COGITO

CONSTRUCTION PHASE DIGITAL TWIN MODEL

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Digital Twin Platform Design & Interface Specification v1

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D7.1 – Digital Twin Platform Design & Interface Specification v1

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Disclaimer

Executive Summary

The COGITO Deliverable "D7.1 Digital Twin Platform Design & Interface Specification V1" aims to document the COGITO Digital Twin Platform detailed architecture and report the outcomes of work performed thus far in "T7.1 Digital Twin Platform Design & Interface Specification". Overall, the COGITO Digital Twin Platform lies at the core of the COGITO solution and is responsible for implementing an information management solution that aims to enable interoperability with existing standards and ontologies covering different domains.

To ensure the COGITO functional requirements are met using a generic set of reusable components, the COGITO Digital Twin Platform (DTP) is implemented using a multi-layer architecture. The **Authentication Layer** ensures that user access is restricted to specific user roles and groups. The **Data Ingestion Layer** is responsible for loading new datasets and orchestrating the execution of the Extract, Transform and Load (ETL) services for generating the knowledge graph and populating the corresponding databases. At the same time, the **Data Persistence Layer** provides a cloud-based data storage solution including graph, relational and time-series databases. The **Data Management Layer** satisfies the data needs of the various COGITO applications by providing the platform interfaces. It includes a runtime environment responsible for handling the data requests and delivering the responses using messaging brokers provided by the **Messaging Layer**. The **Data Post-processing Layer** provides software components responsible for model checking and optimising BIM models that conform to Industry Foundation Classes (IFC) standard.

The present document mainly focuses on presenting the operational blocks of the DTP architecture (layers with their subcomponents and their interconnections) and not on the external interfaces, whose design is still in flux and depends upon the development of other COGITO applications. In this version, we describe the architecture following a hierarchical top-down approach starting from the high-level description of each layer and then drilling down with a detailed description of its components.

The final version of this deliverable is expected to be released on M24 and will provide the detailed technology stack used for the implementation and the specification of the interfaces, especially the ones interacting with other COGITO applications, to ensure transparent interoperability among the various data management components.

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List of Acronyms

Term	Description
AAI	Authentication and Authorisation Infrastructure
AMQP	Advanced Message Queueing Protocol
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
BIM	Building Information Model
CoAP	Constrained Application Protocol
COGITO	Construction Phase diGItal Twin mOdel
CRUD	Create, Read Update and Delete
DAO	Data Access Object
DB	Database
DI	Dependency Injection
DT	Digital Twin
DTP	Digital-Twin Platform
DTV	Design Transfer View
ESB	Enterprise Service Bus
ETL	Extract, Transform and Load
glTF	GL Transmission Format
GUI	Graphical User Interface
HSE	Health, Safety and Environment
IFC	Industry Foundation Classes
IoC	Inversion of Control
IoT	Internet of Things
JDBC	Java Database Connectivity
JMS	Java Messaging System
JNI	Java Native Interface
JPA	Java Persistence Layer
JSON	JavaScript Object Notation
JVM	Java Virtual Machine
LoRa	Long Range
MQTT	Message Queue Telemetry Transport
MVD	Model View Definition
OPC UA	OLE for Process Control Unified Architecture
ORM	Object-Relational Mapping
OWL	Web Ontology Language
PaaS	Platform as a Service

RDF	Resource Description Framework
RDMS	Relational Database Management Systems
REST	Representational State Transfer
SaaS	Software as a Service
SHACL	SHApes Constraint Language
SOA	Service Oriented Architecture
SQL	Structured Query Language
SSO	Single-Sign On
STEP	Standard for the Exchange of Product Data
STOMP	Streaming Text-Oriented Messaging Protocol
TD	WoT Thing Description
UDI	User-Driver Innovation
UML	Unified Modeling Language
VM	Virtual Machine
WODM	Word Order Definition and Monitoring Tool
WoT	Web of Things
XML	Extensible Markup Language

