver) and the post-processing modules for result exploration and visualization. Model configuration and result formats are specific to each software package. This scenario creates a very heterogeneous ecosystem in which input models, solvers and result are not interoperable.



There have been some attempts to create interoperable structural simulation modelling formats. The 'IfcStructuralAnalysisModel' defined in the IFC schema or the Structural analysis Format (SAF) (Bau & Umwelt, 2021) are open formats available for the exchange of structural analysis model information. However, they are limited to basic simulation use cases, hindering their propagation within the industry. Additionally, engineering aided by simulations is a relatively old practice, which has established well-defined enterprise procedures using specific simulation software that would find resistance to be changed. Therefore, the homogenization of procedures and formats is an ambitious task with a long roadmap in the horizon.

Then, adding structural simulation capabilities DT cloud platforms implies accounting for this diversity of the available tools. Digital twins should provide ways of storing instances of simulation models, integrate compatible simulation engines that are able to perform the computation, and storing simulation results, that can be meaningfully visualized through a user-interface.

Knowledge graph-based digital twins naturally allow the integration of simulations. Models, solvers, and results can be stored in any format and referenced in the graph using a URL. These URLs are used for two purposes: (1) referencing stored information from models and results and (2) providing a reference to connected solvers that are compatible with the model file format and has the computational power to run the simulation. This approach limits the range of suitable simulation tools to those that provide an API that allows developing online services around their solvers. Furthermore, the knowledge graph contains all kinds of interconnected information regarding a certain asset. This provides the context leading to the decision of performing a simulation, containing the intrinsic value of its results, which may be essential for the management of assets with long maintenance plans and a dynamic change of maintainers.

For the purpose of integrating structural simulations within a wider knowledge graph, a simulation ontology is proposed based on entities representing models, simulation engines and results, and how they relate to carrying out the simulation. The ontology is summarized in Fig. 4 and elaborated in Appendix A (in Turtle format). Although the ontology only specifies elements regarding structural analysis, it is conceived to allow its extension with other types of multi-physics simulation entities.

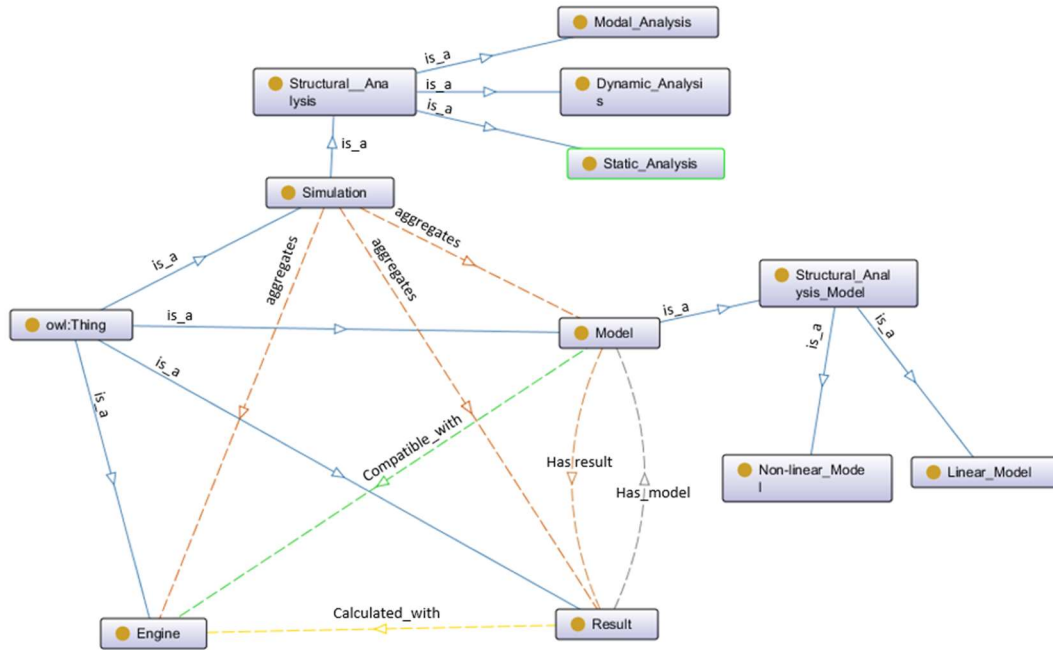


Figure 4. Summary of the proposed ontology

At this point we have set the conceptual base for the development of MatchFEM: an integration of BIM, data and simulations conducted through a knowledge graph-based digital twin. In the following section, we explicitly define how this digital twin system is created within the frame of the ASHVIN platform.

#### 1.4 MATCHFEM WITHIN ASHVIN DT PLATFORM

MatchFEM encompasses a set of capabilities that enable the joint use of IoT, BIM, and simulations. This requires multiple information sources and computational agents to be integrated within the ASHVIN digital twin system using a knowledge graph. The different yet specific building blocks of the system are described in Fig. 5 and as follows:

**Mainflux IoT platform:** a high-performant, scalable, low foot-print and open source IoT solution which can be deployed on the cloud and at the edge. The platform accepts connections over various protocols (HTTP, MQTT, CoAP, and LoRaWan) enabling the two-way connection of all sorts of IoT devices. The platform features three basic entities to perform communication between information producers and consumers: *things*, *channels*, and *users*. A *thing* represents any data source or producer. *Channels* are communication pathways through which *things* send and receive messages. Messages can be addressed to specific topics, providing extra semantics to the communication process, and enhancing data querying and filtering. Both the *Things* and the *channels* allow abstracting away complexities of low-level communication protocols offering a unified and easy-to-use interface for messaging. *Users* are individuals or organizations which own channels and things. Data sent over the

platform can be consumed as a stream via MQTT and WebSocket or can be retrieved from a time-series database via a REST API.

**File-based storage:** Data is stored in the form of files of different formats in a folder-based tree-like hierarchical structure. To be able to allocate and retrieve data, there is a need to know the exact path for it within the tree structure. Since files are the predominant data containers in the construction industry and the main entity for its transaction, file systems are essential containers that underpin the current industry information paradigm. Nowadays, every information bit can be stored as a file. Files ranging from various kinds of BIM formats, spreadsheets, results from simulations, reports, etc.

**Objects storage:** Objects storage is a more recent approach that does not use a structured or hierarchical system. Instead of using paths, data is tagged with metadata and a unique identifier that provide information to search and retrieve data in large data pools. This type of storage system is popular in modern cloud storage for its scalability and easy data accessibility.

**Structural simulation engines:** contain the computational capabilities and algorithms that simulate structural behavior based on a predefined model.

**Microservices:** A microservice is a container with networking capabilities that encodes a specific functionality. An application or system based on a microservice architecture defines its capabilities using a set of coupled microservices that can independently be updated or improved without altering the rest of the system, providing resilience and scalability. Digital twins can largely benefit from this architecture since they are ever-evolving systems that need to be dynamically maintained and improved. MatchFEM uses microservices to add capabilities to the digital twin that use information from simulations combined with other information sources such as data produced by sensors.

**Graphs database:** The Neo4j graph database is used to integrate all the above systems into a single information model using a knowledge graph.

**User Interface:** The user interface uses the graph database as a dynamic index to interact with the information and tools available within the digital twin system.

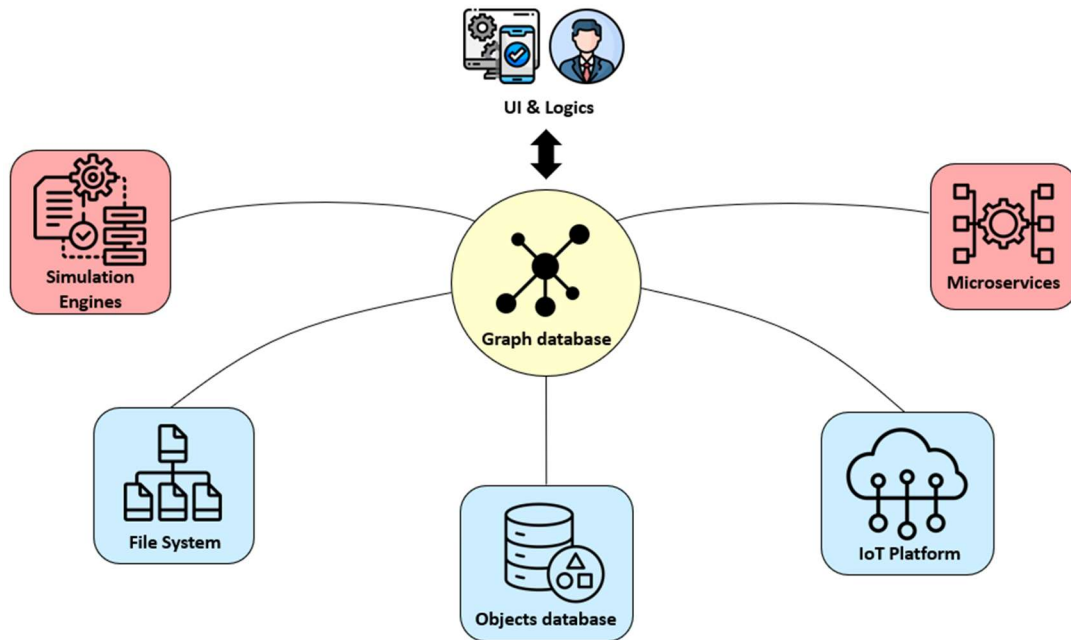


Figure 5. Graph databases and Ashvin building blocks

In the following pages, the process of building a digital twin with MatchFEM capabilities is described in 4 different stages: (1) The transfer of BIM model information to the digital twin system, (2) The integration of IoT, (3) The integration of Simulations and (4) The addition of MatchFEM capabilities.

#### 1.4.1 FROM BIM TO THE DIGITAL TWIN SYSTEM

The creation of a digital twin departs from a geometrically and semantically rich BIM model. In the particular case of Ashvin, the IFC schema is selected as the base OpenBIM standard from which richer digital twins are defined. Then, an IFC importer has been created to transfer the information contained in IFC models to the digital twin system.

The *.ifc* file contains geometric information as well as semantic information. When the IFC file is imported, the geometry is extracted and stored in the digital twin file system using *IfcConvert* which is an open-source command-line application provided by *IfcOpenShell* (*IfcOpenShell*, 2023) that converts IFC files into geometry file formats that are more interoperable, such as OBJ, DAE, GLB, STP, IGS, XML and SVG. The GLB format is selected in this case since it is a binary format that allows for more efficient storage and reading of the geometric information. On the other hand, the semantic information is transferred to the neo4j graph database in the form of a graph. For that purpose, an *IFC2Graph* converter service has been created using a Python snippet. The converter is based on the *IfcOpenShell* library and the Python driver for the Neo4j database.

Once the geometry is stored as a .glb file in the file system and the semantic information is stored in the graph database, the importer creates a new node in the graph referencing the geometry file and links it to its corresponding IFC entity.

### 1.4.2 IOT INTEGRATION

The IoT platform is the mean of communication between the real asset and its digital twin. It also provides a time-series database to storage time-based messages, that can be either accessed from applications on-site or within the digital twin. Sensors that are being represented in the DT knowledge graph are mapped to the IoT platform as *things*. Two main channels are set. One is dedicated to transmitting the past, current and predicted status of each element, sensor, and process. The other is dedicated to transmitting the live measurements emitted by on-site sensor systems and devices. Equivalent entities in the IoT platform and in the BIM knowledge graph share Global Unique Identifiers (GUIDs) which is key for the integration.

To integrate entities that belong to the IoT platform within the knowledge graph, *things* and *channels* from the IoT platform are imported into the graph database along with the BIM model (See Fig. 6). Then, BIM entities that have same GUIDs with the Mainflux *things* are semantically linked with an 'IS\_A' relation. Consequently, to the graph provides means to traverse from BIM to IoT entities and, therefore, interact with the data stored (as well as live-streamed) in the IoT Platform

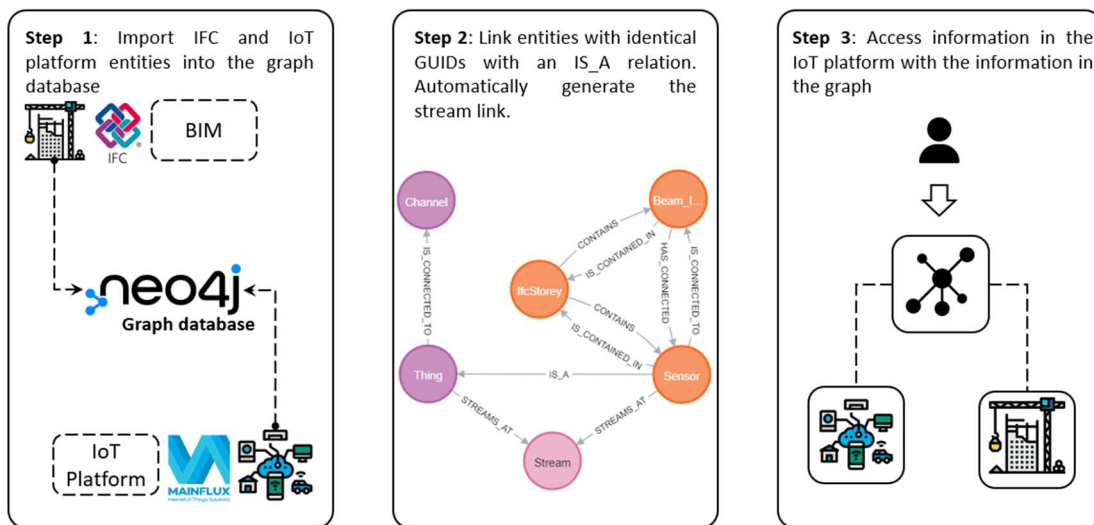


Figure 6. Steps of the integration of IoT and BIM in the graph

### 1.4.3 SIMULATION INTEGRATION

Simulations are integrated into the knowledge graph using the simulation ontology described in part 1.3. Several solvers have been studied as possible options to be attached to the digital twin. Well-known private software packages such as Code-aster, Abaqus or SAP2000 provide users with an API that allows interacting with the solver programmatically. However, they use files to store models and results, and they are thought of as being used as desktop applications, not in cloud-based systems. Then, a developed solver is proposed. The solver is prototyped within the parametric design software Rhinoceros, as a previous step to its integration in the Ashvin DT platform in the form of a containerized service. A JSON data structure is developed to hold information about models as well as about simulation results, which are then stored in the digital twin object database. The solver is loosely coupled to the digital twin system, awaiting to receive events that activate the computation (this part is more detailed in the next chapter). To have a meaningful integration, the simulation entities in the graph need to be semantically linked to BIM and IoT entities.

Computationally expensive simulations must be performed under demand. This is particularly interesting at the maintenance stage. Occasionally, simulations are used as part of standardized verification procedures. Nevertheless, most of the times simulations are used to add valuable information that clarifies the condition of specific issues detected on the asset. With that premise, a new entity called *Issue* is added to the graph. Issues are related to specific parts of the asset and are triggered by human decisions. To solve issues, measured and simulated data are needed to reach the optimal solution. Fig. 7 displays an example of how issues are included in the knowledge graph.

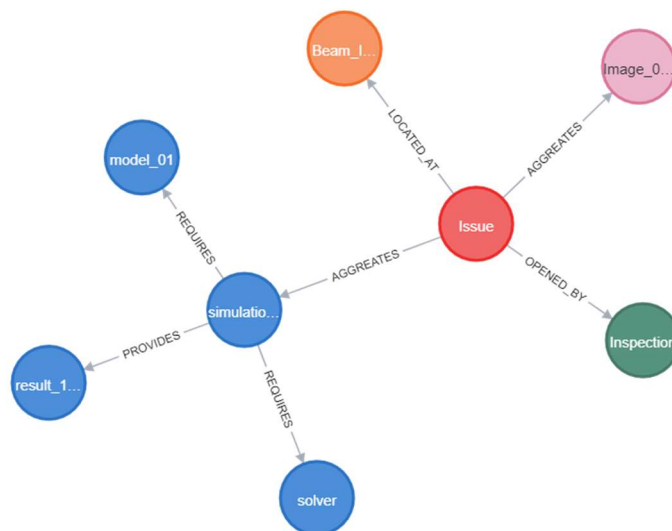


Figure 7. Issues in the knowledge graph

#### 1.4.4 ADDING MATCHFEM CAPABILITIES TO THE DT PLATFORM

MatchFEM capabilities can be integrated permanently within the ASHVIN platform in the form of microservices. Event-driven architecture (EDA) is a software architecture in which decoupled microservices communicate by producing, detecting, and consuming events. Events are snippets of information triggered by any state change or any update that may elicit reactions in the system, allowing it to generate a chain of processes to accomplish some purpose. In MatchFEM, events are JSON structures sent using the MQTT protocol through the MQTT broker in the Mainflux IoT platform. The event contains the following information:

- **Action:** The 'action' specifies which type of process is needed. Depending on the action microservices will activate their functionality or will remain dormant.
- **Resources:** Resources provide a set of URLs from which the information needed to perform the action can be extracted.
- **Repository:** contains the URL of the repository to which the output of the computation is stored.

When a microservice is activated by an event, it will start the extract, transform, and load process (ETL). This system has some advantages. First, the simulation engine and the microservices can be developed and tested without the need of being included within the DT local network or having an API endpoint published on the web. As long as they have access to the web and the credentials to connect to the Mainflux IoT platform they will be able to consume events and be activated. Second, from an operational point of view, the event-driven architecture allows activating simultaneously multiple computational workloads, as well as activating automated pipelines established by event concatenation. Fig. 8 illustrates this concept.

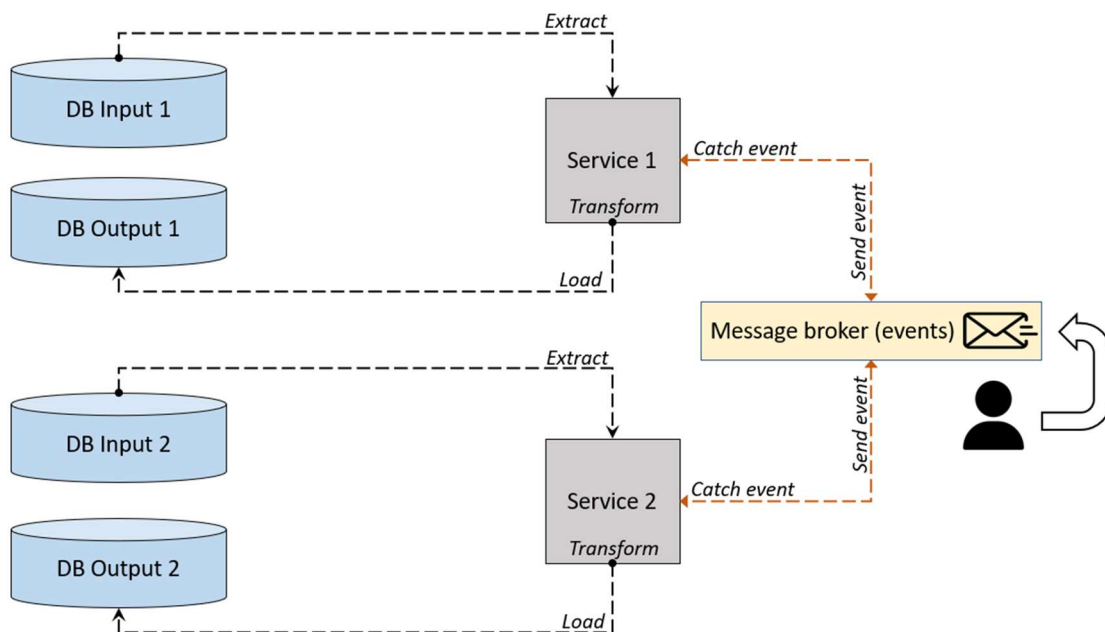


Figure 8. Event-driven architecture in the Ashvin platform



## 1.5 FUNCIONALITIES AND INTEREST OF USE

The development of MatchFEM has been cross-pollinated by many different real situations encountered within the set of Ashvin demonstrators. These demonstrators, which represent a crucial challenge within the project, both provide and request a high level of realism. On the one hand, they provide realistic situations of interest raised during design, construction or maintenance of those assets. On the other hand, they request meaningful events that are applied as event-driven issues as well. In the pool of 10 Ashvin demonstrators, which are of very varied nature, dozens of potential types of events and simulations were identified. Such panorama is ideal for the creation of multiple, useful connections between measurements, simulation, geometries analysis. Each asset provided different challenges, which added also complexity for logistics. Ashvin partners had access to sites under limited conditions also, which filtered the potential twinning situations within the pool of cases. Some possibilities were not technically feasible while other were not feasible administratively. Therefore, simulations were selected to recreate situations through the lens of the following criteria:

- Feasibility to measure magnitudes that would either validate or enhance the simulations.
- Clear needs for these simulations to provide a meaningful impact on the established performance indicators depicted in D2.1(Krenn, 2021), D4.1 (Łukaszewska, 2021) and D5.3 (Stipanovic 2023).

As a result, phenomena related to different types of structural analysis were prioritized in the development of the tool. Closer inspection on the demonstrators showed different material configurations on Buildings, Industrial Buildings and Bridges. Different types of reinforced concrete structures (demo 1, demo 6), steel structures (demo 9) or steel-concrete composite structures (demo 7) provided generality and varied needs when it comes to structural analysis.

Likewise, these demonstrators provided clear needs and improving margins at construction and maintenance stages. The questions raised during developmental phases of MatchFEM were: i) Which simulations developed from these sites could be validated and verified thoroughly? ii) Which simulations may help feeding models with real-time data to impact the construction stage? lii) Which simulations provide meaningful insight to directly enhance decision-making at maintenance stages? iv) How the design stage can be enriched by simulations that use feedback from real sites?. All these questions eventually address the Ashvin concerns on improving safety, productivity, resource efficiency or economy at design, construction or maintenance stages.

Table 1 shows a non-comprehensive list of simulation candidates generated during the development of measurements in those demonstrators.




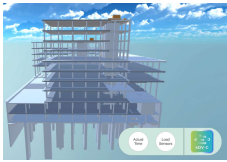

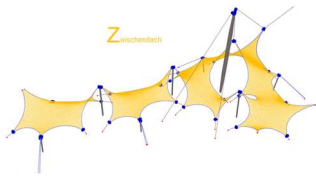
Demonstrator	Potential simulation needs	Potential Measurements
<p>Demo 1. <b>Load Tests in Railway bridges.</b></p> 	<p>Structural response of bridges subjected to controlled static loading.</p> <p>-----</p> <p>Structural response of bridges subjected to controlled dynamic loading.</p>	<p>Response can be measured via displacements and strains at key points during testing.</p> <p>-----</p> <p>Response can be measured via accelerations at key points during testing</p>
<p>Demo 6. <b>Construction of a reinforced concrete structure of an office building.</b></p> 	<p>Structural behavior of RC elements during sequential construction.</p> <p>-----</p> <p>Structural behavior of RC slabs during post-tensioning.</p> <p>-----</p> <p>Structural behavior of RC slabs during casting</p> <p>-----</p>	<p>Temperature and humidity of fresh concrete.</p> <p>-----</p> <p>Strains of the slab during post-tensioning.</p> <p>-----</p> <p>Overall deflection of the slab during construction using point clouds.</p> <p>-----</p>
<p>Demo 7. <b>Road bridge with a composite structure</b></p> 	<p>Structural response of bridges under different season-dependent geometrical configurations</p> <p>-----</p> <p>Structural response of bridges subjected to traffic loads.</p>	<p>Overall and local imperfections of the bridge at different seasons. Point clouds can be obtained using LIDAR.</p> <p>-----</p> <p>Response can be measured via accelerations at key points during operation.</p>
<p>Demo 9. <b>Industrial Building. Stadium. Cable net roof.</b></p> 	<p>Structural response of the cable net under different season-dependent geometrical configurations</p> <p>-----</p>	<p>Position of nodes of the cable net (Roof Structure) using LIDAR.</p> <p>-----</p>

Table 1 Demonstrators, simulation needs, potential measurements

It is worth pointing out that during the development of the project, task 5.2 has also benefited from these testbeds including different types of measurements, in particular, the use of point clouds as a source of information. With the selected cases, the set of tools encompassing MatchFEM were conceived to provide the following functionalities:

- Capability to deploy validation and verification (**V&V**) of simulation by means of established criteria.
- Capability to execute simulations of specific scenarios foreseen during **design** of future monitoring strategies. Design Monitoring Strategies
- Capability to feed and update models with measured data during **construction**.
- Capability to execute simulations requested by decision-makers for assessing potential **maintenance** plans. Plan maintenance

The tool MatchFEM is included in the present version of Ashvin platform within the set of applications as shown in Fig. 9. Its depicted nature allows matching other applications by properly connecting nodes of the corresponding Knowledge Graph depicted in sections 1.3 and 1.4. Together with an adequate geometrical representation of the asset, the toolkit allows functional interoperability. In Fig. 9, the functionalities of MatchFEM are deployed in its corresponding tab as buttons. Details on each functionality are succinctly described in the following subsections.