1 Introduction

This deliverable reports on the first version of the COGITO Digital Twin Platform (DTP) architecture reflecting the outcomes of "T7.1 Digital Twin Platform Design & Interface Specification". The deliverable builds upon the identified stakeholder requirements of "T2.1 Elicitation of Stakeholder Requirements", the overall COGITO system architecture of "T2.4 COGITO System Architecture Design", and the definition of the COGITO ontology network of "T3.2 COGITO Data Model, Ontology Definition and Interoperability Design". This work delivers the detailed multi-layered architecture of the COGITO DTP, the specifications of its core components, and a detailed definition of the interfaces.

The Unified Modeling Language (UML) has been used to deliver the components and interfaces definitions. The UML component diagram describes how components are connected in the layered architecture pattern. In addition, this deliverable defines the data flows and the interfaces specifications among the different layers of the platform.

1.1 Scope and Objectives of the Deliverable

The main scope of this deliverable is to introduce the architecture of the first version of the DTP and analyse the layers and their roles supporting the user-facing COGITO software applications. The objective is to describe: i) the high-level software architecture of the DTP; ii) decompose each layer into distinct software components; and iii) explore the technological stack and interfaces required for the implementation.

A centrally integrated solution appears in the proposed ICT framework of several construction-related H2020 projects and other commercial organisations. In the **SPHERE** project, the raw data produced by machines, systems and products are linked, captured, and managed using a central cloud-based collaborative Platform as a Service (PaaS) ICT solution [1]. In **BIMprove**, the core component is a cloud-based data integration service using modular APIs for information exchange and data processing. These APIs can add/remove and update information in the different layers of the BIMprove solution [2]. Finally, in **ASHVIN,** a microservices-based messaging IoT middleware is proposed [3]. The middleware abstracts the most common IoT protocols specifications such as LoRa, MQTT, OPC UA, CoAP to establish a unified communication interface between devices and software applications.

COGITO's DTP is a cloud-based and semantically enabled data integration middleware that includes a comprehensive suite of services to guarantee scalability, reliability, and enhanced security as it is responsible for: a) handling data from various input sources such as point clouds, 4D BIM, and IoT devices, b) populating the internal data models and knowledge graphs, and c) responding to data requests of other COGITO software applications. The semantically linked knowledge graphs are the COGITO ontologies defined in WP3.

The DTP architecture design considers the variable computation data needs providing synchronous and asynchronous interfaces to increase the performance by minimising the query response time as much as possible. Additionally, the functional components will be deployed as microservices, enabling flexibility and high-availability capabilities to render COGITO's DTP into a federated 'loose' system of interoperable tools instead of a rigid, tightly integrated system.

1.2 Relation to other Tasks and Deliverables

This deliverable is the outcome of the "T7.1 Digital Twin Platform Design & Interface Specification", which falls under "WP7 COGITO Digital Twin Platform" activities. There are several dependencies of this work to other deliverables and tasks:

- The configuration of the user roles in the authentication layer is based on the work performed in "T2.1 Elicitation of Stakeholder Requirements" and the corresponding deliverable "D2.1 Stakeholder requirements for the COGITO system".
- The layered architecture design of the platform is primarily based on the work performed in "T2.4 COGITO System Architecture Design" and the corresponding deliverable "D2.4 COGITO System Architecture V1".
- Furthermore, the design of the data ingestion and persistence layers is based on the work performed in "T3.2 COGITO Data Model, Ontology Definition and Interoperability Design".