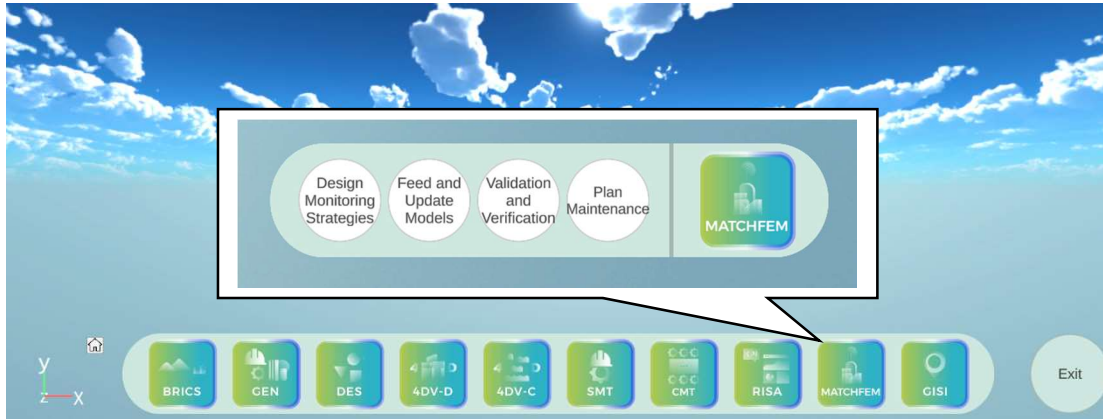


Figure 9. Ashvin toolkit and MatchFEM functionalities

### 1.5.1 VALIDATION AND VERIFICATION

From the perspective of the behavior, the DT of an asset is based on measurements from reality and on predictions from models. When models are systematically compared to measurements and established criteria suggest the accuracy of that model, a systematic further use of it can set. Calibration is a method used to evaluate the accuracy of a model's predictions. It involves comparing the predicted values produced by the model with the actual observed values.

Verification and validation (V&V) are two important steps in the development of any model or system. Verification involves checking that the model or system has been designed and implemented correctly, and that it meets the specifications or requirements set for it. This typically involves testing the model or system to ensure that it functions as expected and produces the expected outputs.

Validation, on the other hand, involves assessing the model or system's ability to perform its intended function in the real world. This typically involves comparing the model's predictions or outputs with actual observations or measurements to determine how well the model or system performs in the real world. Validation helps to ensure that the model or system is accurate, reliable, and relevant for its intended purpose.

Together, verification and validation help to ensure that a model or system is of high quality and can be trusted to produce accurate and reliable results. From the perspective of DT, when simulations are trustful sources of information, decisions are taken on the basis of reliable data.

The part two of this deliverable will include a comprehensive description of V&V of a bridge during the episode of load testing. Since measurements, models and loads are controlled entirely, comparisons are established and subsequently, what-if scenarios during its lifetime are depicted. The reader is referred to Part 2 for more details.

### 1.5.2 PLAN MAINTENANCE

An efficient maintenance plan can provide several benefits for an asset. Some of these benefits include i) Improved safety: A regular maintenance plan can help to identify and address potential safety issues on a bridge, such as cracks, rust, or loose bolts. This can help to prevent accidents and ensure that the bridge is safe for use, ii) Extended lifespan: By regularly maintaining an asset, it is possible to extend its lifespan and avoid the need for costly repairs or replacements. This can save money in the long run and help to ensure that the bridge remains in good condition for a longer period of time iii) Reduced disruptions: Regular maintenance can help to prevent unexpected disruptions or closures due to problems with the asset. This can help, for instance, to keep traffic flowing smoothly and avoid inconvenience to users of the asset and iv) Enhanced reliability: A well-maintained asset is more likely to be reliable and capable of performing its intended function. This can help to ensure that the asset is always available for use when needed, and can help to reduce the risk of unexpected failures or disruptions.

For the sake of tackling specific issues raised on the asset during its lifetime, managers may need to activate specific simulations that come under request. These simulations may range from simple to very complex, from reduced- to full-order, from local to global models of the asset or from single to coupled physical phenomena. The possibilities and needs are large even for a specific asset.

This functionality addresses two perspective of owners and managers:

- Visual inspection or other routine maintenance strategies suggest an issue on the asset. Further studies are needed. Specific measurements are taken and numerical simulations are triggered in the system for the sake of gaining a deeper phenomenological insight of the structural issue. Both measurements and predictions are used in this evaluation. The corresponding result of this evaluation improves the decision-making process vis-à-vis the maintenance plan.
- Extreme yet non-destructive events occur. Managers are keen to assess the integrity of the asset in the aftermath. Specific measurements are taken and numerical simulations are triggered in the system for the sake of gaining a deeper phenomenological insight of the structural consequence of the extreme event. Both measurements and predictions are used in this evaluation. The corresponding result of this evaluation improves the decision-making process vis-à-vis the maintenance plan.

The reader is referred to sections 1.6.3 and 1.6.4 to illustrate the use of simulations including advanced GMNIA in demo 7 and reduced-order models studied at laboratory tests to better plan measurements in demo 9.

### 1.5.3 FEED AND UPDATE MODELS

Feeding models with measured data is a functionality of interest during the construction stage. On the erection process of structures, initial geometrical conditions, rheological and other material properties or boundary conditions become real. Initial designer-assumed conditions may be then updated with data obtained from the real asset. During construction, including such more realistic conditions may contribute to adding data to the decision-making process concerning changes, pace acceleration, analysis of recently casted structural elements whose integrity is at stake etc.

On the other hand, model updating of a given asset during its lifetime is a process used to improve the accuracy and reliability of a specific model of that asset. It involves incorporating new data or information into the model and adjusting the model's parameters or assumptions based on this new information. This can help to improve the model's ability to accurately represent the system or phenomenon it is modeling. Model updating is often performed on a regular basis as new data becomes available. This can help to ensure that the model remains accurate and relevant over time and can help to prevent the model from becoming outdated or irrelevant. There are several methods that can be used for model updating, including Bayesian updating, Kalman filtering, and Markov chain Monte Carlo (MCMC) methods. The appropriate method to use will depend on the type of model being updated and the availability of data. In MatchFEM, this functionality is conceived as a first step. In further developments, more sophisticated model updating techniques can be added.

The reader is referred to section 1.6.2 to illustrate the use of simulations including sensor-to-simulation flow of data in demo 1 and demo 6.

### 1.5.4 DESIGN MONITORING STRATEGIES

This functionality is conceived as an attempt to answer two questions: i) Can we plan monitoring strategies during construction and maintenance at the design stage? Can we foresee future scenarios of that given asset in which simulations, measurements and comparisons between the physical and the virtual realms are established?

The design of a monitoring strategy involves identifying the specific goals and objectives of the monitoring effort and developing a plan for achieving those goals. This typically involves several key steps, including i) Identifying the goals and objectives of the monitoring effort. These may include goals related to safety, reliability, efficiency, or other aspects of the system being monitored ii) Determining the key performance indicators (KPIs) that will be used to measure the success of the monitoring effort. These may include metrics such as uptime, response time, error rate, or other relevant measures iii) Developing a plan for collecting data on the KPIs. This

may involve selecting appropriate sensors or other measurement devices, establishing a schedule for data collection, and defining the processes and procedures for collecting and storing the data and iv) developing a plan for analyzing the data collected. This may involve defining the specific algorithms or methods that will be used to analyze the data, as well as the processes and procedures for conducting the analysis and interpreting the results.

Developing a plan for using the results of the analysis to improve the system or process being monitored. This may involve defining specific actions or interventions that will be taken based on the results of the analysis, as well as the processes and procedures for implementing those actions. During the design stage, detailed models are generated. These design models include BIM and simulations concerning structural analysis. Designers are usually aware of details of their design in which it would be interesting to keep an extra eye during construction and operation stages.

In the MatchFEM Grasshopper environment, BIM, simulations and measurements co-exist. Designer can thus leverage these functions for the sake of providing detailed information about monitoring plans within the same environment. Expected values of the response of the structure at specific locations can be delivered for further use during the lifecycle of the asset as well.

The reader is referred to section 1.6.1 to illustrate the use of simulations for planning measurements in adequately conceived BIM models in demo 6.

## 1.6 TESTBEDS FOR MATCHFEM AND MODELS IN THE FRAME OF ASHVIN

As depicted in section 1.5, the numerical models that have been dealt within the frame of task 5.2 of WP5 are fully aligned with the demo cases depicted in D7.1 (Łukaszewska 2021). These demonstrators have provided realistic testbeds during the design and development of the procedures and systems involved in MatchFEM. From these demos, several examples of potential necessary simulations are pointed out and described thoroughly in this section. These examples were developed according with the description of task 5.2. The key findings on these testbeds enriched the core of development of the set of recommendations presented in part 2 of this deliverable.

Firstly, initial material conditions derived from measurements are used to calibrate fiber-based beam models. These numerical models are time-based and fully nonlinear from the material and geometrical perspective. The models are computationally tractable (three dimensional beams) and can be used under the assumption of uniaxial behaviour of fibres (filaments) along the cross-section. This assumption allows reducing the order of the simulation from full 3D solid models to beams with an efficiently discretized cross-section. The structural model chosen for this purpose is the beam of *Viaducto de la Plata*, one of the bridges of Demo 1.

Secondly, an attempt of infusing data directly from sensors to the simulation is performed with structural models that can be applicable to demo 6, *MILE Structure, Reinforced Concrete Columns and Beams*). Data from the evolution of temperature of

the material during hardening was collected. When fresh concrete hardens, an exothermic reaction occurs, and this temperature evolution can be correlated with the properties of the material following many different concrete maturity models. Data flows from sensor to simulation is achieved in this application.

Thirdly, models based on realistic geometrical conditions are developed from measured data. Demo 7 is a composite bridge with stiffened plates prone to buckling. The ultimate capacity of a member prone to buckling can be derived using shell models with full order. Displacement- strain and stress fields can be obtained from full geometrical and material nonlinear imperfection analyses. Demo 7 provides an ideal realistic case in which the capacity of the bridge is needed for evaluation purposes (and consequently, maintenance or reparation) under specific circumstances. Higher computing performance is required after warnings and flags occur during, for instance, visual inspection.

Finally, an attempt of developing computationally tractable models of Demo 9, *Olympiastadion*, was performed by testing a similar structure under laboratory conditions. With the aim of testing different measuring configurations and different use of cable-net models, the laboratory test was instrumented, measured and simulated.

In the following sub-sections, simulations deployed on four demo sites are described with the corresponding key takeaway.

### 1.6.1 MATERIAL CALIBRATION FOR REALISTIC INITIAL STATE.

To ensure structural performance and durability of a building or infrastructure, the mechanical properties of the materials must roughly match the values assumed at the design stage. As concrete is a heterogeneous mixture, the uncertainty of its mechanical properties increases, therefore, calibrating a realistic state of the material may be crucial in singular infrastructures such as bridges.

**As concrete is a heterogeneous mixture, the uncertainty of its mechanical properties increases, therefore, calibrating a realistic state of the material may be crucial in singular infrastructures such as bridges.**

For the post-tensioned slab of *Viaducto La Plata*, one of the bridges of Demo 1 (see Table 1), a calibration of the elastic Young's modulus was necessary. From measurements, it is possible by performing reverse engineering to infer more realistic values based on strain measures acquired during the load test. The Young's modulus of the concrete changes over time, thus, predicting a reliable value is key to properly checking the structural performance of a bridge, comparing measured and simulated deflections and strains.



*Viaducto La Plata* is a hyperstatic 4-spanned concrete bridge and is part of the Madrid – Badajoz highspeed railway. It is located near the cross of *El Tajo* River. Fig. 10 shows the location and the overview of the bridge.



Figure 10 Location and overview of La Plata Viaduct

The lengths of the inner and outer spans are 32.0 and 25.0 meters respectively. The cross section of the bridge's deck is a continuous post-tensioned voided slab of width 14 meters and height 2 meters. Fig. 11 presents front-views as well as the cross section of the bridge.

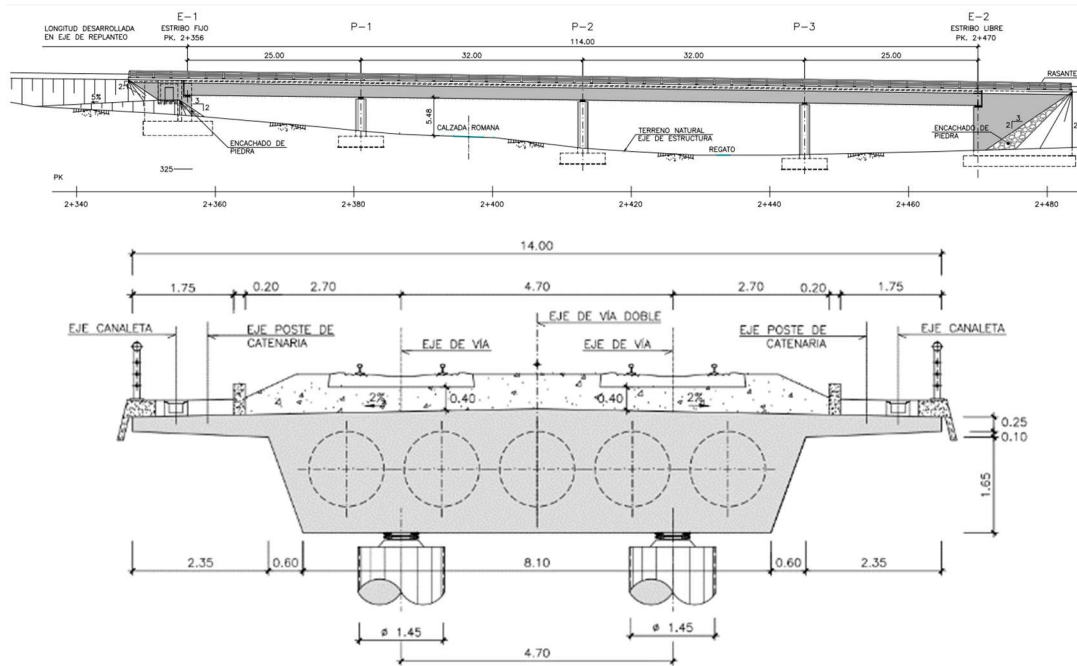


Figure 11 Longitudinal and cross section of La Plata Viaduct

The construction stage of *La Plata Viaduct* ended. To approve the initiation of the operational stage, a load test was required. Drace, one of the collaborators of the project project provided access during the load test and shared the collected data from sensors such as vertical displacements, strains, and accelerations. Details on the overall participation of Ashvin partners in this site are given in Chacón et al. (2022<sup>a</sup>).





Figure 12 Load test of La Plata bridge and a sample of collected sensor data

The structural analysis model to simulate the multi-physics of the bridge and check the executed load test is based on a numerical model of nonlinear and time-dependent analysis for three-dimensional reinforced and prestressed concrete (Marí 2000). The mathematical model implements frame finite elements with six degrees of freedom per node. These elements are discretized into filaments, with each having a length and prismatic cross-section that are defined by their area and position relative to the sectional local axes and are associated with a specific concrete or steel (Fig. 13).

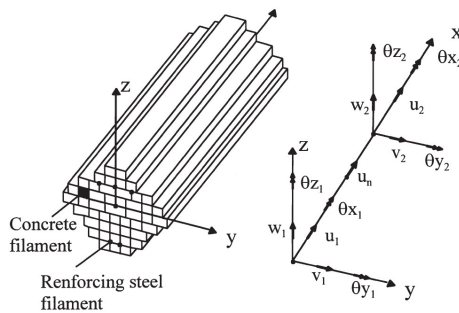


Figure 13 Filament frame element (Source: Marí A, 2000)

Strain compatibility exists between all materials belonging to a given cross-section. A perfect bond is assumed. The principle of plane strain is applied for mechanical and non-mechanical strains. The constitutive models for concrete, active and passive reinforcement, include the rheology of the materials and implement uniaxial stress-strain principles. Loads are assigned to nodes at specific instants, allowing the introduction of load increments and enabling a step-by-step analysis over time. Prestressing loads are applied using an equivalent load vector, defined by balancing the forces of the arrangements of the tendons. This numerical model was the basis for the existing computer program called CONS, which is routinely used for research at the Technical University of Catalonia (Bairán & Marí 2007, Marí et al. 2003, Chacón et al. 2007)

To accurately represent multi-physics simulations within the Digital Twin of an asset, the capabilities of CONS are being leveraged to a powerful graphical environment, using Rhino and Grasshopper parametric software, where discretization of complex cross-sections is possible, enabling a direct construction of fiber-based models. The shape of the bridge cross section, the number of filaments for discretization, the constitutive models of the materials, the pre-stressing loads and tendons, and the internal loads are set up on a visual programming script, enabling a parametric structural analysis, where any changes in the input data will generate a dynamic change in the results, facilitating the calibration of materials' properties or loads. Fig.14

shows the assembly and results of the parametric fiber-based model of La Plata Viaduct's cross section.

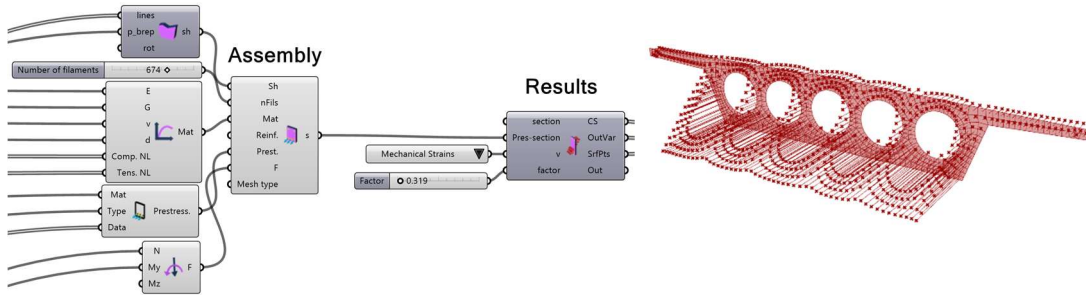


Figure 14 Parametric fibre-based model of La Plata Viaduct cross section

During the load test of a bridge, strains are measured to check the structural behavior. However, to verify if the collected data is within the acceptable range, it is required to perform predictive simulations assuming the mechanical properties of the material specified in the project documentation. Given that the concrete is a heterogeneous mix, there may be significant differences between the real and the assumed rheological material properties.

A fiber-based model of the cross section of the bridge (see Fig. 15) allows the matching of the measured strains at the exact location of the sensor, with the strain of the corresponding fiber. Then, by implementing reverse engineering, it is possible to calibrate the elastic young's modulus of the concrete, enabling more precise simulations and improving the verification of the structure's performance, supporting the decision of allowing the initiation of the operational phase.

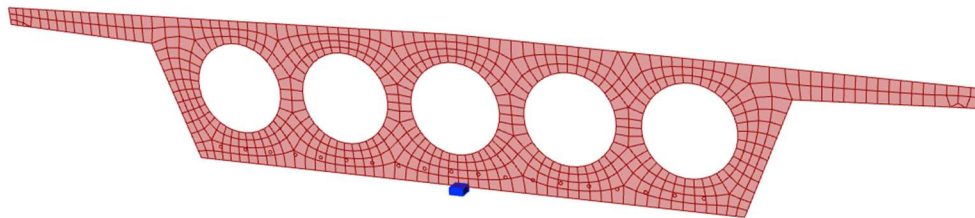


Figure 15. Sensor location and the corresponding filament to match strains

### 1.6.2 CONCRETE MATURITY - DETAILED FLOW FROM SENSOR TO SIMULATION

The Digital Twin paradigm implies an active connection between the virtual and the real realms. Ideally, data from sensors must flow properly in a digital system to feed a virtual representation of a building or infrastructure. During the construction stage, it is of interest to continuously verify the structural behaviour of an asset with real data acquired at the site. Real data embedded within the simulations provide more realistic results and increase confidence on the construction evolution.

This application shows a detailed flow of data from sensors (temperature) embedded in fresh concrete that feed a structural analysis model. The asset corresponds to an office building widely described (Posada et al. 2022). The process provides a way to verify the allowable deflections of the structural elements depending on the evolution of the concrete compressive strength at early ages, estimated through the maturity index method. As a result, construction managers can get reliable information for decision-making on activities such as early formwork removal.

**Can construction managers get valuable digital data based on timely measurements of the concrete maturity directly embedded into structural analysis?.**

Maturity refers to the progression of physical properties in concrete during the hydration process, including the evolution of strength. The commonly used maturity method, defined by ASTM C1074, assumes a non-linear correlation between concrete temperature and the rate of the development of the material properties. This method provides quick data without the need for sample transportation or crushing scheduling, but it does require calibration and is dependent on the concrete mix. Additionally, the model cannot be extended to significant changes in the mix between concrete batches.

The testbeds of this example are developed for Demo 6 (see Table 1), a concrete building under construction in the Poble Nou district of Barcelona. Fig. 16 shows the render and the BIM model of the office building, highlighting the premises where actions were allowed in the collaboration with the construction company.

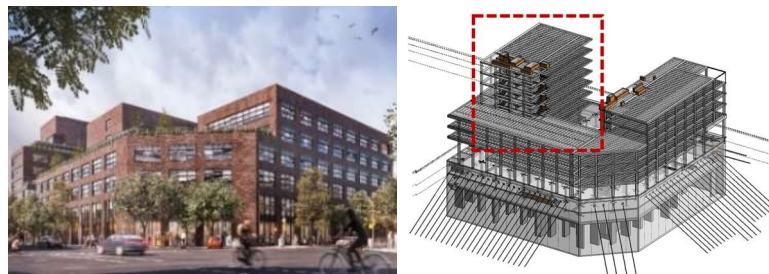


Figure 16 MILE Ávila office building render and BIM model (Provided by BIS structures)

Hardware modules were developed at the Laboratory of Digital Models for Structures and Construction (LMDEC) at UPC for data acquisition, allowing customization of the data flow. To collect data from long-spanned slabs, two types of temperature sensors were used. Two thermocouple K-type sensors with a range from 0°C to 400°C and an accuracy of  $\pm 2.2^\circ\text{C}$ , were connected to a MAX6675 module that converted analog signals to digital. The other type of sensor was a DS18B20, a waterproof digital sensor that communicates through a Wire-1 protocol to read temperatures between  $-55^\circ\text{C}$  to  $125^\circ\text{C}$  with an accuracy of  $\pm 0.5^\circ\text{C}$ . Power banks of 5000mAh were used to supply energy, and the sensors data was saved on an SD card for subsequent processing. The components were connected and synchronized to an ESP32 System on Chip module through the Arduino platform. These hardware modules are cost-effective and have open prototyping functionalities. All codes were developed by the authors of this deliverable.

During concrete pouring, access to the slab was restricted, and sensors were embedded fully in the concrete mix only in the allowed areas. In new sites, there is room for improvement in terms of the number and placement of sensors to collect more specific and reliable data. In this case, due to site restrictions, only a limited amount sensors were mounted, which helped prototyping the whole pipeline of information from sensor-to-simulation.

The structure dimensions are: for the post-tensioned maximum span 15.60 m plus a cantilever of 4.40 m, while the transverse direction spans 5.40 m. The cross-section height is 50.0 cm. Fig. 17 shows the location of the sensors and the obtained results during hours of measuring the temperature evolution while the material hardened.

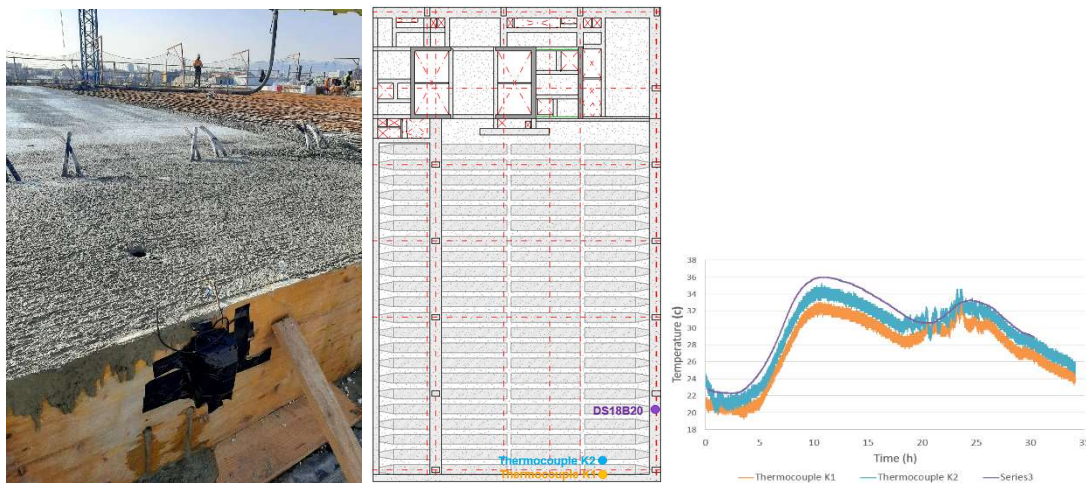


Figure 17 Collection of data, sensors location and measures acquired

After data collection, hardware modules were removed, and measures stored in the SD cards were saved on a local PC as CSV files. Then, this data was imported to the parametric software Grasshopper, where a developed Python script estimates the maturity index and the concrete compressive strength evolution with calibrated data for the specific concrete mix, as shown in Fig 18.

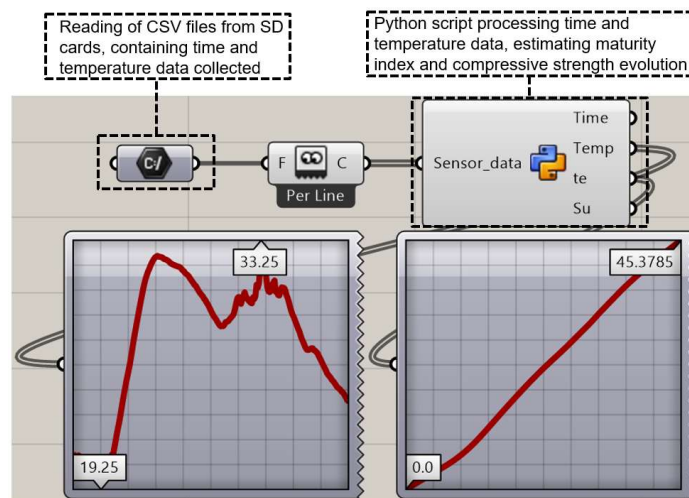


Figure 18 Maturity index and compressive strength estimation from temperature data within Grasshopper





### 1.6.3 GEOMETRICAL AND MATERIAL NONLINEAR ANALYSIS WITH IMPERFECTIONS (GMNIA) DERIVED FROM GEOMETRICAL RECORDED DATA

Composite bridges are prevalent and offer the benefits of both concrete and steel structures, leading to cost-effective and efficient solutions. Typically, these bridges consist of concrete slabs supported by steel plate or box girders. The beams of these structures are often made up of welded steel plates with transversal and longitudinal stiffeners, prioritizing material efficiency, weight, and cost in the design. However, this design can result in slender steel plates that are susceptible to buckling under certain stress levels. Buckling could lead to out-of-plane deformation, which would adversely impact the bridge's overall structural integrity.

In the design phase, sophisticated full-order numerical models are commonly used to forecast occurrences of plate buckling or other instability-related phenomena. Theoretical assumptions are made concerning the initial imperfections of steel plates prior to construction. Nonetheless, the post-construction "as-built" configuration of the plates is infrequently utilized to confirm these assumptions, and its transformation over time is not observed. The question to ask in this application is: How does information flow from measurements to geometrically and materially nonlinear simulations with initial imperfections?

**The question to ask in this application is: How does information flow from measurements to geometrically and materially nonlinear simulations with initial imperfections?**

This application aims to infer about the flow of information between simulations developed with advanced commercial Software and automated procedures for incorporating both BIM geometries and actual measurements from the site. The particular study seeks to perform structured and systematic evaluations of plates, stiffeners, diaphragms, or other asset subsets that are related to the structure stability. In order to integrate bridge information into larger information constructs, utilizing open BIM standards such as the Industry Foundation Class (IFC) (ISO 2018) is crucial. In terms of the incorporation of measurements, it entails developing semi-automated processes for identifying the initial imperfections of steel plates and subsequently integrating these geometries into advanced inelastic FE simulations for structural analysis at various levels.

The example is based on the PR-04-B015 bridge, located in the national highway network surrounding the Metropolitan Area of Barcelona (Spain). It links two of the main highways in the network: the AP-7 Highway (heading North) and the A-2 Road (Heading West). The PR-04-B015 bridge is a crucial connection point between these two highways, providing commuters with a bypass to circumvent the metropolitan area's suburbs during the transition from north-south to east-west corridors, and vice versa. As a result, the bridge has become a strategic asset for the transportation of goods from Catalonia to Northern Europe. In September 2021, the bridge was opened

to traffic, and it has an approximate length of 846 meters. Shown in Fig. 21, the bridge comprises a continuous horizontally-curved composite beam that spans a river (Llobregat), a creek (Rubi), various roads, and railway lines. The bridge is divided into two viaducts, one for each driving direction, with each viaduct consisting of 12 spans of varying lengths supported by concrete piers. The cross-section is made up of a steel box section with a variable web height ranging from 3.5 to 5.0 meters, along with a concrete slab with a width that varies between 11.50 and 17.00 meters. The steel box contains transversal and longitudinal stiffeners and diaphragms.



*Figure 21. Location and general view of PR-04-B015 bridge*

The original bridge design project was completed many years ago, during a time when digital tools and BIM were not sufficiently developed. Most of the bridge's information was stored in pdf files, containing all the relevant details in the form of deliverables and 2D drawings. A comprehensive 3D geometrical model had to be generated. The BIM model was developed according to the IFC open standard, which, in its latest release, permits modelling bridge constitutive parts assigned with a geometric representation, physical properties, and additional semantic information. As illustrated in Fig. 22, the developed model comprises detailed representations of bridge plates, slabs, piles, and stiffeners.



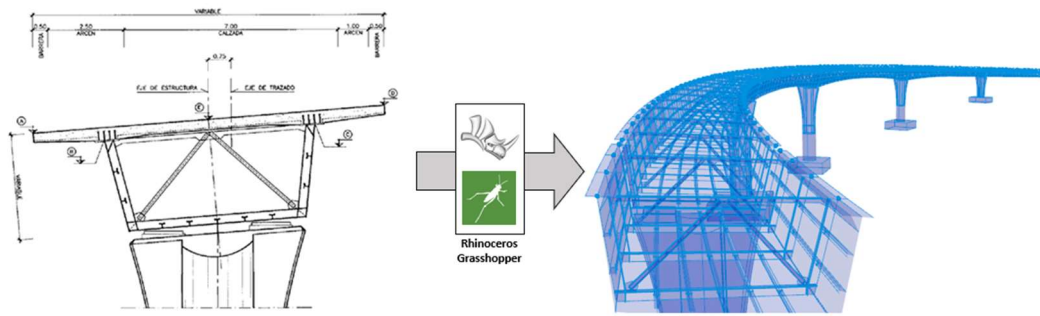


Figure 22. From drawings to IFC accessible geometries

Measurements on the bridge have included, among others, laser scanning. Laser scanning is a technique for capturing reality that produces large point clouds representing the 3D geometry of objects with high accuracy. A point cloud is a disordered set of points that include their coordinates  $(x_i, y_i, z_i)$  in a specific coordinate system, as well as other properties that determine the colour and type of surface being scanned. Laser scanners are widely available in the market and are high-performance devices that can capture the geometry of large structures with sub-millimetre accuracy within minutes. However, the primary challenge with this technique is processing the point clouds, which usually comprise millions of unstructured points requiring abstraction of geometrical features. In demo 7, during a given episodic scanning process, two measurements are taken from different points of view in order to capture the whole geometry of the steel box of the bridge. Each measurement takes 30 minutes and generates a point cloud representing a 360 view from the device standpoint with a density of one point every 3mm at a distance of 10m. Both measurements are co-registered into the same reference system using 7 spherical targets placed on fixed points on the ground. As a result of the co-registration process, a single point cloud is obtained containing over 100 million points. Figures 23 and 24 shows an example of the point cloud resulting from the scanning process in which the spheres and the positions of each measurement are marked. During the first measurement, the position of the spherical targets is precisely marked in order to replicate the measurement throughout the years. A total of 4 seasonal episodic scans have been performed until the development of this report. The first scan was taken on March 2022, the second on July 2022, the third on September 2022 and the last in January 2023. Two more episodes are planned in 2023.

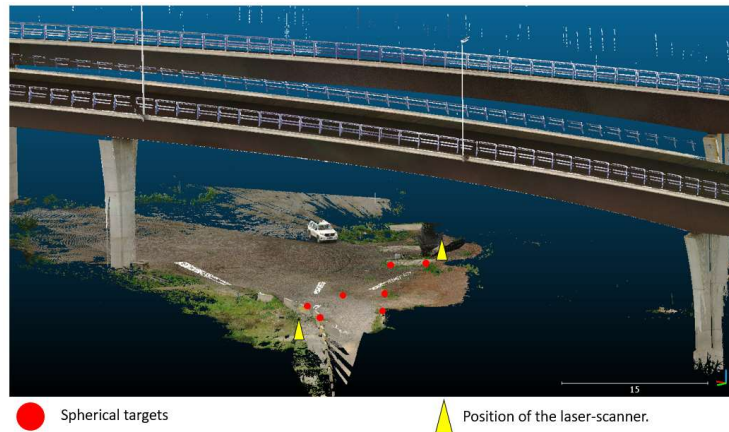


Figure 23. Final point cloud after the registration process. The position of the scanner and spherical target is highlighted.

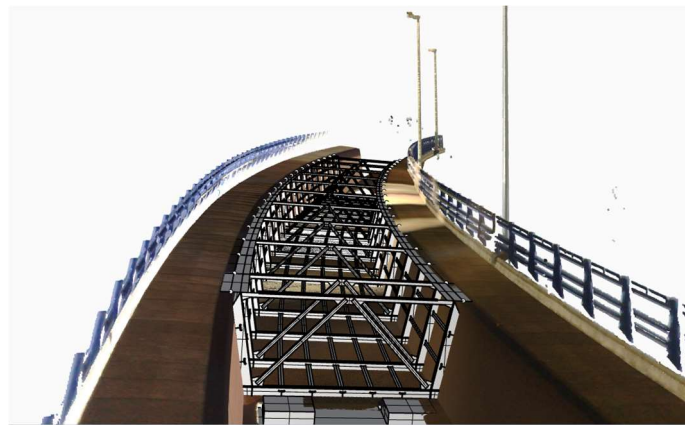


Figure 24. Geometrical model and pointcloud after the registration process.

Subsequently, the scans and its as-designed geometrical model are aligned to the same coordinate system. Two automated data pipelines have been created. The first pipeline involves two steps to streamline and simplify the point cloud. Initially, the point cloud is cropped using the bounding box of the bridge area being studied (as shown in Fig. 25-A). Then, voxel subsampling is employed to decrease the point cloud's size, where points in each voxel are combined into a single averaged point. This approach significantly reduces the point cloud's weight, making it more suitable for demanding computational processes. The second pipeline relates the reduced point cloud to each steel plate in the bridge steel box girder's geometrical model. The point clouds are segmented utilizing the geometrical model's oriented bounding boxes for each individual subpanel (refer to Fig. 25-B).

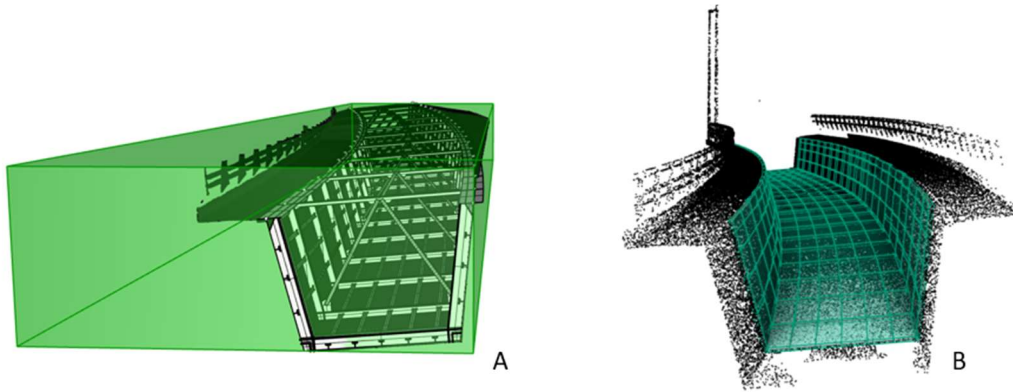


Figure 25. A: bounding box used to reduce the pointcloud to points contained in the region of study. B: Pointcloud segmentation using oriented bounding boxes of the box girder sub-panels

As a result, point clouds of specific steel plates can be retrieved under request of the user. This is a crucial aspect since this automated process provides a way of systematic addition of new measured information to the system of the bridge and allows linking individually the as-designed geometry in the model with as-built information provided by the point cloud at global and local levels. Fig. 26 shows how, for a given plate, seasonal episodes of point clouds are available and usable.

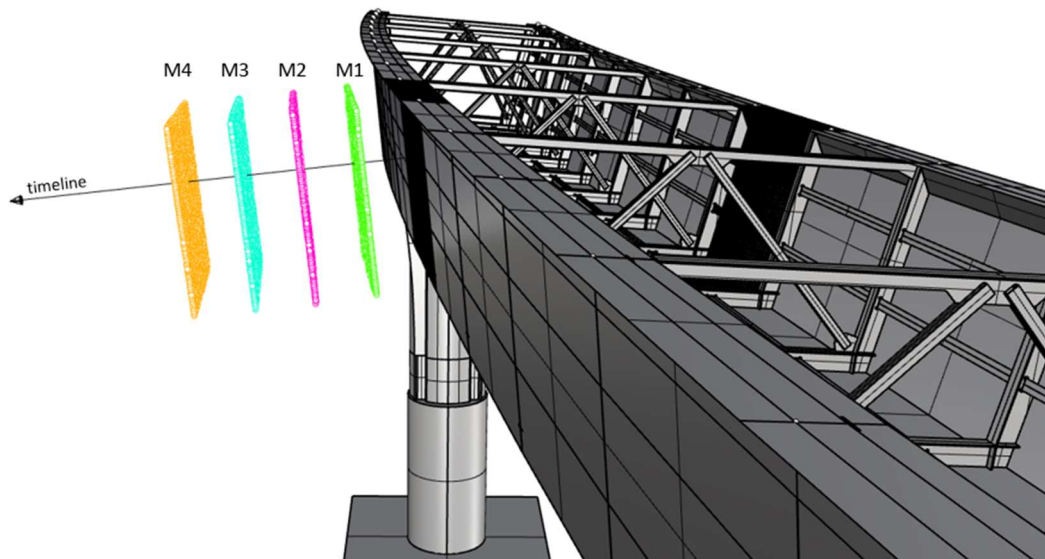


Figure 26. Multiple scans (M1 to M4) result in overlaid pointclouds that are associated with the elements of the bridge

It is interesting to compare the differences between the as-built point clouds and the as-designed surface of the geometrical model. To calculate the deviation, the perpendicular distance vector was computed between the measured points and the surface of their corresponding sub-panel in the model. The outcomes are shown in Fig. 27, indicating four episodic measurements. Deviations for measurements taken in March and September (under similar environmental conditions) have comparable patterns, while measurements taken in January and July have different configurations

of deviation distributions (Chacón et al. 2022<sup>b</sup>). The previously presented global deviation analysis captured the initial imperfections of the steel box girder's sub-panels. Interpolating the corresponding points, a new as-built surface was calculated for each panel. These surfaces can be saved and queried with varying levels of granularity and subsequently used for non-linear FE analysis.

The developed procedure facilitates the generation of models at various levels. As a result, during operation, different types of numerical models may be requested (according to different complexity levels shown in Fig. 28). Namely, one can request: i) Instability Eigenvalue analysis of isolated plates, ii) inelastic analysis of stiffened plates (partial strips or full webs) iii) cross-sectional analysis of the composite bridge considering the full section at given locations or iv) full advanced inelastic analysis of the whole asset (which may be computationally intractable nowadays though). In the following, brief discussions of the developments in this example are shown.

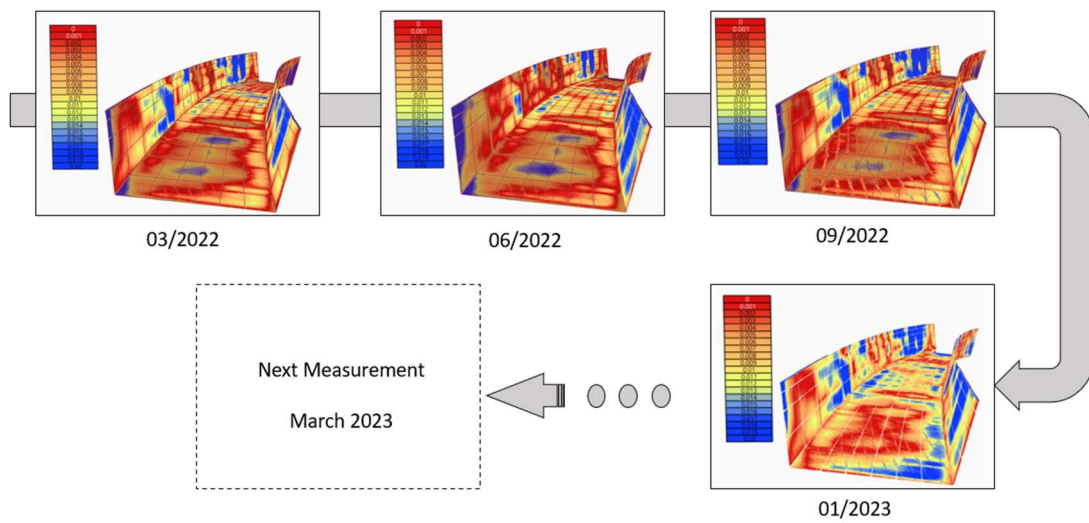


Figure 27. Results of the deviation analysis conducted on the bridge span for all the scans up to date

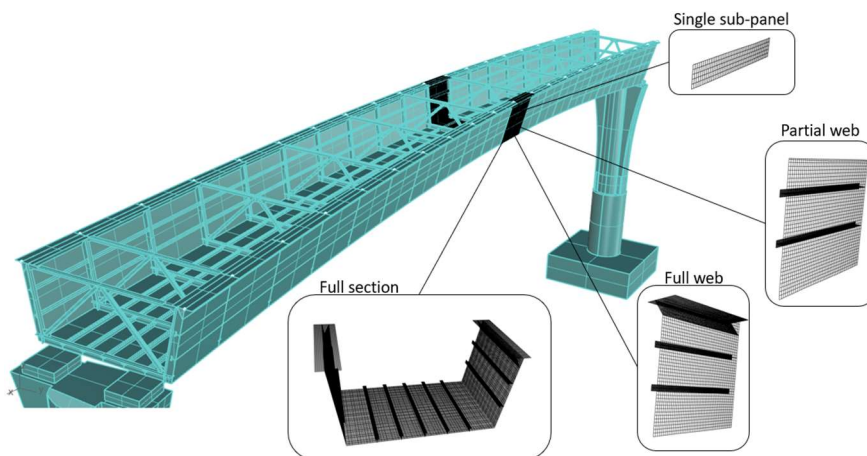


Figure 28. Different levels of available as-built information, from full sections to single web sub-panels



The geometrical models store metadata and information concerning all elements, including the geometrical configurations of both stiffened bottom flanges and webs. The IFC model records all necessary details about the girder, such as thicknesses, widths, heights, stiffener dimensions, and locations. From this model, users can choose specific panels and retrieve necessary information to conduct plate buckling analysis. Earlier versions of these models employed EBPlate (EBPlate, CTICM, 2007), software that predicts the Eigenvalues and Eigenshapes of in-plane loaded stiffened plates. Fig. 29 displays a selected stiffened web plate exposed to bending, compression, and shear stresses, with results aiding structural modellers in understanding this web portion's stability behaviour. The simulations rely on discretization and Fourier series and Fig. 29 also illustrates the outcomes obtained using the open-source Software EBPlate. The platform's current development emphasizes integrating these results at the precise panel location under investigation.

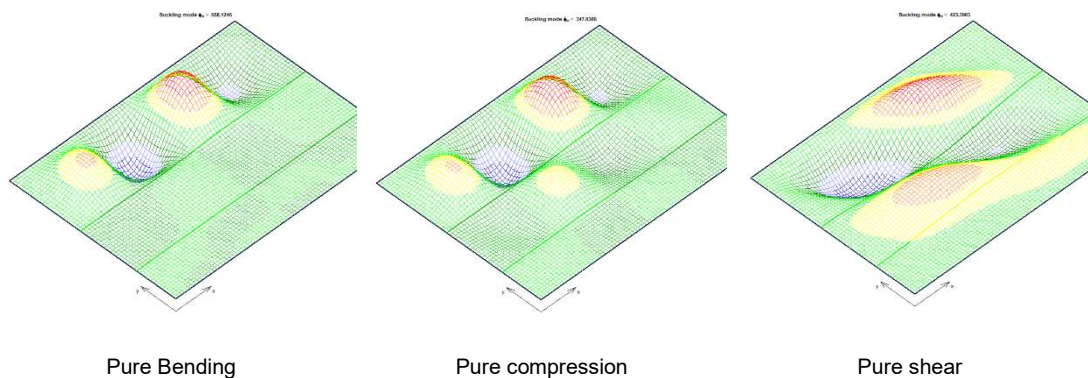


Figure 29. Stability analysis of a longitudinally stiffened partial web

Subsequently, geometrical configurations of both stiffened bottom flanges and webs are stored and processed. These realistic shapes can activate different levels of simulation models. To assess the accuracy and realism of these models that rely on imperfect plates, GMNI analyses were performed on these partial strips. Fig. 30 depicts a linear perturbation analysis of a strip of the web experiencing pure compression. Abaqus Simulia (Simulia 2013) was used to analyse a region between longitudinal stiffeners. Boundary conditions are assumed to be simply supported at this level. Using this Eigenshape as the starting imperfection for advanced inelastic analysis enables numerical solutions for evaluating its sensitivity. The magnitude of these imperfections is always a concern for designers (Chacón et al. 2009). Fig. 31 illustrates a plot that explores the sensitivity to the magnitude of this imperfection, which is related to the Eigenshape.

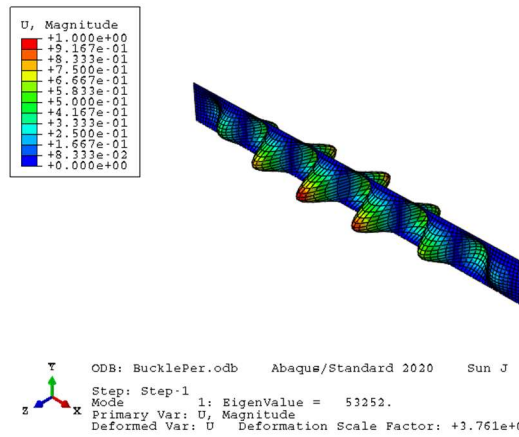


Figure 30. Eigenvalue analysis of isolated panels.

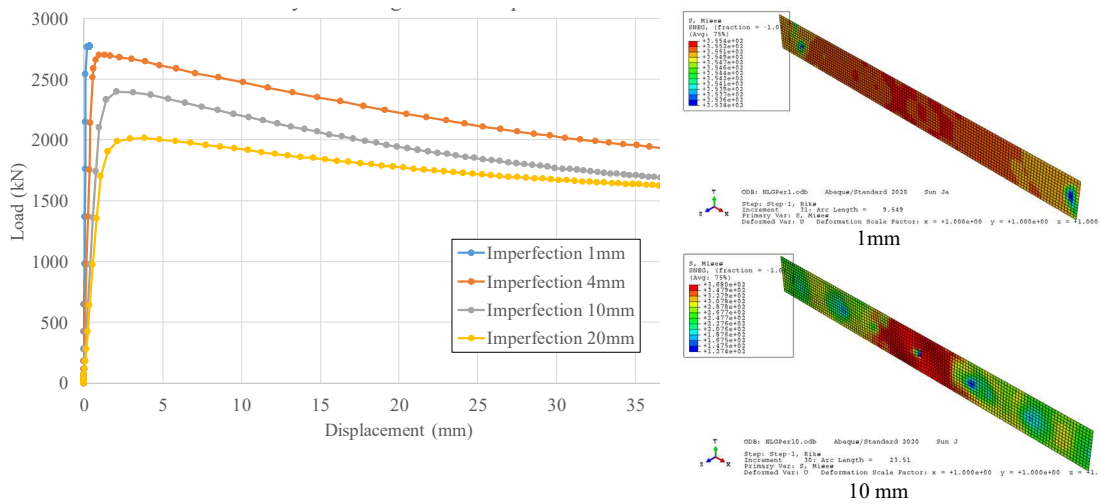


Figure 31. Sensitivity of the magnitude of imperfection on the load bearing (pure compression)

Structural analysis of isolated stiffened plates but in this case, using realistic imperfections have also been addressed for different episodes. While modelling, special care must be taken with the boundary conditions of the edges to avoid local failure in those regions. The resulting imperfect surfaces require detailed meshing. Small deviations on the surface imply that meshes must generally be unstructured. In some cases, sizes and elements are conditioned by the meshing algorithms. Additionally, special attention must be given to contact regions between elements in the IFC model (for example, between the plates and the stiffeners) which, due to the small deviations introduced, generate small gaps that condition the quality and usability of the meshes and, thus, may require a human-in-the-loop re-modelling process for those specific regions (Fig. 32). The hitherto used data transfer files between surfaces (fitted from point clouds) and FE-friendly meshes are serialized in STEP, a standardized 3D model exchange format that is widely recognized by computer-aided engineering software (STEP-file, ISO 10303-21). Fig. 33 shows an unstructured FE- mesh developed with a medial axis mesh generator.

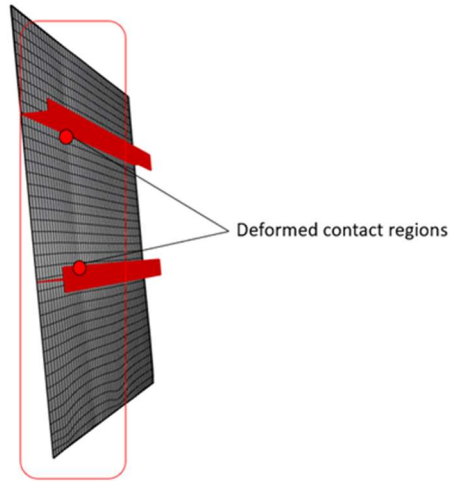


Figure 32. Imperfect contact between ‘as-built’ surfaces derived from the pointcloud measurements and ‘perfect’ stiffeners from the model

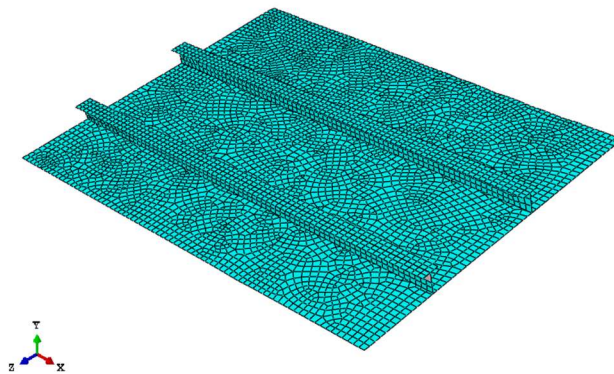


Figure 33. Mesh generated from surfaces fitted to the point cloud measurements

Subsequently, Fig. 34 shows advanced full order nonlinear models developed based on the realistic initial conditions. A detailed assessment of the ultimate load capacity of specific plates or vaster models can then be activated by the user.