1.3 Structure of the Deliverable

The rest of the deliverable is organised according to the structure of the COGITO DTP:

- Section 2 presents the overall architecture of the DTP, introducing its layers and their interfaces.
- Section 3 presents the architecture of the *Authentication Layer*, which provides a centralised user management solution among the COGITO software applications.
- Section 4 presents the architecture of the *Data Ingestion Layer*, which includes a set of services for loading and semantically linking resources into the internal data models.
- Section 5 presents the architecture of the *Data Persistence Layer*, which provides a cloud-based data storage solution including graph, relational and time-series databases.
- Section 6 presents the architecture of the *Data Management Layer*, which handles the incoming and outgoing data flows supporting synchronous and asynchronous interfaces.
- Section 7 presents the *Messaging Layer* and the proposed technologies for handling asynchronous messages and notifications.
- Section 8 presents the architecture and the *Data Post-processing Layer* specifications, which provide services for checking and enriching BIM models.
- The document concludes with Section 9, where the possible future implementations are discussed, paving the way for the final version of the architecture.

2 Overall Architecture

The DTP is a cloud-based and semantically-enabled data-integration middleware that includes a comprehensive suite of services responsible for loading, populating, and managing data used by the various COGITO applications. This section describes the six-layered architecture of a cloud-based middleware that enables interoperability between construction-related applications developed within the COGITO project, a set of interfaces that define the high-level data interactions among the layers and the orchestration of the operation of the layered components.

2.1 Multi-layered Architecture

The DTP is responsible for loading the as-designed and as-built data, populating the corresponding knowledge graphs and databases, and handling data queries from the various COGITO applications. The platform architecture follows a six-layer approach to guarantee horizontal scalability, reliability, and enhanced security. Figure 1 displays an overview of the high-level architecture of the DTP which includes the defined layers with the high-level interactions and the information flow among the layers.

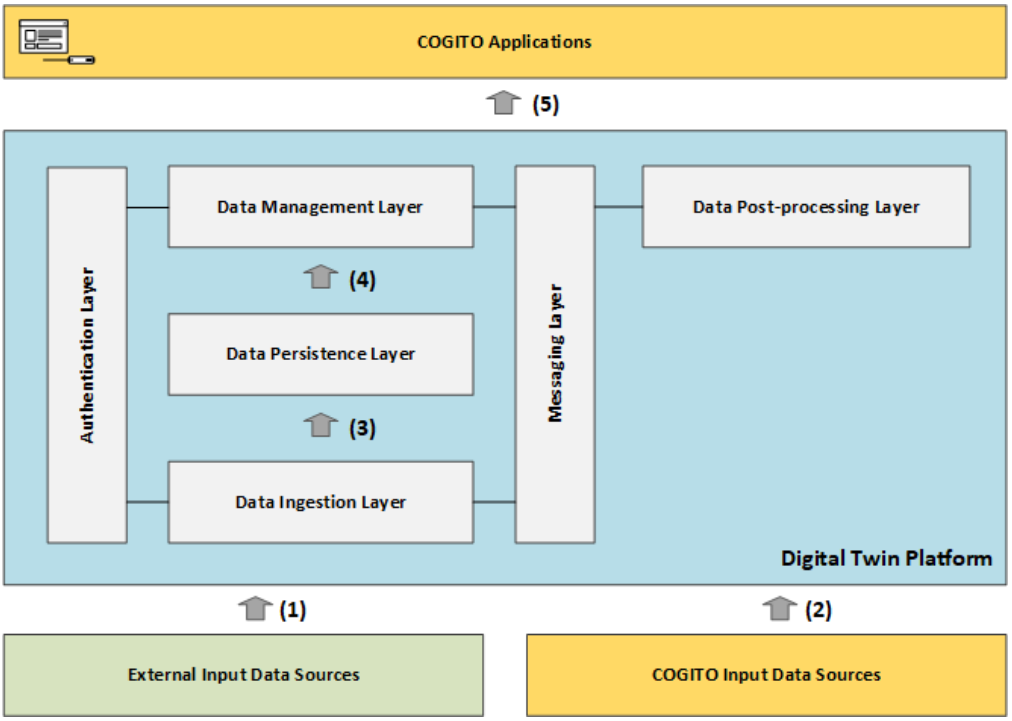

Figure 1 DTP high-level architecture

As shown in Figure 1, we identified the following six layers as a basis for the first implementation of the DTP:

- The **Authentication Layer** ensures that access to resources and services is restricted to specific users with the appropriate permissions. The authentication layer is based upon the open-source project Keycloak serving as a central identity and access management provider.
- **Data Ingestion Layer** loads the as-designed and as-built data and real-time IoT data to the DTP and orchestrates the execution of the included Extract, Transform and Load (ETL) services to generate the knowledge graph and populate corresponding databases.
- The **Data Persistence Layer** provides an integrated cloud-based storage solution for COGITO data, providing data stores such as file storage and relational, key-value, time-series, and triplestore databases.
- The **Data Management Layer** manages the data requests of the various COGITO applications by providing flexible interfaces and an actor-based runtime environment for the synchronisation of the internal operations and preparation of the data responses.

- The **Messaging Layer** provides an Enterprise Service Bus (ESB) for enabling asynchronous communication between the DTP services and the other COGITO applications. In addition, the ESB is used for intra-layer communications.
- The **Data Post-processing Layer** facilitates reusable data integration and quality checking services to ensure end-user COGITO applications (outside of the DTP) are provided with quality data. As COGITO complies with openBIM data (IFC), the following services are envisaged initially to be developed and deployed: Model-View Definition (MVD) checking, IFC optimisation, and B-rep geometry generation on the loaded BIM models.

A quick overview of Figure 1 shows that the starting point of the information flow is the input data sources. Within COGITO, the input data come from two different sources: a) external applications **(1)** such as BIM authoring tools and project management tools, providing the as-designed 3D BIM along with the corresponding 4D like construction schedules data, and b) the COGITO data pre-processing tools **(2)** such as the Visual Data Pre-processing tool and the IoT Data Pre-processing tool, providing imagery and location tracking data along with their meta-data.

When external sources send data to the DTP, checking and optimisation operations are initially performed before loading the data into the Data Persistence Layer. For instance, in case of the BIM model, an ETL service of the Data Ingestion Layer process the IFC data and performs transformations based on a pre-defined set of mapping rules. Regarding the transformations of contextual data (construction schedule, as-planned resources) that conform to machine-readable formats, such as JSON, CSV and XML, various ETL services of the Data Ingestion Layer generate RDF data in line with the ontologies defined in "WP3 COGITO Data Model and Reality Capture Data Tools" [4].

The Data Ingestion Layer is responsible for orchestrating the transformation processes to generate the knowledge graph and populating **(3)** the various databases of the Data Persistence Layer.

After the ingestion process is complete, the knowledge graph is available, and databases at the Data Persistence Layer are populated. The Data Management Layer can then respond to data requests from upstream COGITO applications. The Data Management component then uses a set of suitable software adapters (API wrappers) for retrieving data **(4)** stored into the databases of the Data Persistence Layer. In some queries, the corresponding responses require data arising from different types of databases. For instance, in the case of a 4D BIM query, two requests are performed: one to the knowledge graph for retrieving the tasks and another to the BIM database for retrieving the corresponding IFC objects. The Data Management Layer is responsible for orchestrating the internal data exchanges, harmonising the returned data, and sending responses **(5)** to the COGITO applications.

2.2 Components and High-Level Interfaces

The DTP follows a multi-layered architecture comprising six core layers. Each layer contains a set of software components implementing various business logic operations to support the main objectives of the DTP. These components are packaged and deployed as microservices in a cloud-computing infrastructure, providing flexibility, availability, and scalability. The main components included in DTP layers are the following:

The *Authentication Layer* contains COGITO's **Identity Provider** that offers a central identity and access management solution.

The *Data Ingestion Layer* contains a) the **Project Management** component, responsible for project creation, user assignment, loading input data and supervising the internal running services, b) the **BIM Management** component, which is responsible for parsing, validating and versioning IFC data, and c) **Knowledge Graph Generation** which is responsible for orchestrating the various transformation processes to generate the knowledge graph and populate the triplestore.