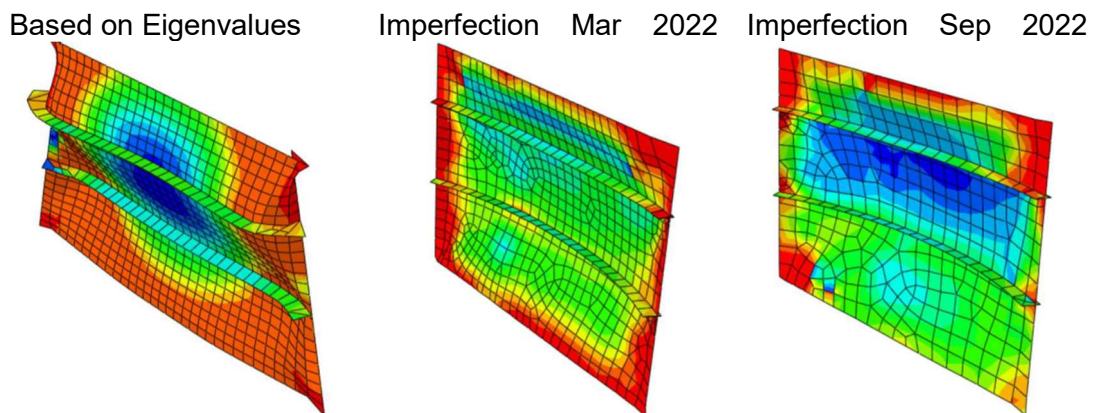


Figure 34. Full-order GMNIA models based on seasonal imperfections.



In order to visualize these results in the digital twin platform, information must be encapsulated in a JSON format and send back to the corresponding service defined in the data architecture depicted in section 1.4. From measurements to advanced models, this example of application provides a pipeline of information that can benefit maintenance plans. For instance, regular tracking of the shape of the bridge as well as regular visual inspections together can help managers to plan more carefully maintenance plans with more detailed levels of prioritization. The implementation of the results within the Ashvin platform are expected to be included in the final version of MatchFEM at the end of the project.

#### **1.6.4 LABORATORY TESTS - COMPUTATIONALLY TRACTABLE MODELS - COMPUTATIONALLY EXPENSIVE DATA PROCESSING (POINTCLOUDS)**

Cable nets are a type of tensile structure that are stabilised by a pre-stress rather than by bending stiffness. They can be configured in multiple ways to enhance their height and load performance. They can also accommodate different geometries, such as doubly curved or planar surfaces. A prominent example of cable nets in European architecture is the Plexiglas-clad roof of the 1972 Munich Olympic Stadium, which spans 74800 square meters with doubly curved cable nets. However, they also present a challenge for the design, construction and operation phases, as the force distribution along the net is difficult to determine precisely.

The main cables at those structures are either strand bundles or fully locked steel cables. The cable forces are large, and the cable diameters range from 82 mm to 182 mm. A direct measurement of forces would require unpinning the cables and using hydraulic jacks or cable tension meters. This would involve invasive and costly procedures that are not practical to be established by managers on a regular basis. In demo 9, which corresponds to Olympiastadion, the access to the site was restricted and only contact-less remote sensing techniques were allowed. Therefore, indirect measurement methods were needed to estimate the cable forces. In this matter, remote sensing using laser scanners was an alternative non-invasive solution to obtain valuable geometrical measurements from which the cable forces could be derived. In order to gain understanding of the use of such measurements, a laboratory-scale reduced model was developed as a testbed of methods for understanding its application of at the Munich Olympic Stadium. A terrestrial laser scanner was used in the lab to obtain a pointcloud from which the movement of the cable net nodes at different load configurations was captured. Then, computationally tractable numerical models were fed with the captured node configuration to obtain a real-time view of the cable force distribution on the net.

For the design of the net reduced-scale model, The Force Density Method (FDM) was used. Details about the algorithm can be found in Linkwitz (2014) Nodes connecting the ends of cable elements were arranged in two levels, using compressive clamps connected by a frictionless bolt, to allow relative rotations of the cables attached to them. The net is anchored to two “C-shaped” steel beams. A steel mast is fixed is used to give some lift to some of the net anchors. Holes in the mast and beams enable the

connection of the cable net by using hooks. The resulting mock-up and details are shown in Fig. 35.



Figure 35. Prestressed cable net

The cable net mock-up as built point cloud can be obtained with a single measurement from a TLS placed below the net. The resulting pointcloud contained considerable amount of noise in the zones surrounding the cables due to their reduced section size. However, the geometry of the nodes was successfully captured. Fig. 36 displays the result of a single scan of the mock-up cable net.

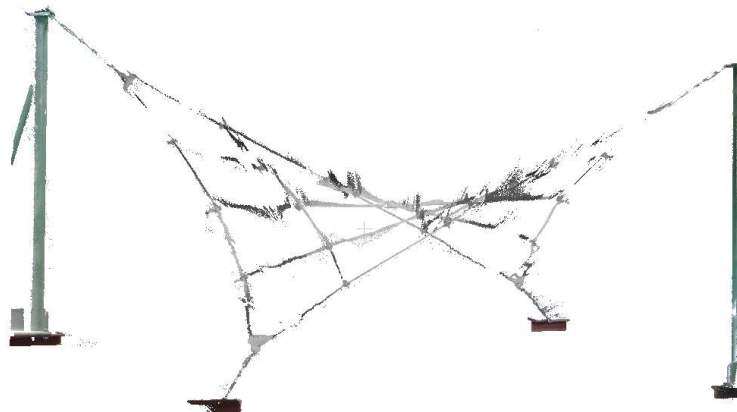


Figure 36. Initial TLS scan of the prestressed cable net mock-up

Point clouds need to be processed to obtain the points representing the as-built position of the nodes. The regions of the point cloud corresponding to each node need to be identified, segmented, and finally collapsed into a single point representing the node position. Automated point cloud identification and segmentation processes still remain a challenge in the industry, then, human intervention is always needed, resulting in a time-consuming process, normally involving tools that demand high computational power. Once the new point positions are determined, they are paired with the nodes in the as-design geometrical model to calculate their corresponding displacement. This process is repeated for sequential measurements with different loading conditions. Fig. 37 a) displays two superimposed sequential measurements

and b) displays the final superimposed as-built models derived from the new node positions.

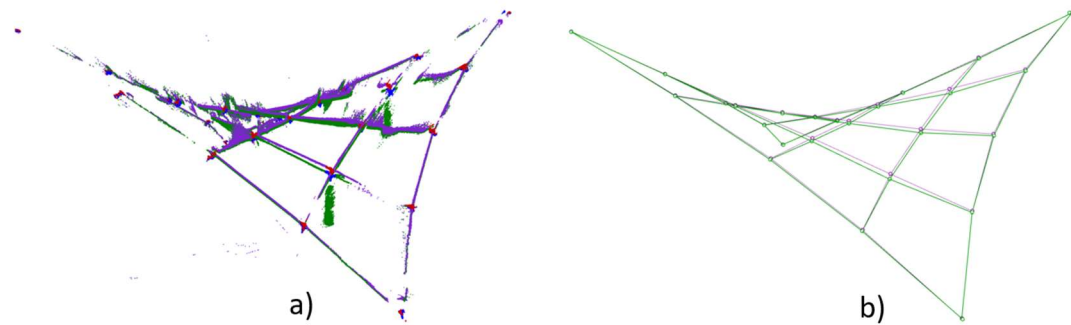


Figure 37. a) unloaded (purple) net pointcloud with identified nodes (red) superimposed to a loaded configuration (green) with identified nodes (blue). In b), the derived net configuration (points and lines) after processing the pointclouds.

From the unloaded node configuration of the net, a BIM model of the has been generated according to the IFC specification. Cable properties such as the sectional area, the current tension force, and the material information are defined in the model to be accessed by external computational agents dedicated to analysing its behaviour. A linear elastic structural analysis model has been established as defined in Ramonell et al. (2022). The model allows calculating the cable force configuration from the new point positions of the nodes of the net and its connectivity matrix. The model is fed with the material parameters defined in the BIM model and temperature measurements measured on-site. The calculation algorithm is encapsulated in a microservice to be integrated within the net digital twin ecosystem. The obtained tensional force distribution is used to update the information in the BIM model. The pipeline is depicted in Figure 1-28. Pointclouds, derived node locations and tensional results are timestamped and stored within the ASHVIN digital twin platform in JSON format. Thus, the systematic upload of new pointcloud measurements enables the acquisition of a performance history metrics for monitoring the evolution structural state of the net throughout its life.

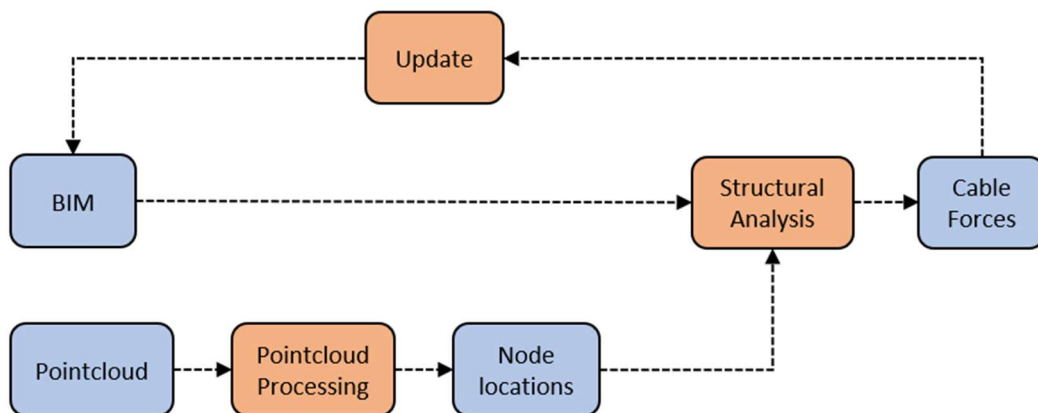


Figure 38. Pipeline for updating cable force information from pointcloud measurements. In blue, information snippets that are stored in the ASHVIN platform. In orange, computational processes executed.

## 1.7 DISCUSSION

Simulations coupled with varied SHM techniques belonging to varied sites is the core of this part. Structural health monitoring (SHM) has become a popular technique for assessing the condition of civil infrastructure. However, formal descriptions of SHM systems are limited to a small subset of information such as sensor data. When it comes to encompass varied simulations and varied sources of data, a strategy towards developing more abstract concepts in the form of knowledge graphs is an interesting alternative.

The knowledge graph facilitates the explicit interlinking of concepts defined in BIM with measured and simulated data from various sources. This provides the data foundation that enables the creation of computational processes that harness data and its context. As such, pipelines can be constructed to integrate capabilities into the digital twin, in line with the functionalities of MatchFEM in Ashvin. These functionalities encompass model validation and verification, maintenance planning support, and asset monitoring planning support. The potential combinations within these functional domains are limitless, necessitating the development of customized digital twin solutions for each individual case.

To this end, it is essential to adopt software architectures that support the modular development of pipeline components. This modularity enables the tailored design of each digital twin to meet the specific requirements of its physical counterpart. Additionally, it allows for the reuse of these components across multiple digital twins and seamless integration with the rest of the digital twin platform. Additionally, pipelines need to be reactive to actions carried out by users, devices and applications interacting within the platform. Consequently, we have chosen to employ an event-driven microservices and Docker for the integration tasks related to MatchFEM in the cloud.

Finally, the MatchFEM Grasshopper implementations have been developed to connect to and leverage the information architecture designed in the cloud. This provides an optimal development and experimentation environment that integrates multiple programming languages and offers extensive capabilities in computational geometry and visual representation. This enables unrestricted exploration and manipulation of information on the cloud platform, as well as the design of prototype pipelines and visualizations for future integrations into the digital twin. It is within this environment that the conceptualization of digitizing load tests, as outlined in section 2, has taken place.

## 2 RECOMMENDATIONS FOR THE DEVELOPMENT OF DIGITALLY TWINNED LOAD TESTS

### 2.1 INTRODUCTION

Load tests are an ideal episode of a bridge for generating its digital birth. During this episode, the staff involved brings to the asset the convergence of measurements, structural models and complex logistics for loading the structure. The corresponding reporting of results and comparisons between the physical reality and predictive models represents the outcome of load tests. This outcome in its digital twin version may represent an excellent opportunity for maintenance planners and other stakeholders.

Assets are expected to be at the peak of their condition and a considerably clear picture of the structural behavior of the asset is gained at this episode. As a matter of fact, during these episodes, administration, constructors, designers and other managers converge in space and time with a sharp focus on these assets.

The aim of this part is to dissect the load test episode as the ideal situation for the digitalization of the asset. In the following, the current practice of load tests is described together with the development of the load tests.

### 2.2 TOWARDS DIGITALIZATION OF LOAD TESTS.

#### 2.2.1 CURRENT PRACTICE

Load tests provide great insight into the current state of bridges. Nowadays, load tests are conducted for the assessment of newly constructed and in-service bridges for verifying design assumptions, developing field-verified finite element models, evaluating the effect of material degradation, analysing heritage buildings or determining their remaining life. In practice, bridge load testing can be split into Diagnostic Load Tests and Proof Load Tests (Lantsoght 2019). In Diagnostic Load Tests, known loads are applied to the bridge while it is being monitored by a set of sensors that provide sufficient data to represent its structural behaviour. The data recorded during the test is used to validate analytical models that can be used to better predict structural behaviours for a variety of purposes. On the other hand, Proof Load Tests are more detailed assessments in which the as-design full load capacity of the bridge structure is verified. Test loads are applied in a multi-step process that is continuously monitored to account for any signs of distress or non-linear behaviour.

Besides being used for validating analytical models, the proof load test provides a lower bound on the true strength capacity of the bridge.

At the time of writing this report, the provisions for Proof Load Testing in railway bridges in Spain are given by the norm NAP 2-4-2.0 (NAP, 2021) expedited by the Administrator of Railway Infrastructure (ADIF), which manages the whole Spanish high-speed railway network. According to the Spanish legislation, proof load tests must be performed in bridges located in newly constructed lines as a transition check from construction to operational stages, although they can also be carried out on bridges in lines already in service which need to be checked on a routine basis or that report special casualties that require this type of assessment. According to NAP 2-4-2, static and dynamic tests are carried out to monitor the structural performance of the bridge:

Static tests are performed according to a series of load hypotheses, that establish different load configurations along the bridge length in order to account for all unfavourable load scenarios. Each hypothesis is assessed in a 5-step process: (1) measurements start when the bridge is unloaded, (2) vehicles are placed along the bridge according to the load hypothesis configuration, (3) loads remain static until measurements of the deformed shape of the bridge are stabilized, (4) the bridge is unloaded and (5) measurements are taken until they are the shape recovery of the bridge is stabilized. Furthermore, a quasi-static test is carried out as well, in which a moving load passes over the bridge at a reduced speed (5-10 km/h).

Dynamic tests consist in applying moving loads to monitor the dynamic response of the bridge. At least three types of tests must be performed: First, the loaded vehicle passes over the bridge moving at an intermediate speed, secondly, the vehicle passes at the maximum authorized speed, and last, the vehicle circulating at maximum speed breaks when passing over the bridge.

Load tests are complex and rather expensive procedures. They require experienced personnel and technicians, proper planning and suitable equipment. The procedure requires the realization of multiple steps, which are summarized as a flowchart in Fig. 39:

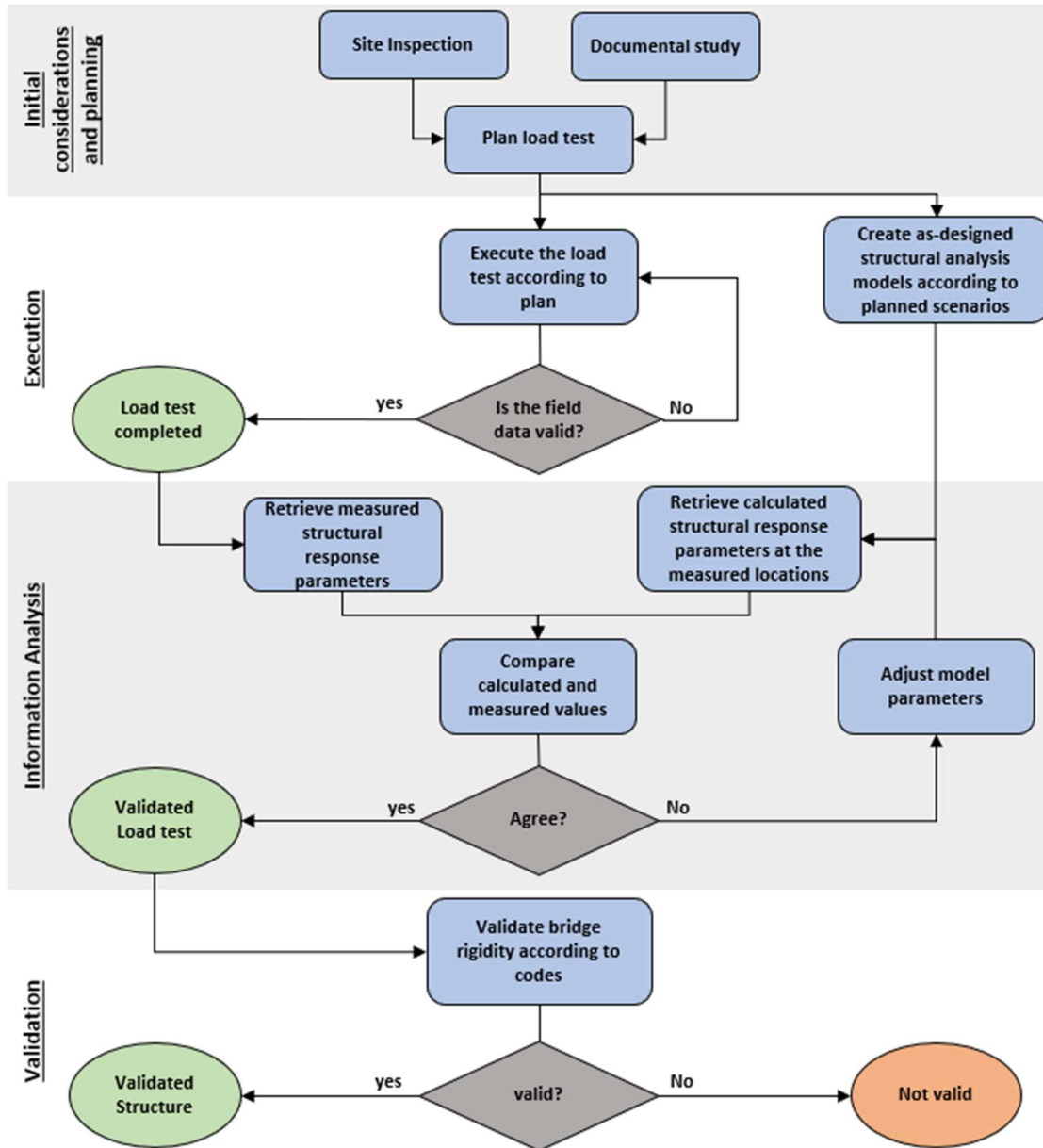


Figure 39. Flowchart of the proof load test procedure according to NAP 2-4-2.0

### Step 1: Key considerations and planning

To perform a proof load test in bridges it is required detailed information about the structure and its updated state. All the available documented information about the bridge is revised, including drawings, its geographical location and the viable accesses to the structure, the physical and mechanical information about the structure and the materials, the exploitation conditions of the railway line as well as all the relevant information obtained during the construction process. Additionally, a preliminary inspection is carried out to account for anomalies and imperfections, as well as to plan the procedure in-site. The gathered information is used to plan the execution of the load test, including the number of static and dynamic tests to be performed, the instrumentation required, and the position of the measuring devices and the human workforce needed.



## Step 2: Execution

Dynamic and static tests are performed as planned. The most work-intensive part of the execution is the deployment and removal of the monitoring systems, which are used to measure vertical displacements, deformations, and accelerations at the bridge deck, as well as the vertical descent of the deck supports. Simultaneously, an analytical model is developed to predict the structural behaviour of the structure during each of the static and dynamic hypotheses executed.

The equipment to perform measurements from which the load test parameters are derived is traditionally composed of strain gauges, for measuring strains, LVDTs for measuring vertical displacements and accelerometers for measuring accelerations. The deployment and removal of the sensor system is the most time-consuming procedure during tests. The system communicates each sensor node using long cable runs that need to be properly labelled and connected to the Data Acquisition device. Emerging technologies pose an interesting option that overcome some of the difficulties of using the traditional system. For example, in some cases the scale of the bridge structure makes the use of traditional sensors unaffordable. In these cases, the use of remote sensing technologies such as the Terrestrial Laser Scanner (Riveiro et al 2013) and the Ground-Based Interferometric Radar (GB-INSAR) (Rodriguez-González et al., 2022) are able to remotely yet accurately monitor the static and dynamic behaviour of the structure (Fig. 40).

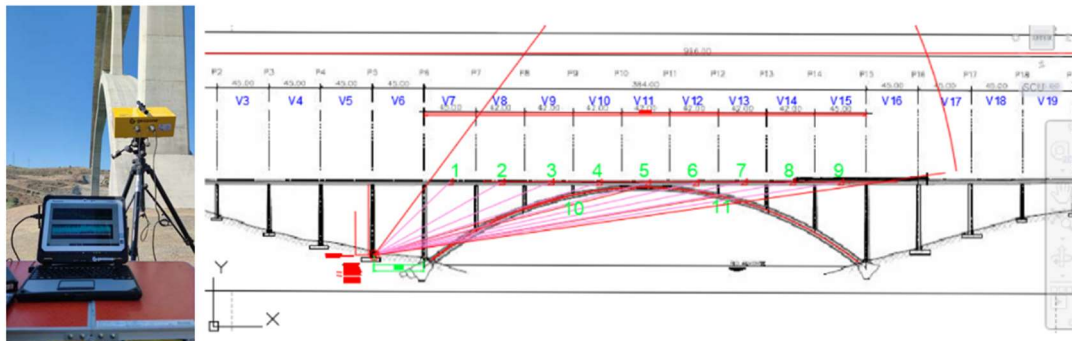


Figure 40. Measuring vibrations and displacements with a GB-INSAR in a large arched bridge

Additionally, new IoT-enabled wireless sensor systems allow connecting measurements directly to cloud-based platforms, providing an efficient organization and treatment of the raw data.

## Step3: Data Processing and comparison

Data gathered during static tests is processed to obtain:

- The deflection measured at the centre of each bridge span.
- The net deflection of each bridge span, obtained by subtraction of the deflection values obtained at the supports to the deflection measured at the centre.
- The remaining deflection after the bridge is unloaded, in order to evaluate whether the bridge correctly recovers the original shape.

Data gathered during dynamic tests is processed to obtain:

- The impact coefficient, obtained as the ratio of the vertical deflection during the quasi-static test and the vertical deflection during each dynamic test.
- Natural frequencies of the bridge.
- The damping of each bridge span.

The same parameters are estimated from the calculations performed using the theoretical structural analysis model. The parameters of the analytical model can be tuned to optimize the agreement between measured and simulated quantities. Exemplary tables of results according to NAP2.4.2 requirements are shown as follows:

SPAN	TEST ID	ELEMENT ID	SENSOR ID	PREDICTED	MAXIMUM	NET	%	REM	%REC
2	STA_01	Beam_21	EP_21		-0.97				
2	STA_01	Beam_22	EP_22		-1.08				
2	STA_01	Beam_21	P_21	-6.20	-4.99	-3.97	64	0.07	100
2	STA_01	Beam_22	P_22	-6.20	-5.09	-4.07	66	0.05	100
2	STA_01	Beam_21	G_21	76	82	82	108	-0.38	100
2	STA_01	Beam_22	G_22	76	82	82	108	-4.89	100

Table 2 Results for static tests

Where the predicted strain and displacement values provided by the analytical model are compared to the maximum values recorded by each sensor (SENSOR ID) connected to a specific structural element (ELEMENT ID) during a specific test (TEST ID).

SPAN	ELEMENT ID	SENSOR ID	STATIC_TEST ID	STATIC VALUE	DYNAMIC_TEST ID	DYNAMIC VALUE	IMPACT COEFF.
2	BEAM_21	P21	PS_STA	1.15	DYN_MAX	1.15	1.00
2	BEAM_21	G21	PS_STA	22.91	DYN_MAX	26.38	1.15

Table 3 Impact ratio results for dynamic tests

Where the impact ratio is calculated with references to the sensors, and static and dynamic tests.

SPAN	TEST ID	ELEMENT ID	SENSOR ID	MODE 1	MODE 2	MODE 3	MODE 4	...	MODE N
2	DYN_40	BEAM_21	ACC_2	3.99	4.26	6.75	7.56	...	-
2	DYN_MAX	BEAM_21	ACC_2	4.40	4.75	6.57	6.95	...	-
2	DYN_FREN	BEAM_21	ACC_2	4.32	4.60	6.33	6.97	...	-

Table 4 Exemplary peak frequency results table for dynamic tests

Where the modes are derived from acceleration measurements. The number and nature of modes provided depends on the structural typology of the bridge including geometry, materials, boundary conditions, etc.

SPAN	TEST ID	ELEMENT ID	SENSOR ID	DAMPING RATIO ( $\delta$ )	DAMPING RATIO (%)
2	DYN_40	BEAM_21	ACC_2	0.08	1.27
2	DYN_MAX	BEAM_21	ACC_2	0.078	1.25
2	DYN_FREN	BEAM_21	ACC_2	0.082	1.30

Table 5 Exemplary damping results table for dynamic tests

Where the damping ratio is calculated from the acceleration measurements.

#### Step 4: Validation

The validation is performed according to the recommendations. It is required a minimum percentage of agreement between the estimated and the measured structural performance parameters. Additionally, the resulting characterization of the structure is derived from national codes, allowing the categorization of the structure from different perspectives according to its typology and structural behaviour. After validation, a report is delivered containing all information regarding the tests and the obtained results.

#### 2.2.2 A DIGITAL APPROACH. FUTURE CHALLENGES.

A digitally twinned load test on a bridge becomes the ideal scenario for the generation of the digital birth of the asset. DT can be thus defined as:

- **Assistant for load test planning:** Digital twins are meant to host all the information regarding a specific asset. This single source of truth allows planning effectively the load test. Things like asset documentation review or virtual site visits will optimize the resources at this stage.
- **Assistant for load test Execution:** Having access to a digital platform with all needed information to deploy sensors and perform the tests will make planning more effective. The possibility to use connected IoT sensors will reduce data hand-over times.
- **Assistants for load test Analysis:** Data stored in the platform can be downloaded and processed on demand through the platform's API. The platform also provides interfaced forms to add the results to the load test representation after the analysis.
- **Assistants for Automated Validation:** Once information about the results of the load test is stored and linked to the platform, the validation becomes trivial. The set of rules imposed by each standard are revised programmatically and the validation can be automatically performed.

The beneficial effects of creating a digital asset during load testing are still challenged by technical needs. The use of IoT-connected equipment: IoT sensors are available in the market, however, the solutions are restricted to their in-house cloud platform where data is stored and processed. This is a difficulty when the target are more complex digital twin platforms with such IoT capabilities. They are also very expensive. On the other hand, a big challenge corresponds to the generation of a Standard virtual representation that encompasses load tests internationally. To date, each country deploy load tests according to their own specifications for data acquisition and presentation. Integration of data is also a crucial part. The virtual representation needs to be integrated its physical counterpart. Sensor raw data must be linked to the virtual representation of the load test (Ramonell & Chacón 2022). Equivalencies between entities in the load test data model and other data models such as BIM (IFC) need also to be stated. Fig. 41 shows a data model architecture of load tests that aims to overcome such challenges.

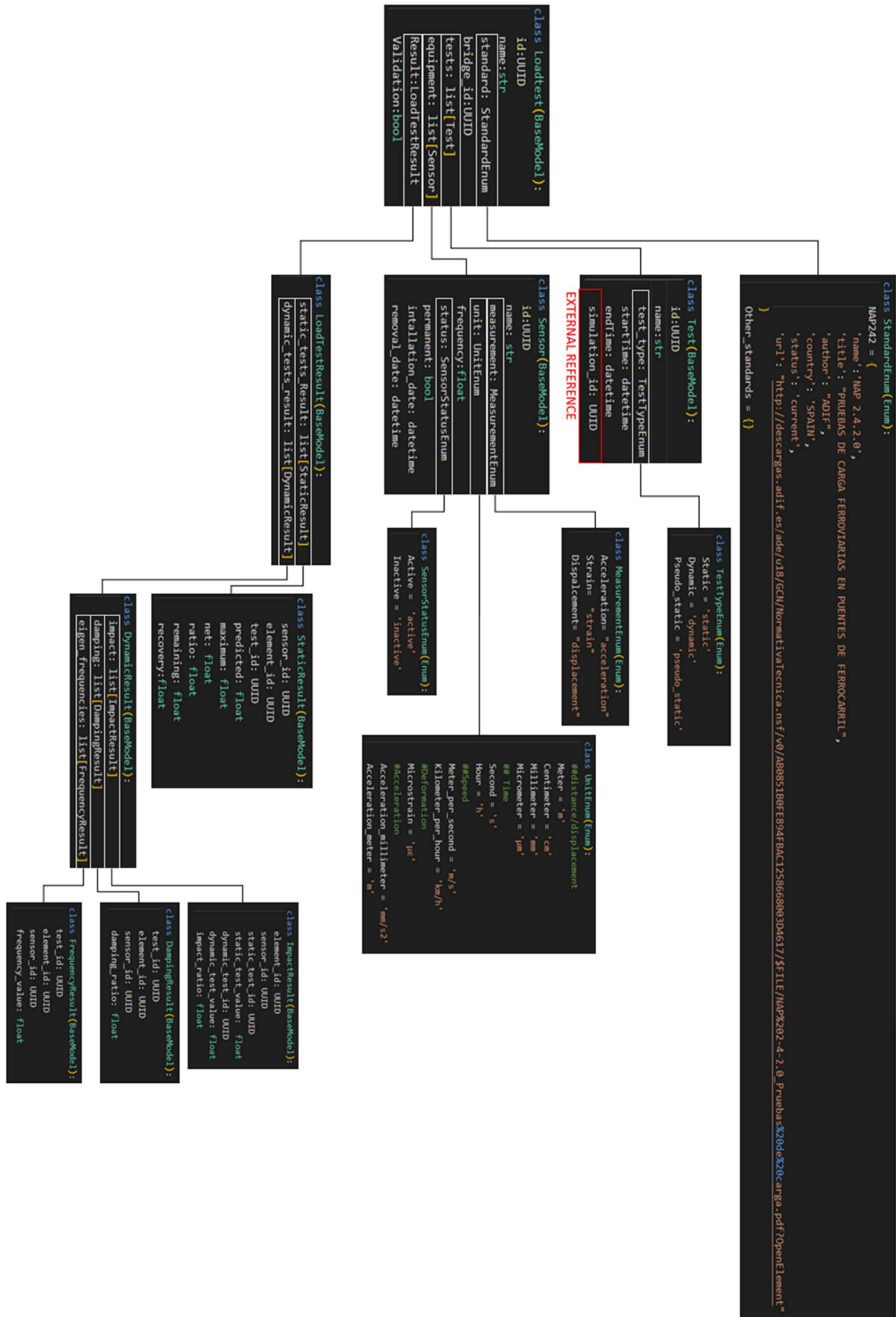


Figure 41. Load test data model

### 2.3 LOAD TESTS IN DEMO #1. BRIDGES

Bridges are vital structures that connect different regions and provide social and economic benefits. Proper design, construction, and maintenance of these assets are essential. The capacity to collect and manage data from bridges has increased in recent years, therefore, the approach to a Digital Twin paradigm is feasible.

A DT has the potential to represent the multi-physics of a bridge to generate scenarios capable of monitoring accurately the structure of an asset. Load testing of bridges provides an ideal scenario to simulate and adjust physics behaviours. The imposed load is known and controlled, the serviceability of the asset is restricted, a detailed plan of types, numbers and locations of sensors is available, and a set of specific requirements have to be accomplished according to the official local standards.

Load tests are relatively expensive. Quite considerable coordination between owners, machinery, designers, monitoring staff and construction companies is needed. This experimental analysis though (static and dynamic), represents a precious episode in the bridge construction or operational phase that can also be leveraged in economic terms. It is thus, interesting to extract the maximum amount of information from the bridge during these load testing episodes. Economic benefits can also be extracted from the digitalization of the sector.

The load tests represent an ideal milestone for twinning bridges in digital platforms. On the one hand, specific, bespoke structural models are performed. On the other hand, measurements quantifying the structural response are taken. If both results are matched using not only basic comparisons but comprehensive IoT-based digital twinning, the asset enters the service phase not only physically, but also virtually.

The focus of this chapter is to present a set of recommendations for the development of DT in the frame of load tests for bridges. Requirements for the virtual asset, data collection, data processing, multi-physics simulations, and analysis of results are described, as well as the interoperability and centralization between all components involved, implementing an IoT platform and an online game-engine based DT platform.

Two viaducts part of the demo case 1 (a highspeed railway network in Extremadura – Spain) have been selected for the development of comprehensive digital twinning during load testing, and therefore, for the set of recommendations presented in this chapter.

One viaduct consists of simply supported beams and another viaduct consists of a continuous beam. Both structural types are repetitive throughout the depicted railway, which adds usefulness to the demo case. The former is called Valdelinares Viaduct. It is an 8-spanned structure with a total length of 280.4 meters. Fig. 42 displays the location of the asset and Fig. 43 shows a drone-view of the Viaduct.





Figure 42. Location of Valdelinares Viaduct



Figure 43. Valdelinares Viaduct. Drone view

The latter is called La Plata Viaduct. It is a 4-spanned structure with a total length of 114 meters. Fig. 44 displays the location of the asset and Fig. 45 shows a drone-view of the Viaduct.



Figure 44. Location of la Plata Viaduct



Figure 45. La Plata Viaduct. Drone view



On the other hand, it is worth pointing out that Valdelinares has a cross-section with two prestressed concrete girders and a concrete slab (Fig. 46) whereas la Plata has an *in situ* casted pre-stressed concrete deck (Fig. 47).

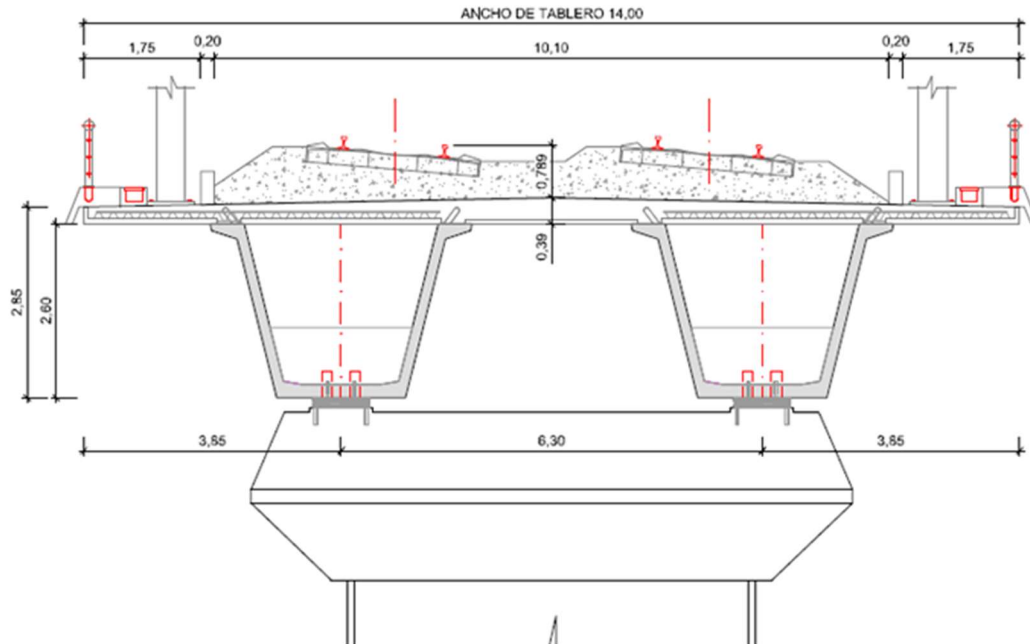


Figure 46. Valdelinares Viaduct. Cross-section

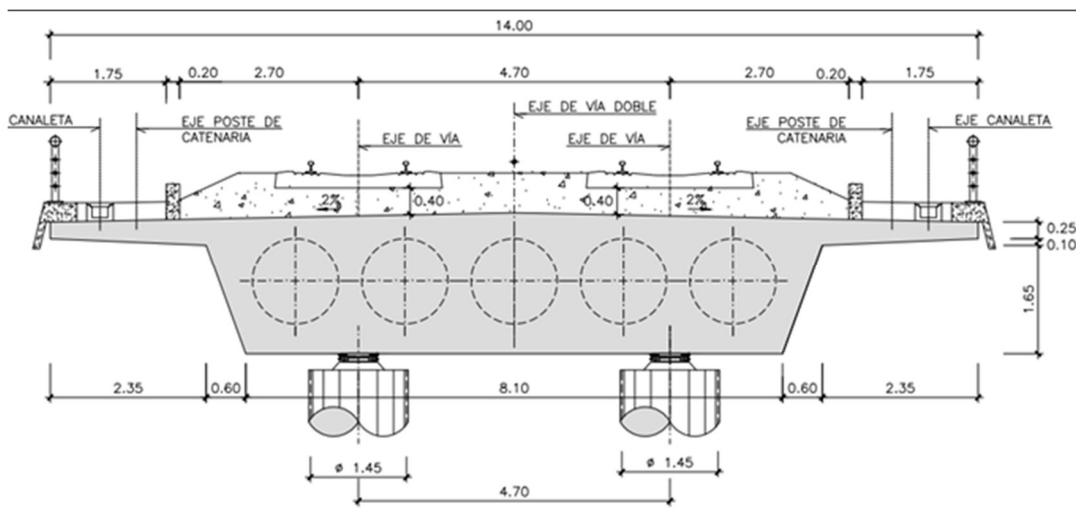


Figure 47. La Plata Viaduct. Cross-section

### 2.3.1 EXECUTED LOAD TEST PLAN

#### Static tests

The collected measures during the static load test were:

- Beams vertical displacements (deflection).
- Supports vertical displacements.

The measures of the deflections were performed through LVDTs (Linear Variable Differential Transducers) with a range of +/-25mm and a precision of 0.01mm for the beams' vertical displacements. For the vertical displacements at the supports, LVDTs with a range of +/-5mm and a precision of 0.01mm were used.

The locations of the measures of vertical displacements are described in Fig. 48 and Fig. 49. The measured deflections correspond to the active deflection produced by the load, which was the load trains supplied by the administration of the bridge. At the center of the spans, two LVDTs were placed for each track of the railway. At supports, one LVDT was placed.

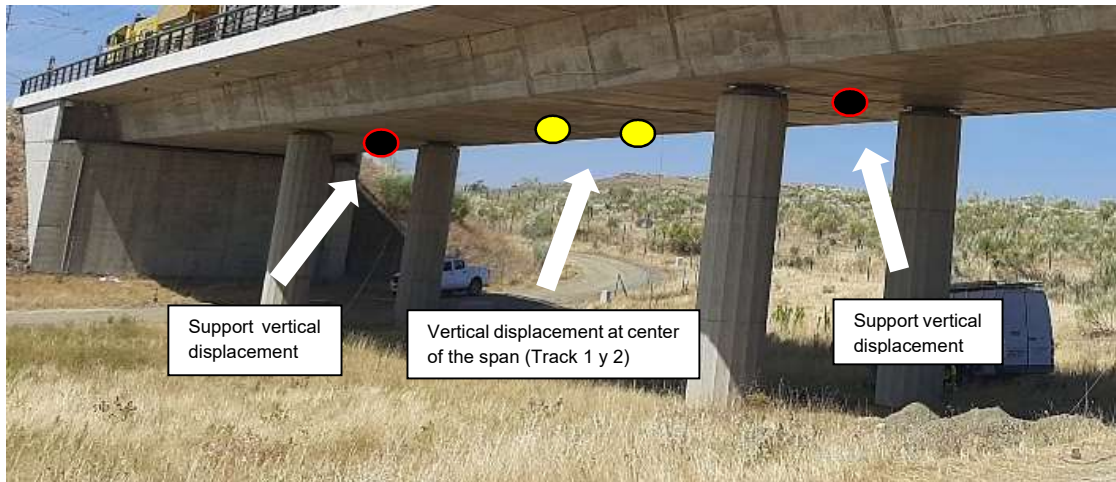


Figure 48. LVDTs labels and locations for static load test at span 3

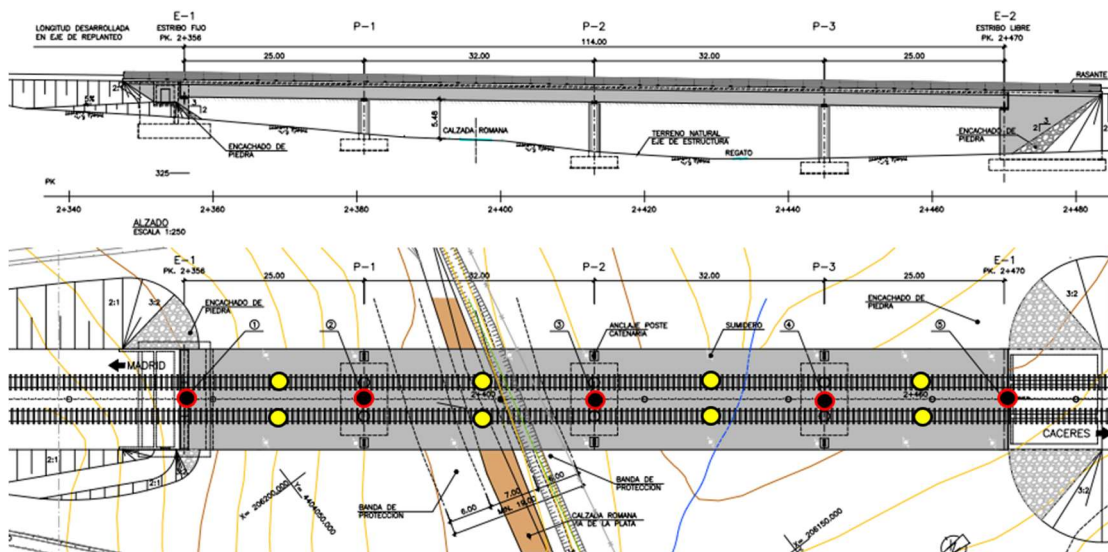


Figure 49. Locations schema of LVDTs sensor for deflection measurement

In addition, to measure the strains at the bottom of the prestressed concrete slab of the bridge, PL-60 strain gauges with active length, thermally self-compensated and directly complemented by a data acquisition system, were installed at the center of the spans for each track as described in Fig. 50.

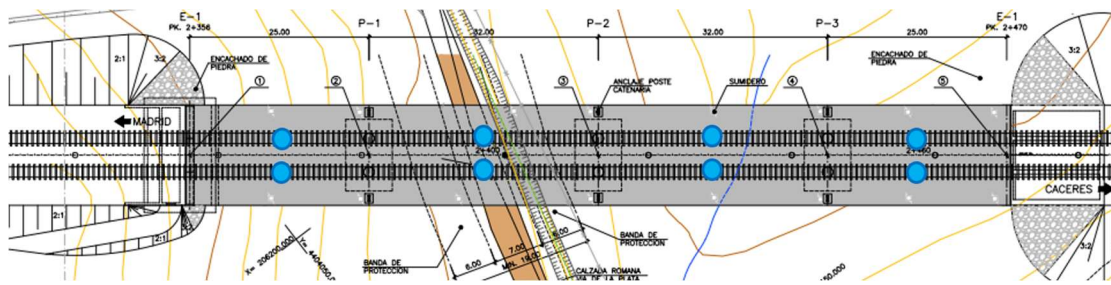


Figure 50. Strain gauges location (plan view)

Five hypotheses were planned for the static load test to evaluate the 4 spans and the 3 supports of the bridge. Three hypotheses with most of the load applied at the supports were defined to analyze the stresses produced by the negative bending moment. Additionally, two hypotheses with a considerable part of the load applied at the center of the spans were set to check the stresses generated by the positive bending moment, and for the verification of the maximum allowed vertical displacements. The positioning of the load and the data-acquisition at the location of the sensors were carried out following the next sequence:

- Step 0: Initiation of continuous measures acquisition.
- Step 1: Placement of the load at track 2.
- Step 2: Placement of the second load at track 1.
- Step 3: Checking of measures stability.
- Step 4: The load remains for a time of not less than 10 minutes, checking again the stability of the measures.
- Step 5: Track 1 load removal.
- Step 6: Track 2 load removal.
- Step 7: Verification of deflection recovery. It must be at least 85% of the maximum deflection measured.

Each of the executed hypotheses are described in Table 6.



Hyp.	Plan View	Elevation View	Descrip.
1			Maximum negative bending moment at pier 1.
2			Maximum negative bending moment at pier 2.
3			Maximum negative bending moment at pier 3.
4			Maximum positive bending moment at spans 1 and 3.
5			Maximum positive bending moment at spans 2 and 4.

Table 6 Description of the executed hypotheses for the static load test

### Dynamic Tests

The dynamic test was performed by the load train passing over one of the tracks through the entire bridge structure, to get physical parameters such as impact coefficient, damping and vibration frequency.

The dynamic test was executed by the following actions:

- Load train passing over the track at 5 km/h (pseudo-static test)
- Load train passing over the track at half of the maximum speed (40 km/h)
- Load train passing over the track at the maximum speed possible within safety conditions (80 km/h).
- Breaking test over the structure while the train passes over the track at maximum speed (80km/h).

As described in Fig. 51, two accelerometers were installed at the center of the inner spans.

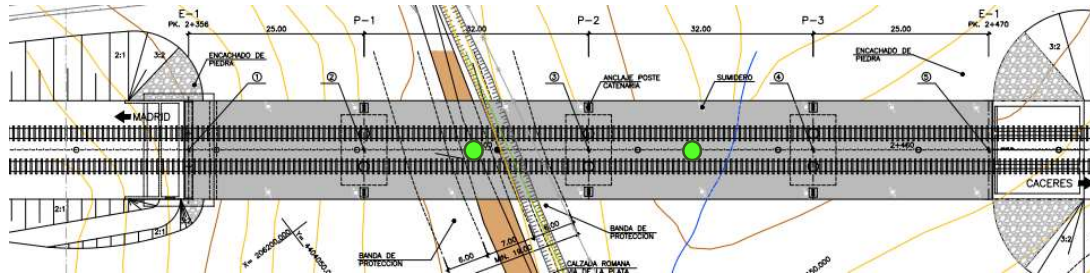


Figure 51. Accelerometers location (plan view)

In Fig. 52, the location of the accelerometers is shown for the cross-section of the bridge prestressed concrete slab.

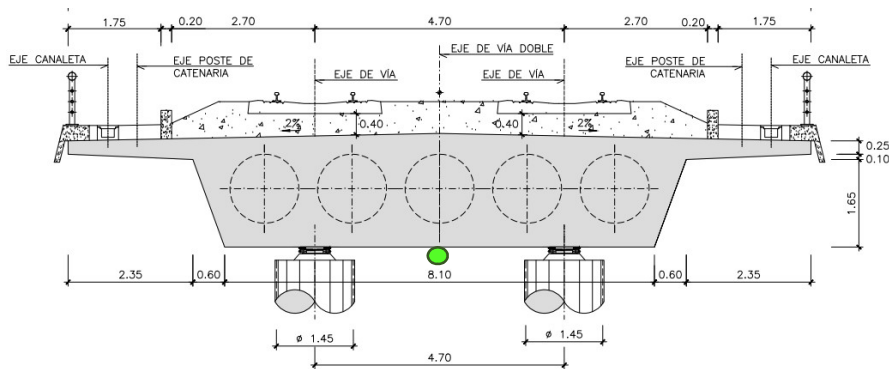


Figure 52. Accelerometers location (cross-section view)

During the Dynamic load test, accelerations were recorded for the three axes X, Y and Z, at the locations previously defined. LVDTs measures were also acquired during the dynamic load test at the locations of the static test.

### 2.3.2 STRUCTURAL ANALYSIS MODELS FOR RESULTS PREDICTION

#### Static load test mode

Preliminary FE-models were constructed based on frame elements representing the cross sections of the bridge deck. For the boundary conditions, displacements were restrained, and rotations were set up as free for all the supports (Fig. 53). It is worth mentioning that these models were not initially connected to the under-development tool at considerably early stages.

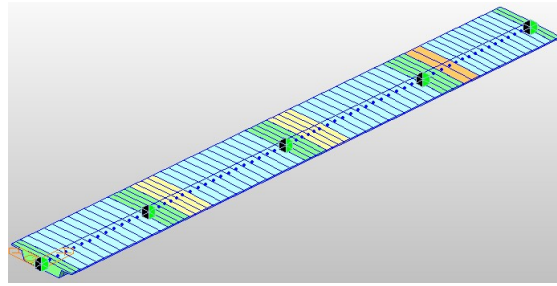


Figure 53. Static load test structural model

The load distribution was intended to be in accordance with the hypotheses planned for the static load test. These loads were applied to the central axis of the frame elements, assuming the effect of the surcharge in both tracks. Table 7 shows the applied loads in the structural model, following the weights of the load trains supplied by the administration of the bridge. The elastic young model was defined as 32.22GPa, considering the elapsed time since the construction of the viaduct.

Hyp.	Model View	Descrip.
1		Maximum negative bending moment at pier 1.
2		Maximum negative bending moment at pier 2.
3		Maximum negative bending moment at pier 3.
4		Maximum positive bending moment at spans 1 and 3.
5		Maximum positive bending moment at spans 2 and 4.

Table 7 Load applied to the model for each hypothesis of the static load test



Table 8 presents the results of bending moments and deflections for each of the hypotheses planned for the static load test.

Hyp.	Diagrams	Results (E=32.22GPa)
1		M- max P1: -10304.77kN-m
		$\Delta$ max Span2: -2.72mm
2		M- max P2: -12016.63kN-m
		$\Delta$ max Span2: -2.42 mm
3		M- max P1: -9154.72 kN-m
		$\Delta$ max Span2: - 2.10 mm
4		M+max Span1: 8223.29 kN-m M+max Span3: 6310.15 kN-m
		$\Delta$ max Span1: - 2.42 mm $\Delta$ max Span3: - 2.77 mm
5		M+max Span2: 9075.69 kN-m M+max Span4: 5395.24 kN-m
		$\Delta$ max Span2: -3.89 mm $\Delta$ max Span4: -1.60 mm

Table 8 Predicted bending moments and deflections for the static load test hypotheses.



Dynamic load test model

A dynamic structural model has been generated considering the variability of the cross sections of the bridge deck. Dynamic behavior was analyzed for the vertical plane, and in some cases for the torsional and bending components according to the instrumentation performed. The permanent loads were included in the model as masses, as it is shown in Fig. 54. Table 9 presents the obtained vibration frequencies for different modes.