The *Persistence Layer* contains: a) a **File Storage** system for storing files, b) a **Relational DB** for storing project and user data, c) a **Key-value DB** for storing the IFC objects, d) a **Timeseries DB** for storing IoT data and e) a **Triplestore** for storing the knowledge graph.

The *Data Management Layer* contains a) a set of **API wrappers** for interacting with the various databases, b) a **Runtime System** for hosting actors to handle the data requests of the various COGITO applications, and c) **Web services** for the communication with the COGITO applications.

The *Data Post-processing Layer* contains a) the **MVD Checker** component for performing model checking in terms of data completeness, b) the **IFC Optimiser** component for de-duplication and lossless compression of the IFC file, and c) the **B-rep Generator** for generating triangulated B-rep solids of the IFC objects. These are the original services envisaged to be developed. However, the Data Post-processing Layer provides an extensible mechanism to provide additional functionalities (if required), like bespoke quality checking, support for additional data models, etc.

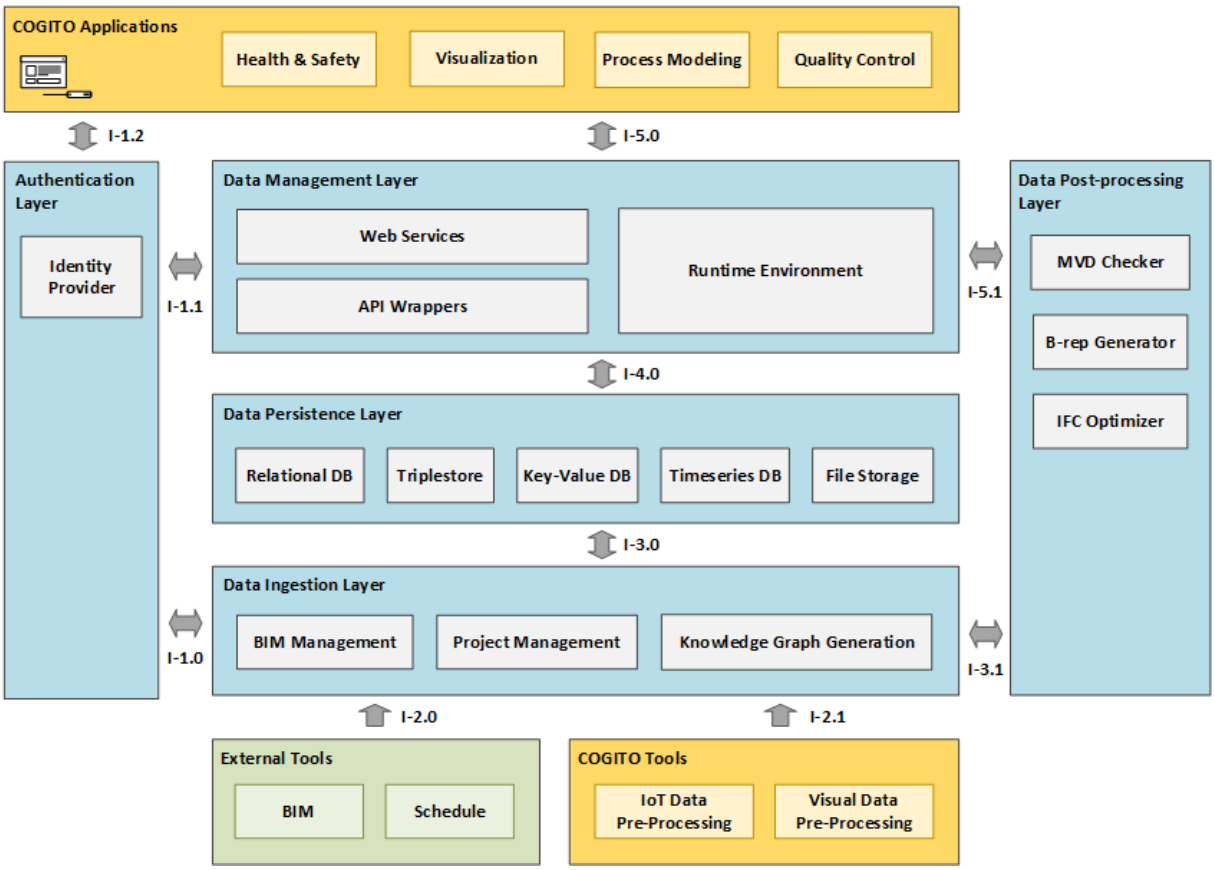

Figure 2 DTP high-level interfaces

Currently, the primary interfaces have been identified and shown in Figure 2 to illustrate the data exchanges among the DTP layers' components. The main internal and external interfaces of the DTP layers and their main uses are the following:

- **I-1.0:** The Project Management component uses I-1.0 to register and authenticate COGITO users.
- **I-1.1:** The Runtime System of the Data Management Layer uses I-1.1 to authenticate low-level modules performing internal business-logic operations.
- **I-1.2:** The COGITO applications use I-1.2 for authenticating the registered COGITO users.
- **I-2.0**: COGITO users use I-2.0 to load data into the DTP. The users upload data such as BIM models, construction schedules and resources using the rich Graphical User Interface (GUI) of the Project Management component.
- **I-2.1**: COGITO applications use I-2.1 to load data into the DTP. The applications use the REST API provided by the Project Management component to upload data such as point clouds, imagery, and real-time location tracking data.
- **I-3.0:** This interface facilitates the communication between the Data Ingestion and Persistence Layers. The Project Management component uses the file storage system and the relational

database to store the uploaded files with their assigned permissions and meta-data. In addition, the BIM Management component uses the file storage system to keep intermediate files and the key-value database to store the IFC objects. In conclusion, the Knowledge Graph Generation component use the graph database to store the generated RDF data.