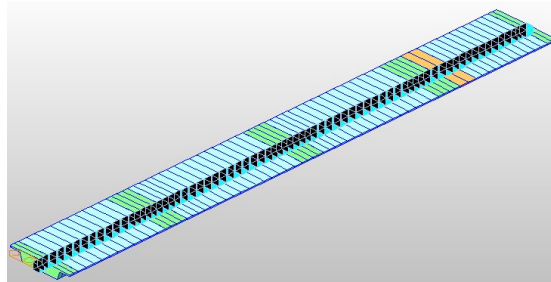


Figure 54. Dynamic load test structural model

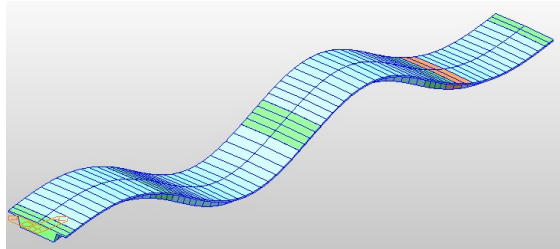
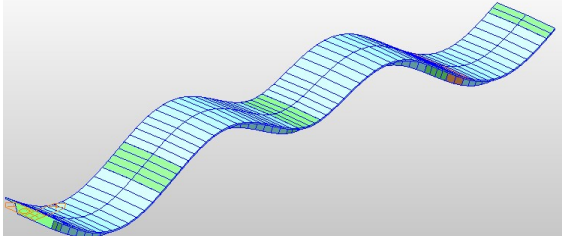
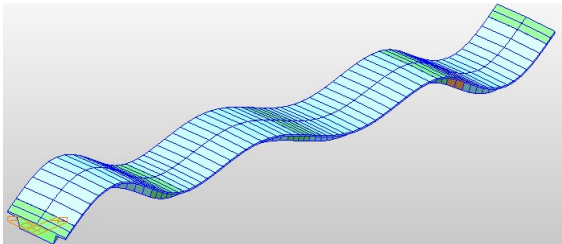
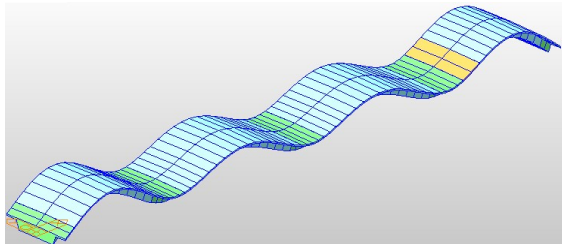
Mode	Frequency	Deformed Shape
1	3,64 Hz	
2	4,93 Hz	
3	6,64 Hz	
4	7,28 Hz	

Table 9 Predicted vibration modes for dynamic test analysis.

The first vibration mode presents vertical bending of the prestressed bridge deck with a frequency of 3.46Hz. From modes 2 to 4, similar to mode 1, vertical bending is the principal stress, but with frequencies from 4.93Hz to 7.28Hz. Mode 5 presented a vibration frequency of 13.42Hz, therefore, after mode 4 every following mode was discarded, given that frequencies greater than 10Hz are considered superior order modes.

### 2.3.3 DATA-COLLECTION

After the execution of the load test, data was collected for LVDTs, strain gauges and accelerometers. Examples of the collected data are presented in Fig. 55 to Fig. 58.

- Vertical displacements at the midspan of span 3 during the static load test:



Figure 55. Vertical displacements at the midspan 3 (static load test)

- Accelerations at the center of span 2 for the pseudo-static test (5km/h):

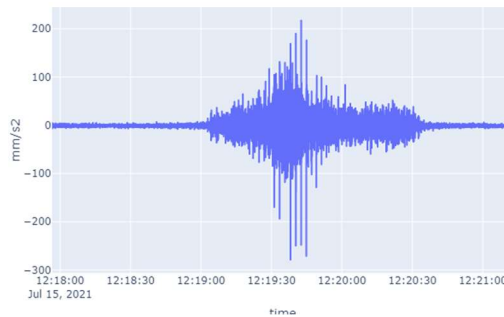


Figure 56. Accelerations at the midspan 2 (pseudo-static test: 5km/h)

- Accelerations at the center of span 2 for maximum speed test (80km/h):

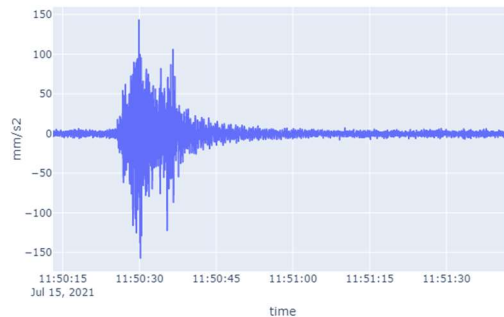


Figure 57. Accelerations at the midspan 2 (max speed 80km/h)

- Vertical displacements at the center of span 1 during dynamic load test for maximum speed (80km/h):

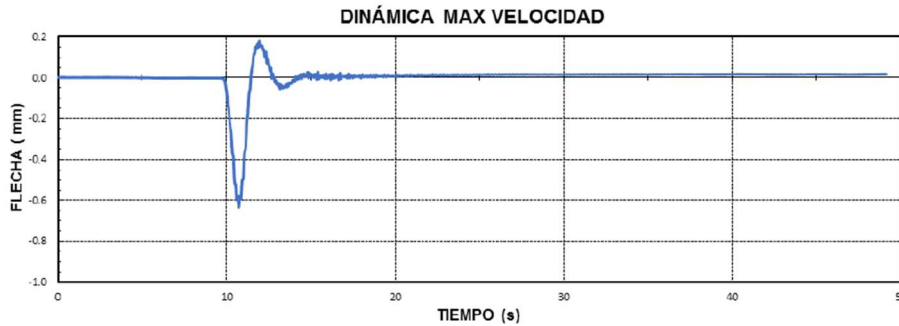


Figure 58. Vertical displacements at the midspan 1 (max speed 80km/h)

This data was processed for the Validation and Verification of the structural performance of the bridge, to decide if the initiation of the operational phase is viable.

## 2.4 IDENTIFICATION OF DIGITAL TWIN COMPONENTS

The DT main components are (1) The Physical asset, (2) The Virtual asset and (3) The Data that connects them. This connection requires a workflow of procedures as Fig. 59 illustrates.

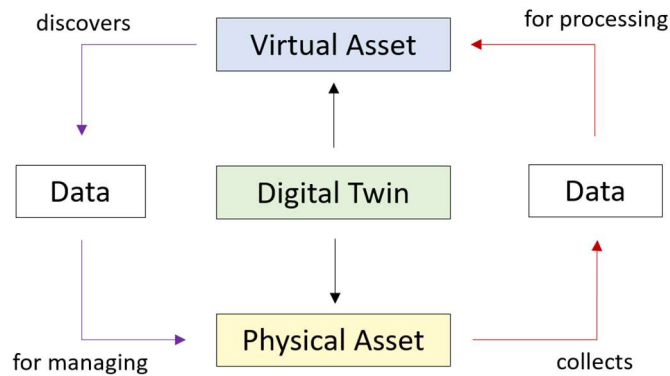


Figure 59. Main components of a Digital Twin

In this section, the construction of the virtual asset, data collection, data processing, data discoveries and data for management, are identified as a set of recommendations for the development of a DT of bridges in the context of load testing for demo 1 (A high-speed railway in Spain). These procedures were performed with the support of scripts developed within Grasshopper.

### 2.4.1 VIRTUAL ASSET

The adoption of digitalization in the AEC sector has been greatly enhanced by Building Information Modeling (BIM) technology. BIM improves the generation and exchange of data within a collaborative environment that considers multiple and diverse stakeholders. A digital twin (DT) paradigm is an information construct that consists of a physical asset, its identical digital representation, a virtual asset, and a data connection between them. This construct becomes the living version of a BIM model. Therefore, a virtual asset for a DT must be generated in a BIM-based environment with accurate geometry representation, spatial location, and metadata properties.

The generation of the virtual asset is crucial, and it requires thoughtful development for the inclusion of many stakeholders. The Level of Development (LoD) is among the current standards in BIM that define the amount and degree of building information that needs to be defined in a BIM model. This not only includes the level of detail of the graphical objects but also the data associated with the physical characteristics of the objects, their sources, their traceability, their as-built characteristics or singularities, and so forth. Catalogues and standards are available to specify a target LoD. The Level of Development specification for Building Information Models (Bedrik et al. 2020) is a well-known reference tool that defines the characteristics of LoD for multiple elements of buildings and infrastructure.

When it comes to load testing, a DT of an asset should follow a similar categorization based on existing industry standards, with added features such as embedded sensors, network capabilities, and comparison and update of multi-physics simulations. However, many existing infrastructures and infrastructure systems have never been virtualized accordingly, or there may be no information available at all. In such cases, scarce or out-of-date information found in drawings may be the only source of information for those in charge of virtualization. To generate the virtual asset of existing infrastructure, a considerable effort is required to initiate its Digital Birth.

Current practice and market-available techniques suggest several means for digitalizing the physical and geometrical characteristics of an asset. Firstly, the traditional creation of virtual geometrical models from 2D drawings. Secondly, digitizing the asset using laser scanning techniques, in which the reflected radiations of the physical asset are gathered in the form of point clouds. Thirdly, digitizing the asset using cameras, in which the emitted radiations of the physical asset are gathered in the form of imagery that is subsequently transformed into point clouds.

#### 2.4.1.1 Available information

In the framework of bridge load testing, there are three possible scenarios regarding the information available to generate a virtual asset of a DT.

##### No information

Load testing is required as a part of the maintenance plan of an existing asset. Depending on the age of a bridge, any information may be available to construct a

digital model. In these cases, it is necessary to collect data from the site. Currently, there are two principal means to digitizing an asset when no data is provided.

Firstly, by using laser 3D scanning techniques, in which the reflected radiations of the physical asset are gathered in the form of point clouds. 3D scanning techniques provide advantageous features during the digital birth of the asset. Full Scan-to-BIM processes are becoming increasingly sophisticated in the digitalization of assets, where manifold data pipelines are being established from raw point clouds to semantically rich 3D models.

Secondly, by digitizing the asset using cameras, in which the emitted radiations of the physical asset are gathered in the form of imagery that is subsequently transformed into point clouds. With the explosion of high-quality cameras, unmanned aerial and ground vehicles, and smartphones, a massive record of imagery of build assets is expected. Image-to-BIM is understood as the process of generating semantically rich IFC-based BIM models using a set of images. It is worth pointing out that two steps are identified. The first step corresponds to the generation of a point cloud from image interpretation whereas the second step is the treatment of the point cloud itself.

### 2D Drawings

Normally, administrations provide 2D drawings of the asset as PDF files or CAD drawings. In this scenario, manual digitalization is required. Methods and procedures for the automatic extraction of data directly from scanned drawings are a tremendous challenge. Identification and geometry generation from 2D drawings are relatively easy tasks when it comes to digitalizing single elements that require extrusion. However, complexity scales very fast when multiple perspectives and scales are to be digitized from drawings with heterogeneous data, as is the case of bridges. Consequently, as automatic development becomes impracticable, the digitalization of drawings becomes faster by using human power and 3D development from scratch.

In this sense, it should be also taken into consideration the fact that the physical asset could not perfectly correspond to the digital replica obtained from design drawings, as errors and tolerances can appear during the construction process. Nevertheless, if “as-built” documentation is restricted thanks to technical issues or high costs, the digital model generated manually from drawings is valuable for constructing a virtual asset.

### 3D Digital Model

Digitalization of the AEC sector had increased in recent years, thus it is possible that the owner supplies a digital model of the asset, especially when a load test is required to check the structural performance of a bridge before putting it into service. In this scenario, it is recommended that the digital model be represented in the IFC schema with the correspondent semantic-rich data, enabling its integration with the Digital Twin platform and other openBIM software.

### 2.4.1.2 DEMO IMPLEMENTATION

For demo 1, the owner of the bridges, which is the public administrator ADIF, supplied PDF files of the drawings with CAD layers data. The digital models must be constructed with at least 350 LoD, to count with a reliable geometry of the elements and their properties. The process started with the import of the 2D CAD sections and elevations of La Plata Viaduct into the 3D Rhinoceros software. Through the extrusion of the existing 2D lines, 3D geometries were generated as Breps (Boundary Representation). By using scripts within Grasshopper, the constructed Breps were transformed into the IFC representation, including metadata regarding the technical project information. IfcBridge and the IfcMaterials entities were created. Then, IfcBeams, IfcColumns, IfcSlabs, and IfcWalls were added to the model. Finally, the semantic-rich IFC model of the bridge is uploaded to the Digital Twin online platform, where is available for the stakeholders involved. Fig. 60 shows the pipeline of La Plata Viaduct virtual asset generation.

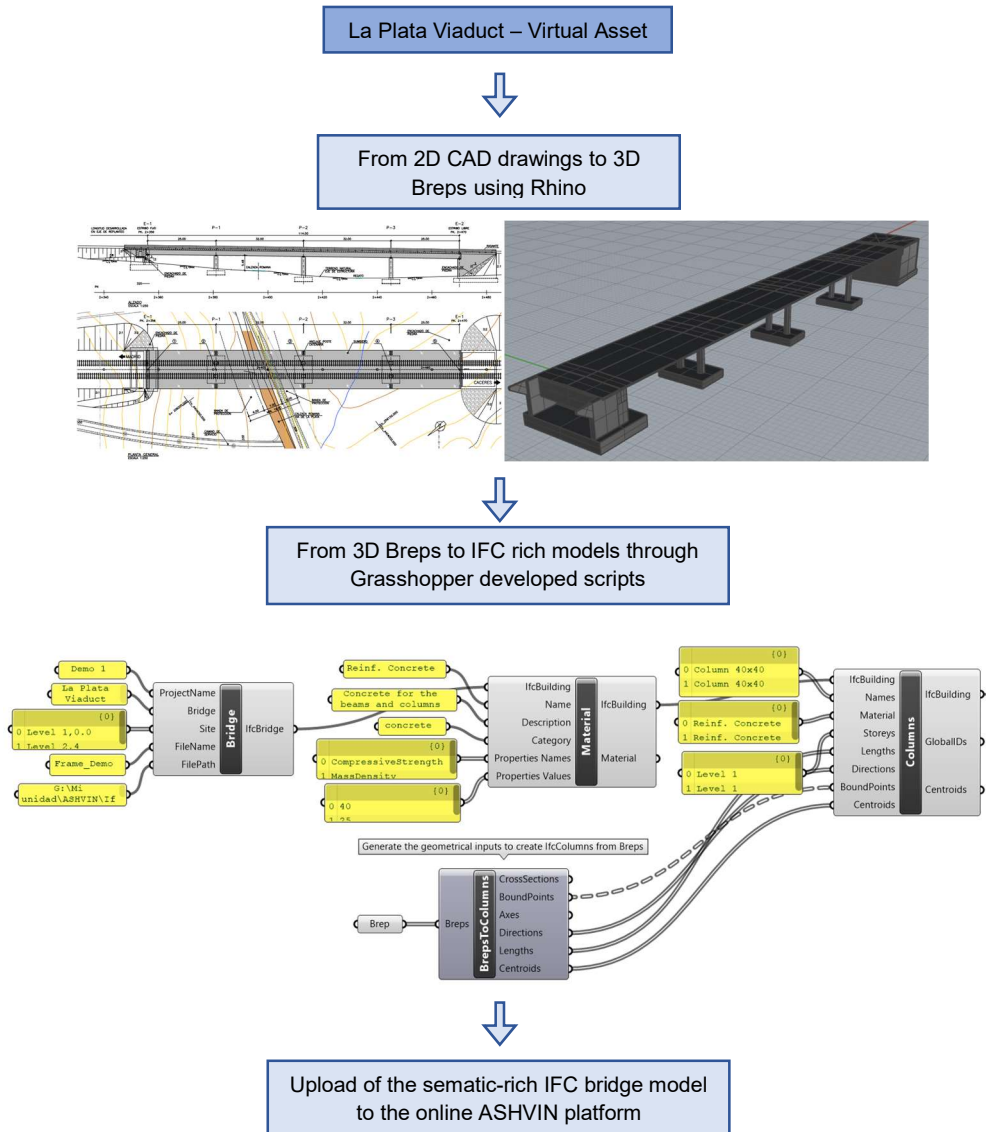


Figure 60. Pipeline for La Plata Viaduct virtual asset generation



## 2.4.2 DATA COLLECTION

Within the main basis of the DT paradigm, data collection plays a key role to achieve a reliable virtual representation of the physics of a real asset. The fidelity of the sensor data-based simulations for a DT technology relies on the inputs for the simulation, which depends on sensor quality, accuracy, and precision.

In the context of bridge load testing, it is necessary to design a project for the execution of the load test, describing the procedure and including the type, amount, and locations of the sensors.

The load testing project must follow the requirements specified in the corresponding national standard and aims to ensure data quality for the following verification of the bridge structural performance.

Furthermore, collected data from sensors must be properly stored and available for structural engineers and Digital Twin platform users. It is required to add sensors to the existing BIM model of the bridge, enabling friendly user accessibility to the sensors' data.

A DT of a bridge for a load test should connect the physical and the virtual realms. This depends on collecting large volumes of data at project sites. An IoT platform emerges as a solution to achieve successful and secure storage of collected data. For this purpose, Mainflux platform is being developed within the project. Its functionalities and characteristics are defined in section 1.4.

The goal of performing data collection for constructing a Digital Twin paradigm is to effectively integrate sensors, measures and the virtual asset, avoiding disaggregate layers of information and reducing data loss risk.

### 2.4.2.1 Demo Implementation

To implement data collection for Demo 1, a load testing project was analyzed, sensors were added to the IFC-BIM model of the bridge, measures were stored, and then data was uploaded to the IoT platform. Each of these steps are described below.

#### Load Testing Project

In Spain, the national standard NAP 2-4-2.0 regulates the load testing of railway bridges. This code requires a Load Testing Project, a document that must include an analysis of the previous documentation, a theoretical analysis of the structure, the purpose of the load testing, the magnitudes to measure, the measures locations, and the procedure of the measurements.

For La Plata viaduct, the Load Test Project defined a total of 23 sensors: 13 LVDT (Linear Variable Differential Transformer) for vertical displacements, 8 strain gauges and 2 accelerometers. Fig. 61 shows the type and location of each sensor.

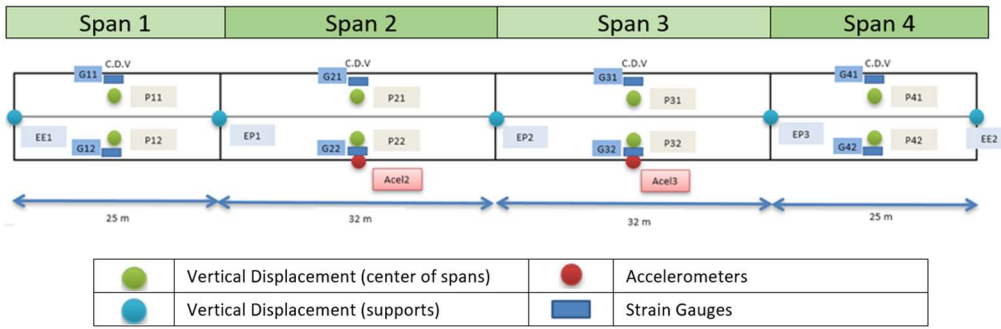


Figure 61. La Plata viaduct type and locations of sensors for the load test

Following the procedure described in the Load Testing Project, data was collected for static and dynamic tests.

### Sensors to IFC-BIM model

To allow access to sensor data within the Digital Twin platform, sensors should be added to the IFC-BIM model following the Load Test Project. This is possible by implementing the relations defined in the IFC schema, as shown in Fig. 62.

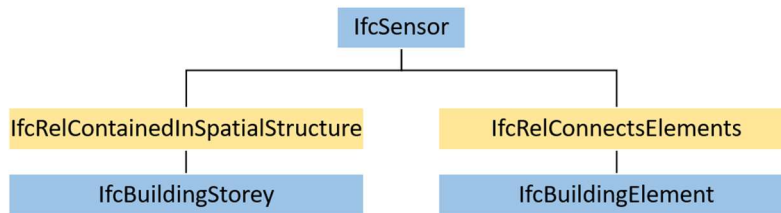


Figure 62. IFC relations to add sensors to a BIM model

The inputs of the component are the IFC model along with the name, description, parent, location and tag of the sensor. As output, users get the updated IFC model with the global IDs and the location of each created sensor. Global IDs are key to linking the sensors to IoT or Digital Twin platforms.

### Tasks for measures to BIM model

The sensors added to the BIM model must be related to tasks for measures according to the Load Test Plan. For this purpose, the IFC schema is implemented and IfcWorkPlan, IfcWorkSchedule, IfcWorkCalendar and IfcTasks are added to the IFC-BIM model. Fig. 63 presents the IFC relationships to properly add those entities.

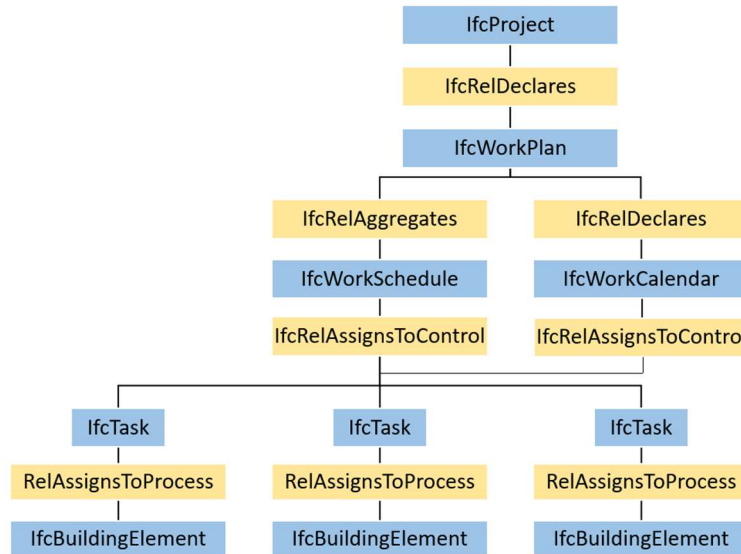


Figure 63. Tasks for measures during the load test

Storage of measures

For LVDTs and strain gauges, measures extracted from the corresponding commercial equipment were saved as CSV files. Accelerometers were set up as a wireless hardware module connected to a Wifi local network provided by a mobile phone to send measures to a laptop, where a python script performs time synchronization and data storage as CSV files (Fig. 64).



Figure 64. Preparation of accelerometers during testing

The information for a V&V of a load test does not have to be immediately available, real-time cloud storage in the IoT platform is not necessary. At locations where internet access is not possible, storing measures in SD cards is an efficient practice.

Data upload to IoT Platform

Data from sensors were uploaded to the Mainflux IoT platform. First, a *Channel* is defined within the IoT platform to connect all data sources of the load testing for La Plata viaduct. Then, for each sensor, *things* are created, which represent data sources in Mainflux. It is mandatory to assign as *thing* ID the same global ID that the sensor has in the IFC-BIM model. In this way, it is possible to retrieve sensor data within the Digital Twin platform. Data is uploaded through the user's credentials, a *subtopic* to identify the data, the *message* containing the data, and the *thing* which is the source of the data (Fig. 65).

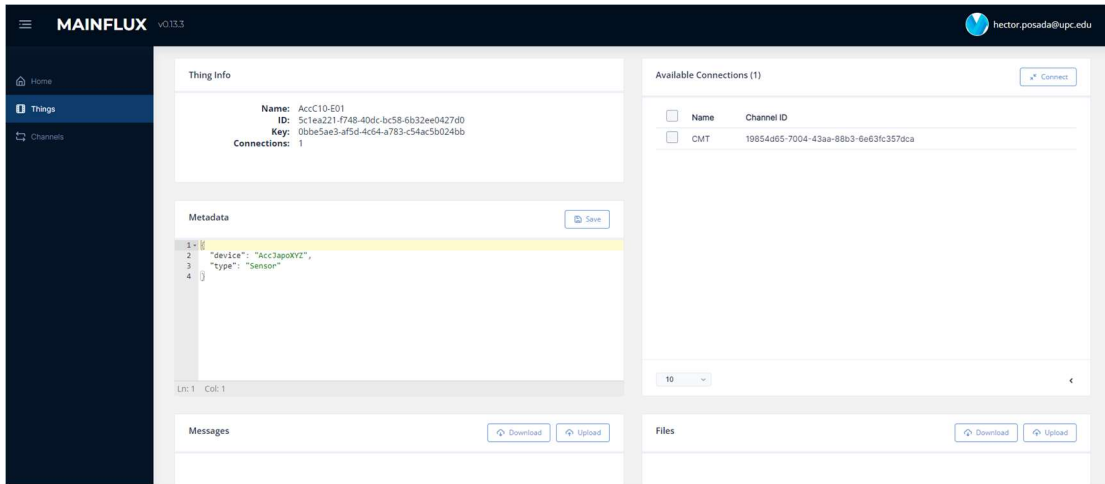


Figure 65. Sensor data uploaded to the IoT platform

For instance, users on the Digital Twin platform can retrieve sensor data by clicking it, given that they share the same ID with the *thing* that holds the data in the IoT platform (Fig. 66).

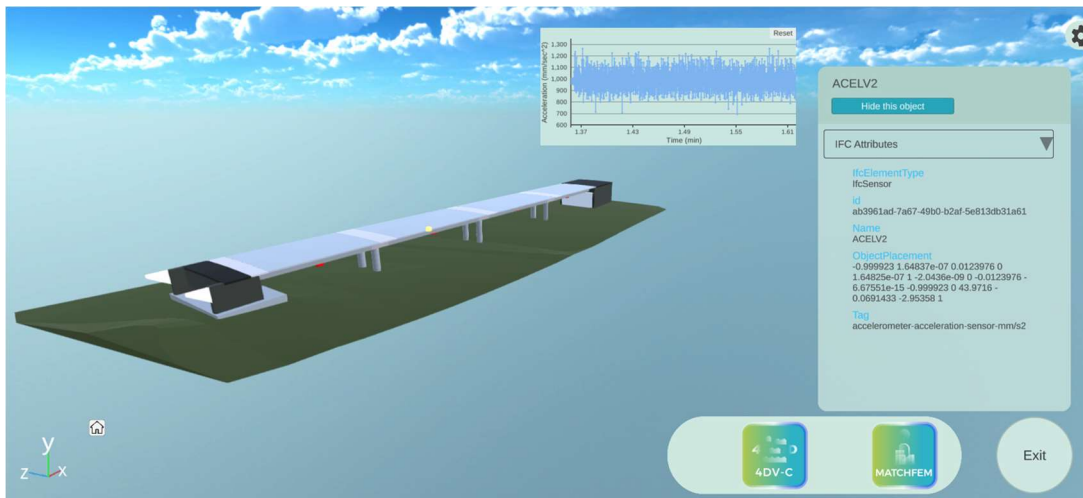


Figure 66. Sensor data retrieved in the Digital Twin platform

### 2.4.3 DATA PROCESSING

Collected sensor data enables a bridge between the real and the virtual realms. However, this data is initially raw and requires processing to accomplish a reliable representation of the asset physics that are relevant for its management. In addition, some sensors collect measures as voltage signals, so is mandatory to convert these signals into the target physical magnitudes.

#### 2.4.3.1 Demo Implementation

As indicated in the Spanish national standard for load testing of railways bridges (NAP 2-4-2.0), the verification of the structure performance demands an analysis of the structure frequencies, displacements and strains. Therefore, data from accelerometers, LVDTs and strain gauges require processing to get the physical magnitudes for checking the asset behavior during the load test.

Implementing Grasshopper scripts, engineers are able to estimate the vibration frequencies of the structure, the maximum displacements at the center of the span, and the maximum strains at locations of interest.

Fig. 67 shows how users can get the results required by the mentioned standard through a Python script. The inputs are the sensor ID, the name of the load test hypothesis, the displacements at the center of the span, the displacements at the supports, and the predicted deflection according to the structural analysis model. As output, users get the span deflection, the ratio between measured and predicted deflections, the residual deflection, and the recovery ratio.

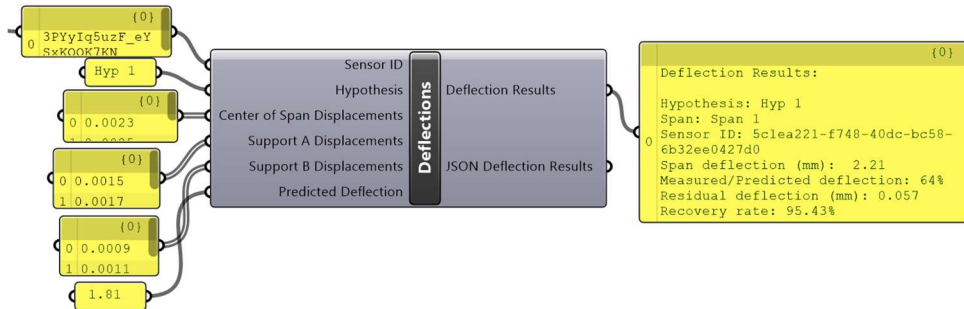


Figure 67. Deflection results for load test checking using a python script within Grasshopper

Additionally, the component generates the deflection results in JSON format, allowing the upload of the information to the IoT platform, then, is possible to retrieve the processed data into the Digital Twin platform.

### 2.4.4 DATA DISCOVERIES

A DT technology should be able to apply embedded engineering models, Artificial Intelligence, or other methodologies to generate high-quality information, meaningful to the management of an asset, which enables reasoning and knowledge for data

discovery capabilities. Simulations must represent the physical phenomenons of an asset with great accuracy, through sensor-based data. This should lead to predictions of successive time scenarios, implementing current and previously measured parameters. Forecasting the behavior or health of a building or an infrastructure is usually required for DT technology. Results of the predictive models should be used for management tasks on the physical asset as a reaction to data discoveries. In the framework of bridge load testing, the predictive models are the structural analysis simulations of the load hypothesis specified in the Load Testing Project. The results of these simulations must be compared with the processed data of the collected measures, to check the structural performance of the bridge.

#### 2.4.4.1 Demo Implementation

For demo 1, the structural analysis simulations are done to discover if the structural behavior of the bridge is ideal for initiating the operation phase. It is of interest for Digital Twin platform users, to access the results of the simulations. The pipeline to perform the simulations and upload their results to the platform requires the interoperability of diverse sources of information. This issue is overcome using Grasshopper's powerful parametric geometrical capabilities (Fig. 68). First, the existing IFC-BIM model of the bridge is imported into 3D Rhinoceros, where the topology of the structural analysis model is constructed (lines and points).

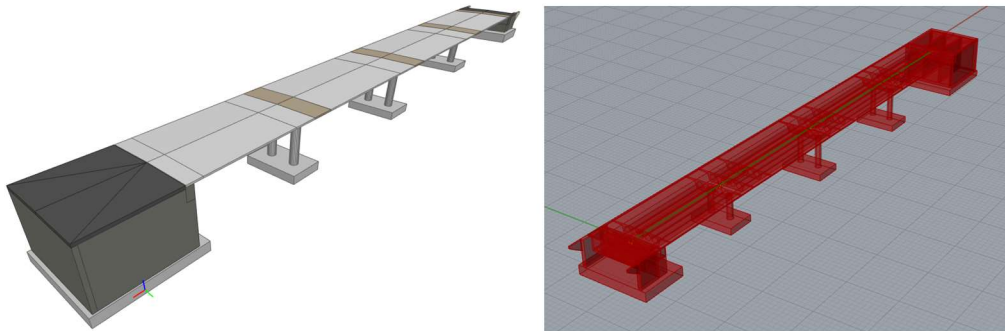


Figure 68. IFC-BIM model to Rhino for constructing the structural analysis model topology

Then, using developed Grasshopper components, the assembly of the structural analysis model is done following the StructuralAnalysisDomain of the IFC schema, enabling transferring the generated models into any commercial structural analysis software which allows the import of this open standard.

Fig. 69 shows the cross sections, boundary conditions, and loads of the generated La Plata structural model.



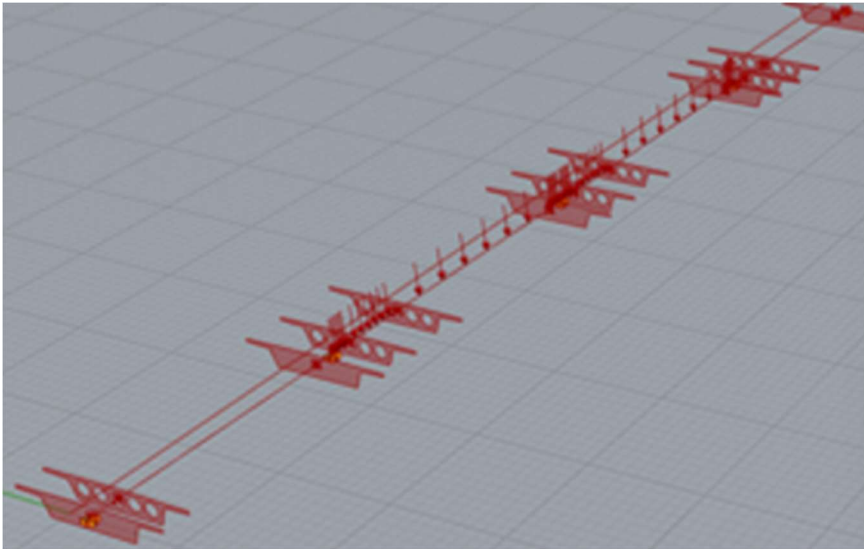


Figure 69. Generation of La Plata structural analysis model

After the construction of the structural model, the simulations can be performed in any commercial software which allows importing IFC Structural Analysis Domain entities. However, for demonstrations of procedures, a solver for continuous beams was developed within Grasshopper python scripts, enabling the analysis of the generated structural model (Fig. 70).

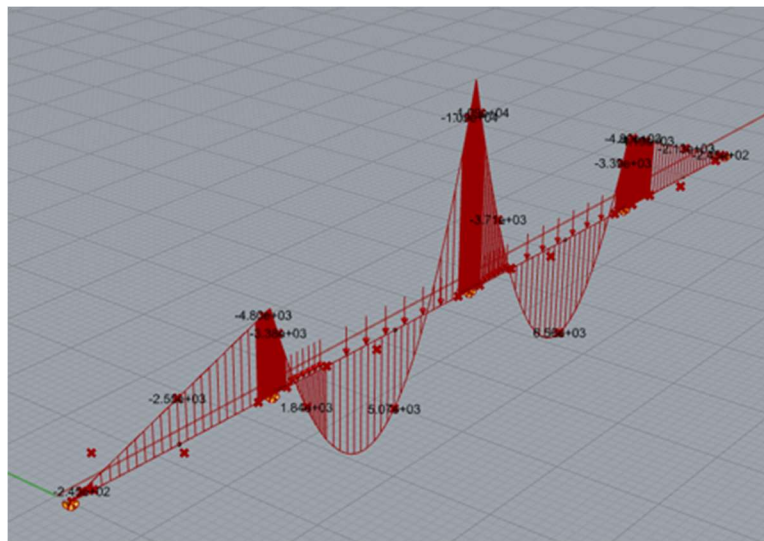


Figure 70. Bending moment diagram of the simulation of La Plata structural model

Simulations of the load hypothesis are executed and the bridge structural behavior is predicted. Results are converted into JSON format, for the following upload to the Digital Twin platform, where data is available for stakeholders involved in a user-friendly interface. Fig. 71 shows the results on the DT platform.

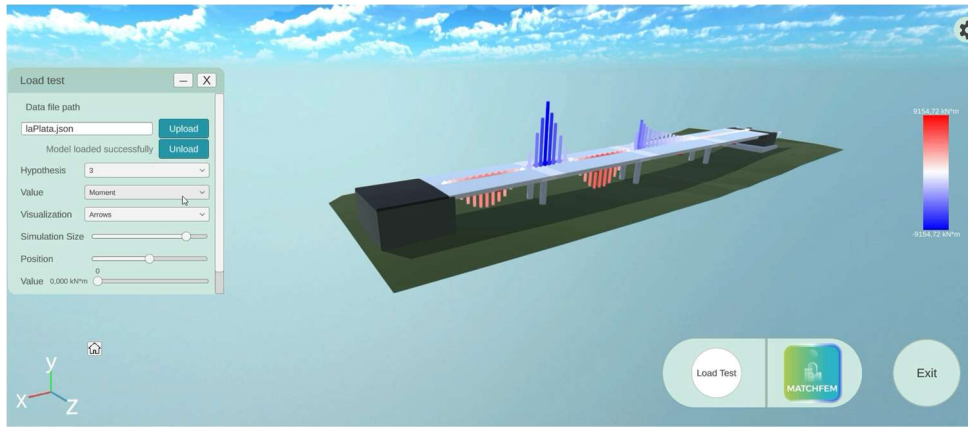


Figure 71. Structural analysis results in the Ashvin Digital Twin platform

## 2.4.5 DATA FOR MANAGEMENT

The final goal of the Digital Twin paradigm is to take informed decisions for the management of the physical asset. This aims to reduce costs, unsafety scenarios, or time wasted.

As mentioned before, in the framework of bridge load testing, managers should be able to decide whether the bridge is in optimal conditions to initiate or continue the operational phase of the infrastructure.

This informed decision should be done by having access to the final report of the load test, which specifies if the ratios of structural performance are within the range established in the corresponding national standard for load testing.

### 2.4.5.1 Demo Implementation

In the Spanish national standard for load testing of railways bridges (NAP 2-4-2.0), it is required to deliver a Load Test Report, indicating the executed Load Test Plan along with the results, analysis, and conclusions.

The main ratios performance and other significant information for deciding if the bridge accomplished the requirements of NAP 2-4-2.0, should be accessible to the managers and administrators of the highspeed railway.

For this purpose, by the MatchFEM Verification and Validation functionality, the automation of the Load Test report is possible. This report is accessible to the bridge administrators, along with the virtual asset which holds the information of the load test, enabling the decision of validating the beginning of the operational phase of the physical asset.

## 2.5 EXEMPLARY ACTIONS FOR TARGET USERS.

### 2.5.1 TARGET USERS

The development of a new tool that matches the needs of different target users is a challenging task. MatchFEM is conceived to be user-friendly, flexible, and effective for diverse industries. It is a tool that can be used by engineers, designers, supervisors, and asset owners who want to improve the knowledge about the performance of their assets.

The first target user of this tool is the set of designers of an asset who foresee key scenarios the asset will overcome during construction and operation life cycle stages. As a matter of fact, during the design phase, designers identify potential issues that may arise during the construction and operation of the asset. They are entitled to create the basis for a digital twin that is able to simulate various scenarios, embed simulations and test different solutions to mitigate the risk of these scenarios. On the one hand, this tool allows designers to create a digital twin that can be used to test different scenarios. On the other hand, the tool allows to prepare the virtual elements for the future installation of sensors.

The second target users of this tool are the engineers who are actually developing a digital twin including simulations and measurements of an asset for the first time. Engineers have a specific interest in the verification and validation of the virtual data to ensure that it accurately represents the physical asset. They need to have a tool that can help them identify potential errors and inconsistencies in the digital twin. This tool provides them with the ability to create a digital twin with a known level of accuracy and reliability.

The third target users are the managers and/or supervisors of an asset during construction who are interested in feeding the models with updated information. The digital twin exists for them, and they are active users. During the construction of an asset, there is a need to constantly monitor and update the digital twin to reflect the changes that are taking place. The supervisor needs to have a tool that can help them keep track of the progress of the construction and update the digital twin accordingly. This tool provides supervisors with the ability to monitor and update the digital twin with ease.

The fourth and final target user of this tool is the owner/infrastructure managers of the asset who continuously verifies its performance and reacts to potential malfunctions. After the asset is in operation, the owner needs to continuously monitor its performance to ensure that it is running efficiently. They need to have a tool that can help them identify potential malfunctions and take action to rectify them. This tool provides asset owners with the ability to monitor the performance of their assets and take action when needed to ensure that they are running efficiently.

### 2.5.2 DESIGNING MONITORING STRATEGIES

Designing monitoring strategies at design is an efficient preparation of the digital twin. The development of structural models during design is a routine task. Insightful information can already be used to simulate different scenarios in which potential monitoring needs are identified and later communicated to construction managers. An informed execution plan of such strategy together with Software tools can be used. MatchFEM allows the establishment of a data flow that enable this process at this stage. Fig. 72 illustrates the process in terms of actions to be performed, whether they are performed in the digital or the physical realm. The specific stakeholders involved in the development of the strategy are pointed out.

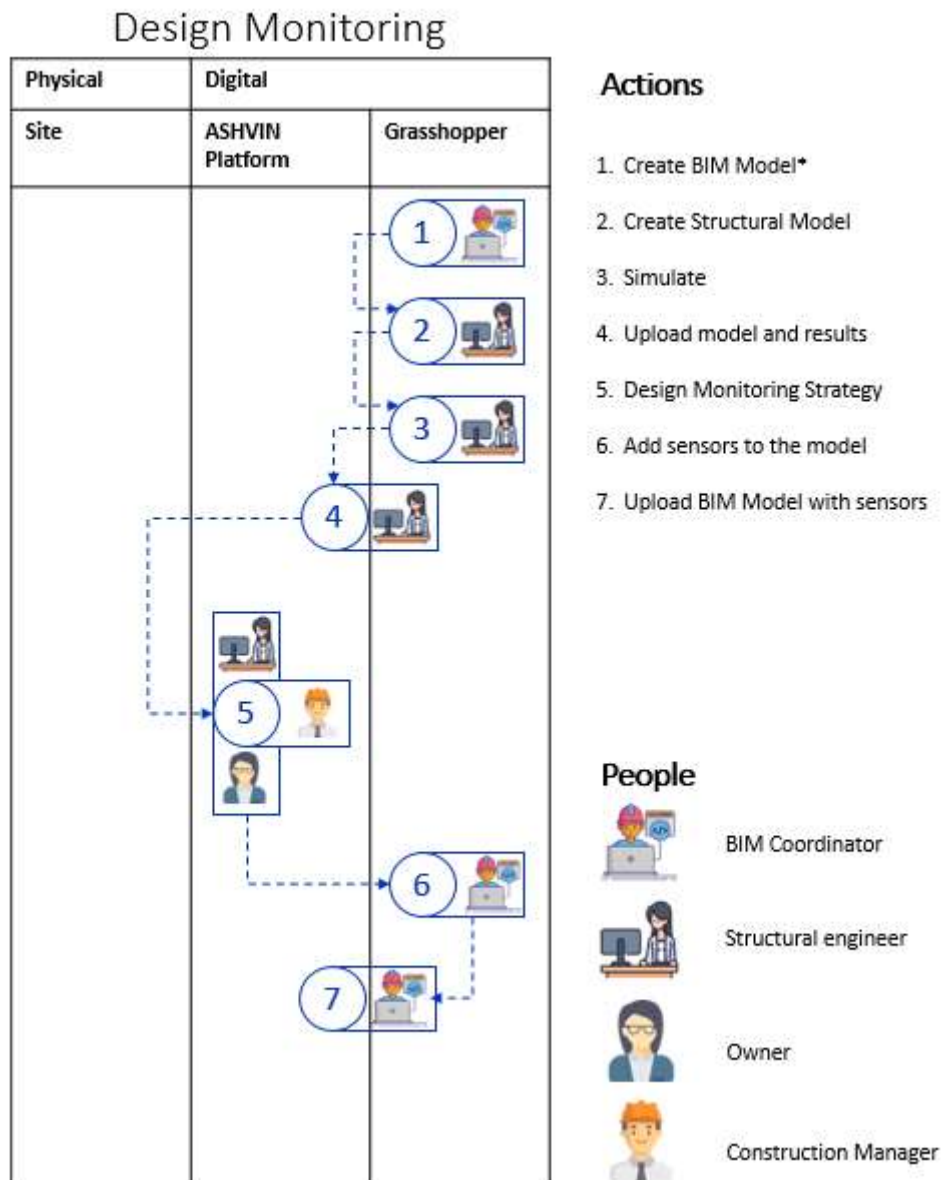


Figure 72. Ashvin vision for planning monitoring strategies at design stages

First, establishing accurate virtual representations (geometry and simulations) of the asset is a need (Actions 1 to 4). Insightful information suggests the design of a monitoring strategy (Action 5). Thus, embedding monitoring systems that are semantically linked to the virtual representation of the asset is the subsequent step in the digital twin-based design monitoring plan process (actions 6 and 7). For this purpose, a single BIM model is defined explicitly connecting the asset's elements and different sets of sensors. The location and characteristics of these virtual sensors are determined by the needs identified by previous structural simulations.

The developments of MatchFEM Grasshopper components provide a series of tools to perform this digital assembly between assets and monitoring systems. It enables computing structural simulations and creating BIM models within the same environment. A direct connection with the platform allows exchanging information seamlessly. Therefore, BIM, sensors and simulations can be uploaded to the platform and be jointly displayed through its interface. This generates a proper collaborative environment for structural engineers, owners and construction managers to decide which systems to acquire and install on-site.

### 2.5.3 VERIFICATION AND VALIDATION

Another target user is the set of individuals performing the process of verification and validation of a load test. This implies verification and validation of existing models used for design and for the understanding of the behaviour of the asset. Fig 73 illustrates the process in terms of actions to be performed, whether in the digital or the physical realms. The specific stakeholders involved in the development of the strategy are also pointed out. Load tests are an excellent example since it is an existing routine episode of verification and co-existence between measurements and simulations. These tests are carried out on the vast majority of bridges.

To enable the digitization of the validation of a load test, the process must be performed on top of already adequate (perhaps existing) virtual representations of such bridges (BIM geometries). This completes the co-existence with existing information. If not available, the BrIM model of the asset needs to be created and uploaded to the platform to establish the basis for further enrichment of the model with other layers. These are the actions found in Fig. 73 (Actions 1 to 5)

Once the Ashvin platform contains the virtual representation of the bridge, operation managers can create a new digital load test through the platform interface. This opens a slot within the bridge information construct to allocate all the information regarding such load test according to the model exposed in Figure 41. This initial set-up of the load test requires the user to interact with the interface to provide information about how many tests will be performed (dynamic and static), select measurement equipment that will be used in each test (which representation is already modelled in the BIM) and which standard is being employed.

Then, based on the load test set up in the platform, structural engineers need to provide a set of simulations that are computed and uploaded to the platform using grasshopper components. Measurements can be then planned by the operation manager based on the simulation results visualized in the platform interface.

As-planned measurements are performed on-site (6 and 7). IoT-enabled sensors can send information directly to the Ashvin IoT platform while more traditional measurement equipment requires uploading data manually through the platform's interface. Then, sensor data can be downloaded to be analysed and processed.

Once data and model results are available in the platform, rules defined in the corresponding standard for determining the validity of the test are applied automatically. Since the validation is based mainly on data-model comparison, the validation may require some iterations of adjusting model parameters to match the measured data (Actions 9 to12).

Finally, once validated, the load test information is permanently stored in the platform as a digital report of the assessment and will be a part of the bulk of information that future users can use to carry out better decisions on the maintenance of the asset. Additionally, calibrated simulation models are also stored for future simulation iterations (Actions 13-14). Sections 2.1 to 2.4 of the present document depict thoroughly these steps in the form of a set of recommendations to enable verification and validation of models during a load test.



## Verification and Validation

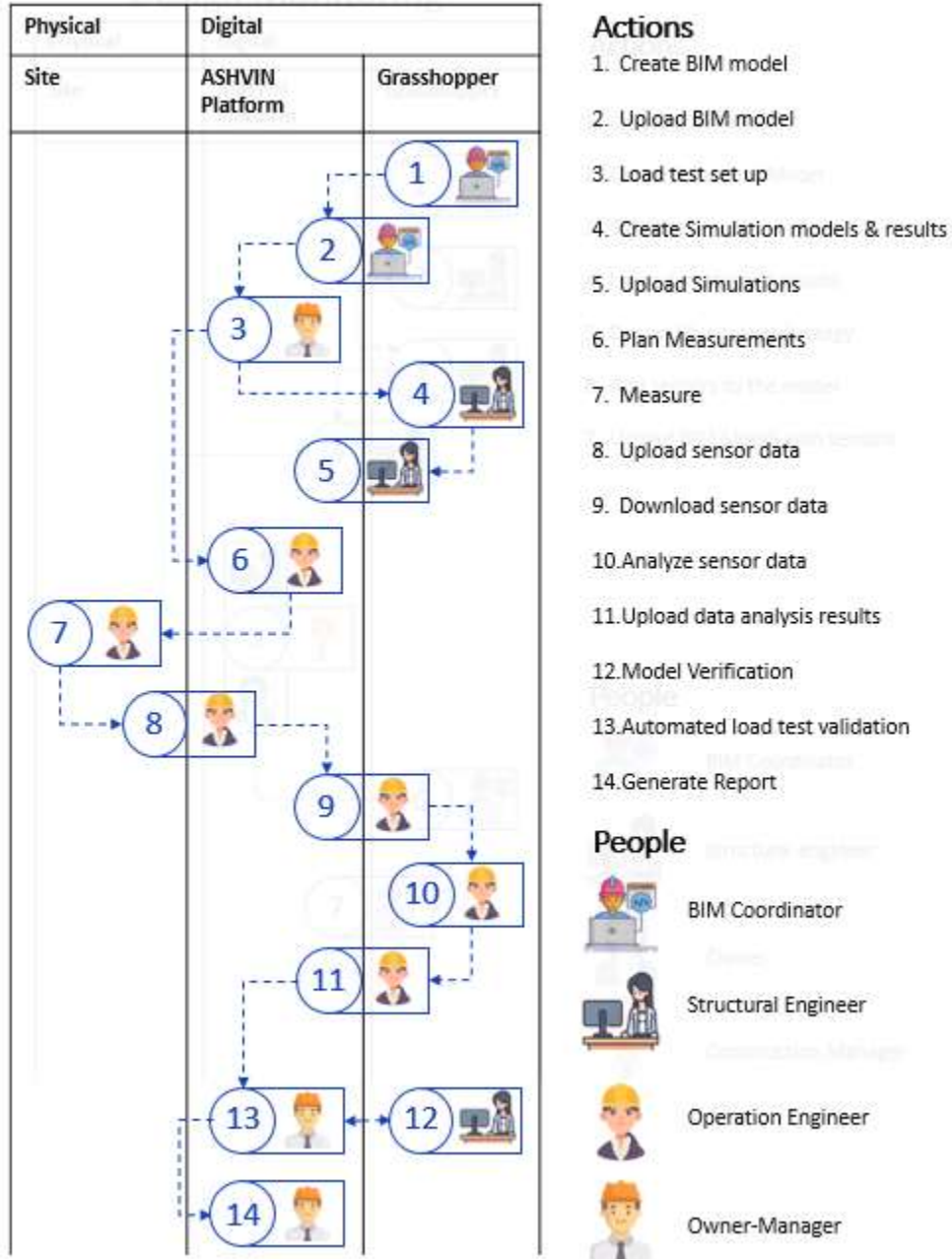


Figure 73. Ashvin vision for validation of load tests

### 2.5.4 FEED AND UPDATE MODELS

During the construction phase of a project, updating the structural analysis models with collected data from the project site gives realism to the simulations performed during the design phase. Construction managers and supervisors can use a digital twin to enhance the performance of the construction process. Models with more realistic geometrical conditions, rheological and other material properties, or boundary conditions, have the potential to support an enhanced data-driven decision-making

regarding construction activities. The expected users are i) technical supervisors and ii) construction managers. By implementing this functionality, users can discover possible issues and optimizations, enabling the commissioning of response actions.

One of the multiple stakeholders involved in a construction project is the technical supervisor of the construction of the structural elements, which is in charge of inspecting whether the construction works are being executed according to the design documentation, controlling the quality of construction products and equipment used, and checking the quality of the performed construction tasks. To perform the methodology and processes involved in Feed and Update, it is necessary to rely on BIM coordinators and structural engineers. Semantic-rich BIM models including sensors type, locations, descriptions and measurement tasks, support the data collection at the construction site. Constant simulations of structural analysis models fed with measured data from an asset enhance the representation of the real-world physics.

For Feed and Update, the plug-in enables the construction of structural analysis models in the IFC schema, including the structural elements along with their geometrical properties, materials, connections, loads, and boundary conditions. Structural engineers can perform simulations with design documentation or with data stored in the IoT platform as input, using the Grasshopper plugin. The uploading of models and results to the DT platform is also possible within the same parametric environment. Figure 55 describes the workflow of the Feed and Update functionality, identifying users and actors along with the tasks that each must complete.

A BIM coordinator must construct a semantic-rich IFC-BIM model, including the sensors and the tasks for measures related to them. A structural model is generated by the structural engineer depending on the progress of the construction, to perform simulations according to the casted structural elements. Construction managers should supervise the acquisition and store of data from the construction site. Structural engineers can feed and update models using data stored in the IoT platform as the input. Finally, after the upload of the simulations, technical supervisors and construction managers have access to the results of analysis and visualized KPIs in the DT platform which will support informed decisions making process. Fig. 74 illustrates this vision.

## Feed Models

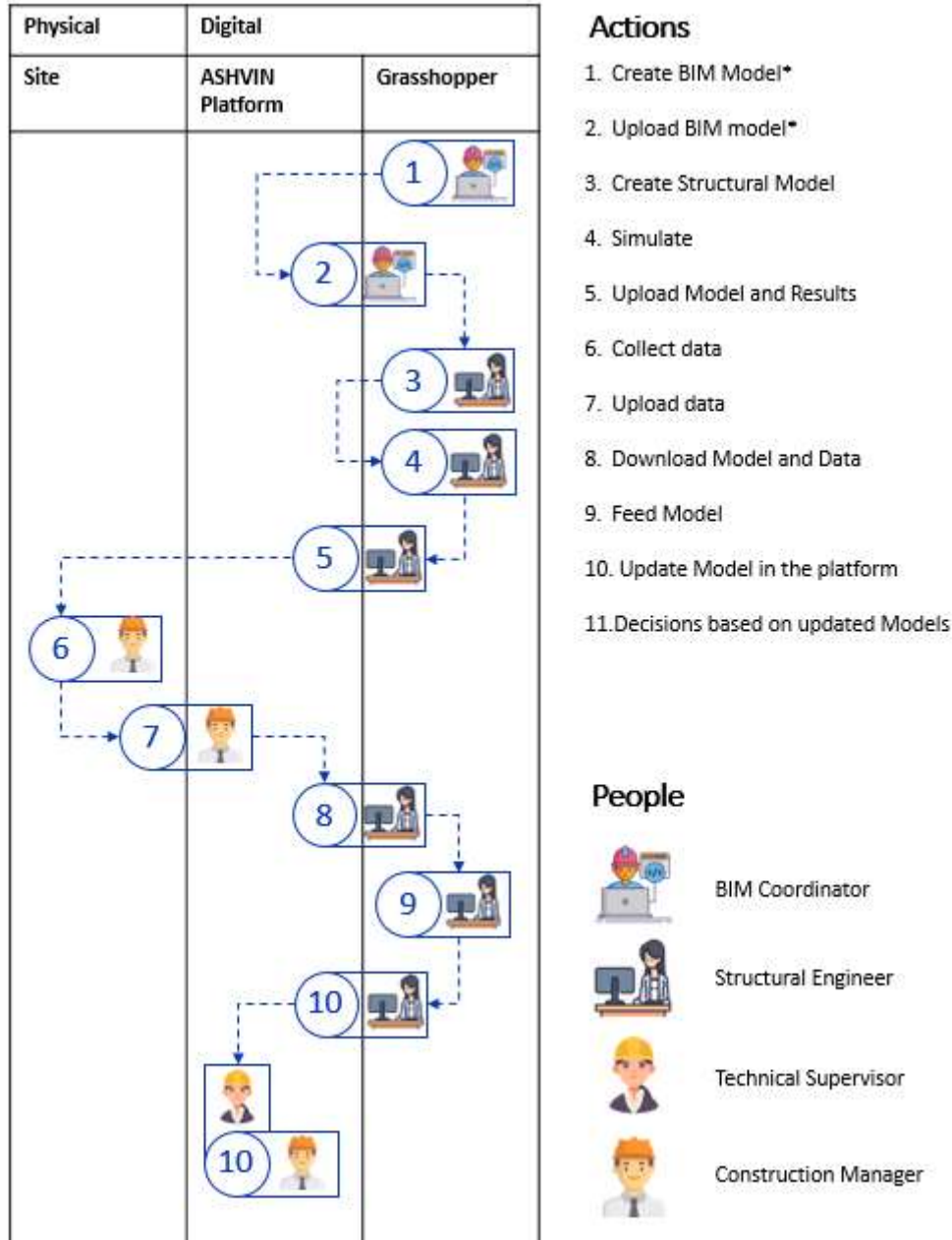


Figure 74. Ashvin vision for feeding and updating models

Feed and Update Models opens a wide range of potential applications for the construction of buildings or infrastructure. Within research and development project, one of the demonstrators is the construction of a reinforced concrete office building in Barcelona. One of the actions performed on this demonstrator, that can be of great interest to technical supervisors and construction managers, was the collection of the slabs' concrete temperature at early ages. With these measures is possible to estimate the concrete compressive strength evolution by implementing the standardized maturity index method (ASTM C1074-19e), generating an interesting scenario for the application of Feed and Update. Concrete compressive strength evolution is crucial for quality control and for construction tasks such as formwork striking and the post-

tensioning of slabs. Constantly feed and update the building’s structural analysis model with measured material properties, provides accurate and reliable simulations of the building’s physics. Fig. 75 presents how Feed and Update can be applied in the described scenario.

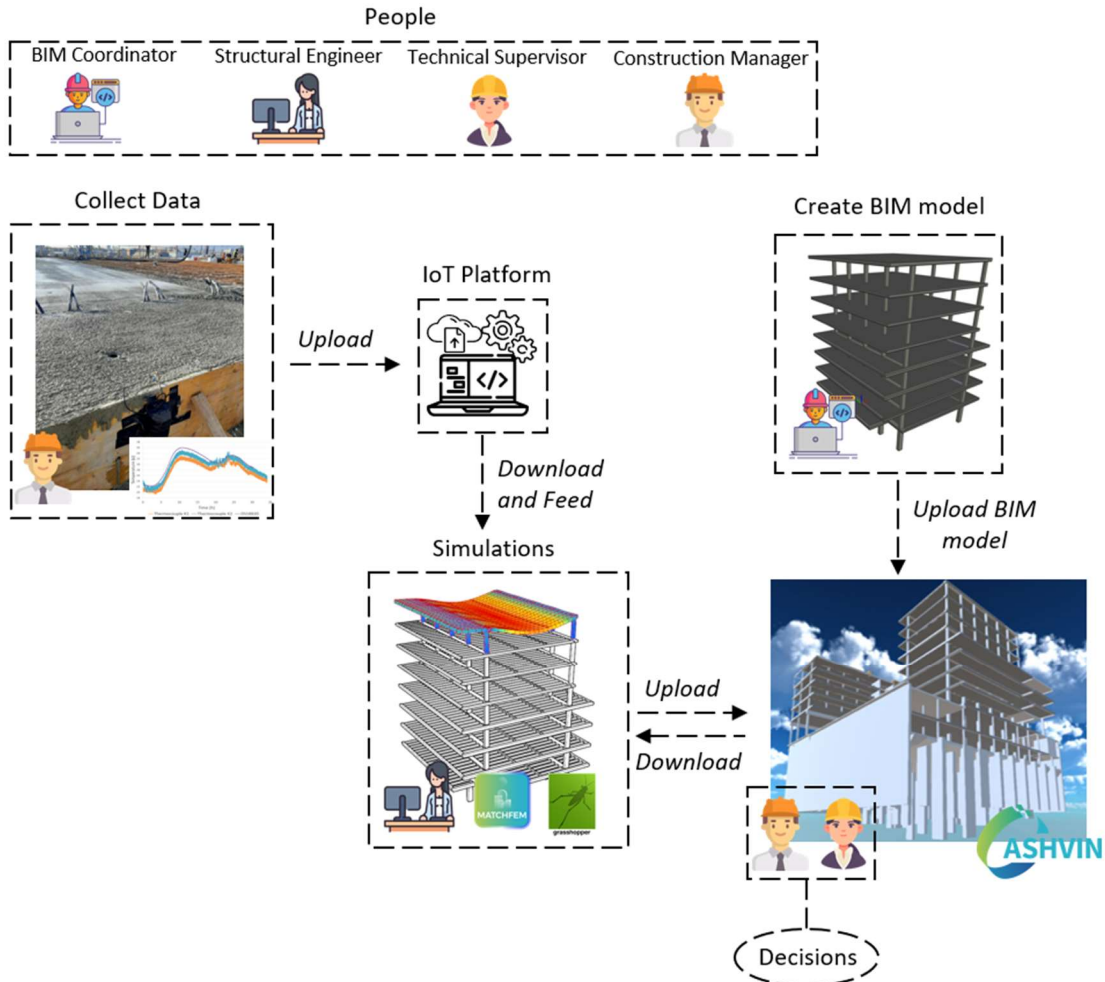


Figure 75. Feed and Update Models application for Demo 6

### 2.5.5 MAINTENANCE PLAN

The operation stage of an asset typically lasts decades, during which time it is subjected to various external and internal factors that may affect its performance. It is therefore important for operation managers to regularly gather data to check the status of the asset and ensure that it is performing as expected.

The data collected by operation managers may suggest two scenarios:

- The performance of the asset is satisfactory. In this case, operation managers can continue to monitor the asset and ensure that it continues to perform at the expected level. They can use the data to identify any potential areas of

improvement and develop strategies to optimize the performance of the asset. This scenario is labelled as routine data gathering.

- There is an issue that needs to be solved. For example, if the data shows that the asset is not performing as efficiently as it should, the operation managers may need to investigate and identify the root cause of the problem. They may need to conduct additional measurements and simulations to determine the cause of the issue and develop a plan to rectify it. Extreme events, such as severe weather conditions or natural disasters, may also suggest that there is an issue that needs to be solved. These events can have a significant impact on the performance of the asset and may require additional measurements and simulations to determine the extent of the damage and the steps that need to be taken to repair it. This scenario is labelled as event-driven issues.

Plan maintenance covers both scenarios. Fig. 76 shows the involved stakeholders, the realm in which they act and the flow of actions. At the physical site, operation managers gather data routinely (action 1). During specific episodes, issues are open (Action 2). MatchFEM tool provides functionalities for requesting more detailed simulations and more detailed measurements (3 and 4). For the sake of tackling specific issues raised on the asset during its lifetime, managers need to activate specific simulations that come under request. These simulations may range from simple to very complex, from reduced- to full-order, from local to global models of the asset or from single to coupled physical phenomena. The possibilities and needs are large even for each specific asset. Simulations are performed in Grasshopper (5) while additional measurements at the site (6). Once additional data is obtained, results are compiled back in Ashvin platform. A decision-making process is then activated according to the established thresholds (7-8).

## Plan Maintenance

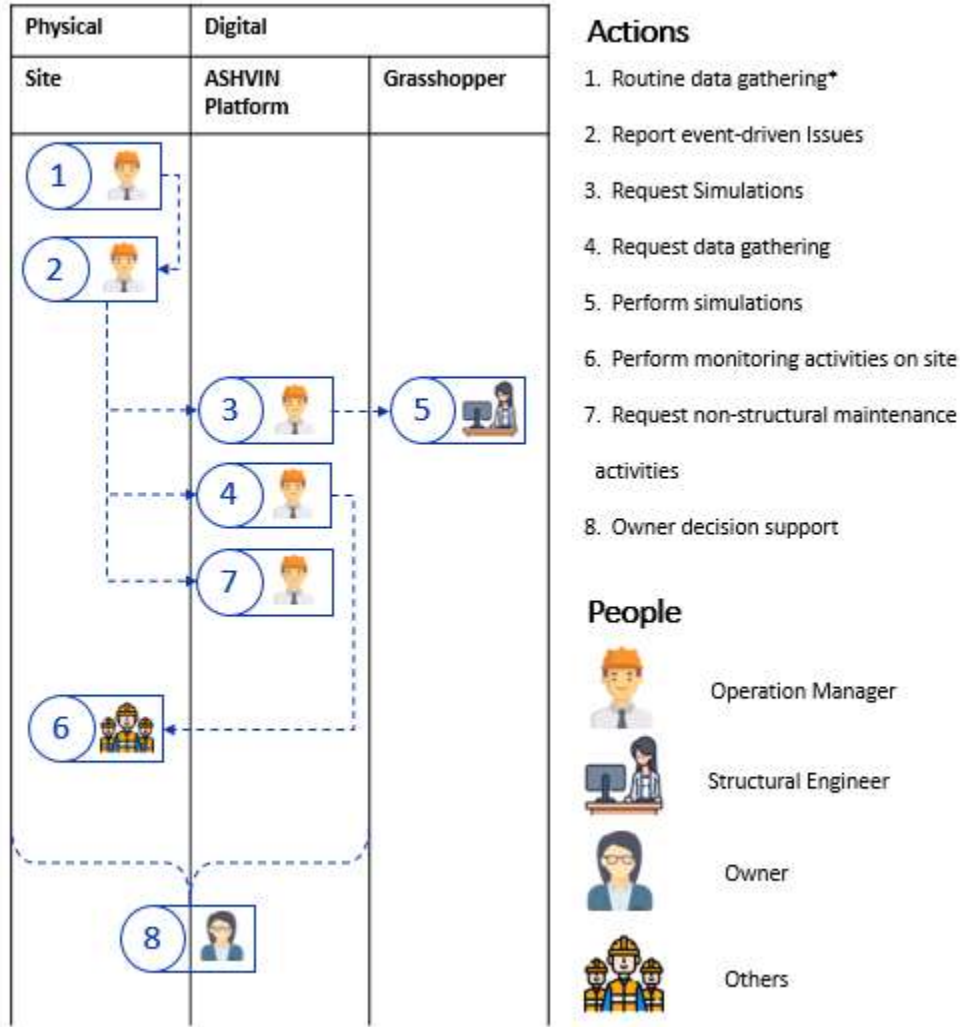


Figure 76. Ashvin vision for planning maintenance

Plan maintenance opens a wide range of potential applications for the operation of infrastructure. Within research and development project, one of the demonstrators is the operation phase of a composite steel-concrete bridge in Barcelona area. The asset has been a test bed for data gathering using sensors and laser scanners. Both types of measurements are embedded within MatchFEM data flow for further analysis.

When it comes to point clouds, the sequential seasonal measurement of the plates using a TLS provides a set of point clouds that can be systematically. Let us imagine a routine data gathering of the shape of the bridge (seasonal, yearly, bi-yearly, etc). Today, laser scanning of a big structure represents a relatively cheap, non-destructive, versatile data gathering technique.

While the operation is satisfactory, data gathering occurs according to the defined plan. At some point though, the bridge may start malfunctioning, an extreme episode may occur or alternative, the routine virtual inspection may suggest abnormal observations (for instance, severe corrosion detected). At this point, operation managers are entitled to suggest more measurements and new simulations based on the measurements. As a result, complex simulations such as FE-analysis can be based on realistic measured



shapes of the bridge. The co-existence of BIM models, simulations and measurements together provide a much more accurate representation of the existing reality of the asset.

With such sources of information, decision making, which is treated in deliverables 5.3 and 5.4 of the suite of documents of WP5 in Ashvin, may become a much more informed process. Fig. 77 presents how Plan Maintenance can be applied in the specific scenario of demo 7. Measurements in this case correspond to point clouds and simulations to a GMNI analysis of a plated structure according to (Braun et al. 2023).

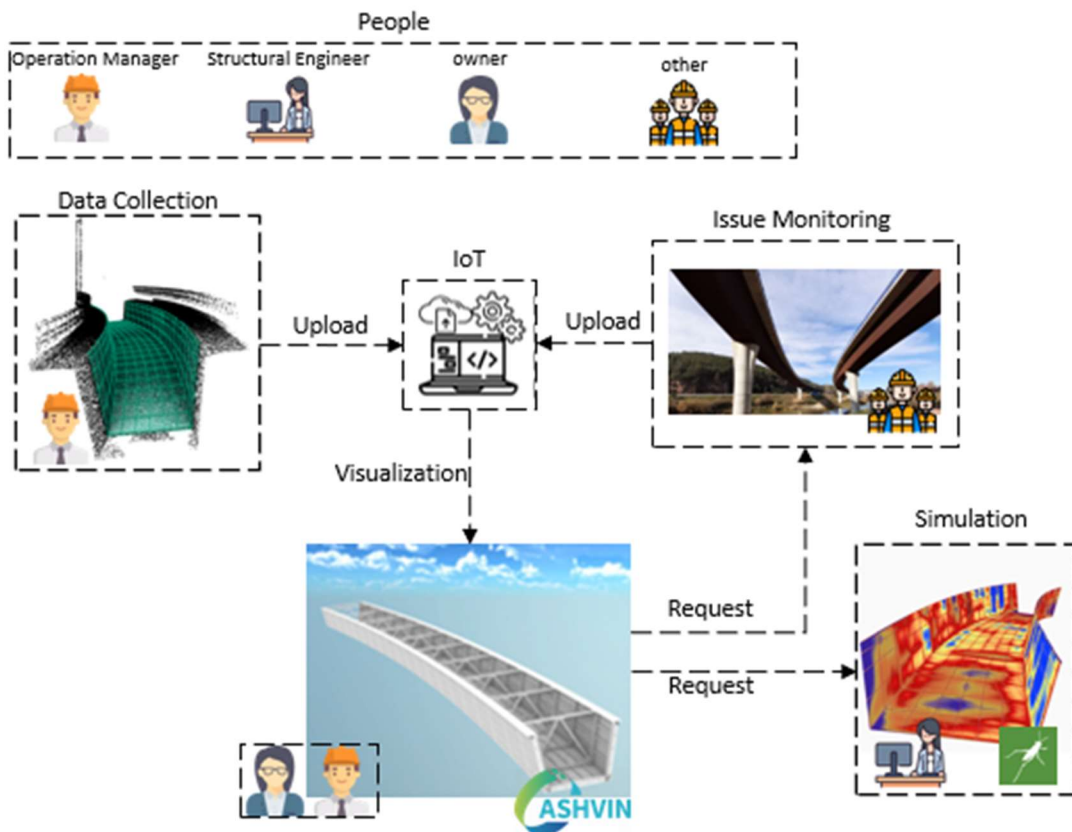


Figure 77. Plan maintenance example of application for Demo 7

### 3 CONCLUSIONS

MatchFEM is a tool belonging to the Ashvin toolkit conceived to be useful in the digital twin management of an asset during its whole life-cycle. Exemplary actions are shown for a bridge in Fig. 78.

- During the design stage of the bridge, MatchFEM can support the generation of a digital twin by providing accurate and reliable simulations of the structure behavior under different loads and conditions. The simulations provide valuable information for the future construction of the bridge. Prior to construction, a set of ideas for future monitoring can be materialized already in the plug-in. It triggers a deeper understanding of the asset that can be directly enriched by the collection of real-time data during the construction phase.
- As the bridge is under construction, MatchFEM can support the update of models with realistic data gathered from sensors or other means. This can help ensure that the digital twin accurately reflects the real-world behavior of the bridge, allowing for more effective management and construction.
- Before the bridge enters the operation phase, a load test on the asset is needed. During load testing, MatchFEM can support the verification and validation of models by simulating the behavior of the bridge under different loads and conditions. This can help ensure that the bridge is structurally sound and capable of supporting the anticipated loads and traffic.
- Subsequently, the bridge begins its operation phase, which can last for decades with no particular malfunctions. During this period, ideally, data gathering should be continuous. In the event that a specific issue occurs with the bridge, MatchFEM can support and assist the operation managers in activating both measurements and simulation protocols to determine the root cause of the issue and develop a plan for addressing it. By providing real-time data and accurate simulations of the structure's behavior, MatchFEM can help ensure that the bridge remains safe and operational throughout its lifespan.

In summary, MatchFEM can support all phases in the digital twin management of a bridge. From the design stage through construction, load testing, and operation, MatchFEM can support the accurate modeling and simulation of the bridge's behavior, allowing for effective management and maintenance planning of the structure over time. By providing accurate and reliable data, MatchFEM can contribute to the decision-making process.

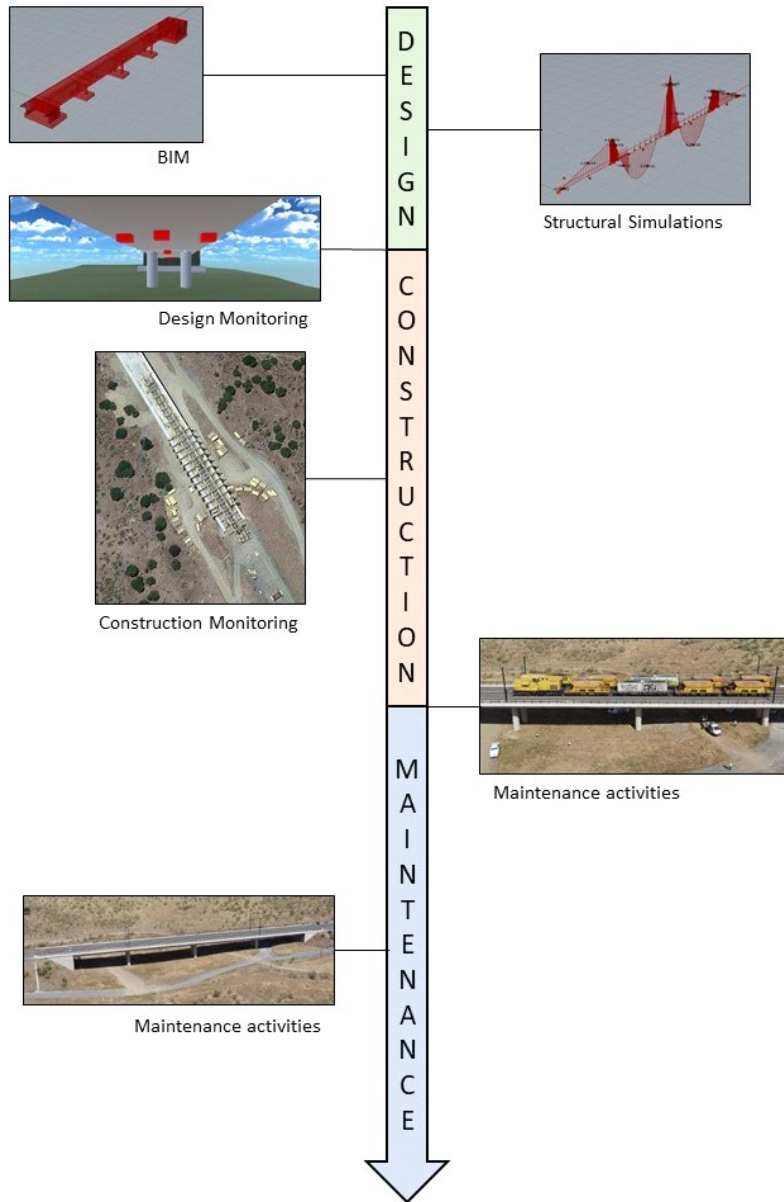


Figure 78. Ashvin vision for the life cycle of a digitally twinned bridge

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## 5 APPENDIX A

```
@prefix : <http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@base <http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt> .
```

```
<http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt> rdf:type owl:Ontology ;
```

```
    rdfs:comment "This is a simple ontology to describe structural simulations in
terms of compatibility between models and solvers. It is intended to be used within Digital Twins as a guide to
activate simulations based on models stored in different formats."@en .
```

```
#####
```

```
# Object Properties
```

```
#####
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Aggregates
```

```
:Aggregates rdf:type owl:ObjectProperty ;
```

```
    rdfs:domain :Simulation ;
```

```
    rdfs:range :Engine ,
```

```
        :Model ,
```

```
        :Result .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#calculated_with
```

```
:calculated_with rdf:type owl:ObjectProperty ;
```

```
    rdfs:domain :Result ;
```

```
    rdfs:range :Engine .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#compatible_with
```

```
:compatible_with rdf:type owl:ObjectProperty ,
```

```
    owl:SymmetricProperty ;
```

```
    rdfs:domain :Model ;
```

```
    rdfs:range :Engine .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#has_model
```

```
:has_model rdf:type owl:ObjectProperty ;
```

```

rdfs:subPropertyOf owl:topObjectProperty ;
owl:inverseOf :has_result ;
rdfs:domain :Result ;
rdfs:range :Model .

### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#has_result
:has_result rdf:type owl:ObjectProperty ;
    rdfs:domain :Model ;
    rdfs:range :Result .

#####
# Data properties
#####

### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#creation_date
:creation_date rdf:type owl:DatatypeProperty ;
    rdfs:domain :Model ,
        :Result ;
    rdfs:range xsd:dateTimeStamp .

### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#globalId
:globalId rdf:type owl:DatatypeProperty ;
    rdfs:domain :Engine ,
        :Model ,
        :Result ,
        :Simulation ;
    rdfs:range rdfs:Literal .

### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#last_edited
:last_edited rdf:type owl:DatatypeProperty ;
    rdfs:subPropertyOf owl:topDataProperty ;
    rdfs:domain :Model ;
    rdfs:range xsd:dateTimeStamp .

### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#type
:type rdf:type owl:DatatypeProperty ;
    rdfs:domain :Model ,
        :Result ,
        :Simulation ;
    rdfs:range xsd:string .

### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#url

```

```
:url rdf:type owl:DatatypeProperty ;  
  rdfs:domain :Engine ,  
    :Model ,  
    :Result ;  
  rdfs:range xsd:anyURI .
```

```
#####
```

```
# Classes
```

```
#####
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Dynamic_Analysis
```

```
:Dynamic_Analysis rdf:type owl:Class ;  
  rdfs:subClassOf :Simulation .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Engine
```

```
:Engine rdf:type owl:Class .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Linear_Model
```

```
:Linear_Model rdf:type owl:Class ;  
  rdfs:subClassOf :Model .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Modal_Analysis
```

```
:Modal_Analysis rdf:type owl:Class ;  
  rdfs:subClassOf :Simulation .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Model
```

```
:Model rdf:type owl:Class .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Non-linear_Model
```

```
:Non-linear_Model rdf:type owl:Class ;  
  rdfs:subClassOf :Model .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Result
```

```
:Result rdf:type owl:Class .
```

```
### http://www.semanticweb.org/cramo/ontologies/2022/11/simOnt#Simulation
```

```
:Simulation rdf:type owl:Class . (2019-02-01T07:24:44Z) https://github.com/owlcs/owlapi -->
```