- **I-3.1:** This interface supports the asynchronous communication between the Data Ingestion Layer and the Data Post-processing Layer. Before the knowledge graph generation, the IFC model is checked for schema consistency and completeness, ensuring that each structural building element has semantic links with the tasks included in the construction schedule. Then, the IFC is optimised, and the geometric information is exported and converted in OBJ format. These operations often require more time depending on the complexity of the IFC data. The data post-processing layer implementation will use the Service-Oriented Architecture (SOA) design pattern, with applications deployed as microservices.
- **I-4.0**: This interface allows the communication between the API wrappers at the Data Management Layer and the corresponding databases of the Data Persistence Layer. The main protocols of these interactions are JDBC and HTTPS.
- **I-5.0:** This interface establishes the communication between the DTP and the various COGITO applications. It supports both synchronous and asynchronous channels using ESB technologies.
- **I-5.1:** Finally, I-5.1 defines the communication between the Data Management Layer and the Data Post-processing Layer. The actor-based runtime system for the DT applications deployed as microservices uses the message broker of the ESB for interacting with the services of the Data Post-processing Layer.

The Messaging Layer of the DTP supports both synchronous and asynchronous communication protocols in a unified manner. Some components can process the data requests in real-time, while others require more time depending on the data processing load. For instance, the BIM Management component of the Data Ingestion Layer often uses the asynchronous communication protocols for exchanging data with the components of the Data Post-processing Layer **(via I-5.1)** to perform MVD-based model-checking, IFC optimisation and B-rep model generation. The software components in the DTP's various layers and the detailed interface specifications are presented in the following sections of this document.

2.3 Service Orchestration

The Service-Oriented Architecture (SOA) design pattern is used to implement the DTP. The proposed multi-layered architecture requires service orchestration and an efficient messaging system that supports loose coupling between the various components of the DTP to achieve flexibility, scalability, and reliability. The messaging system uses the JBoss Fuse ESB, to offer a native integration environment using multiple protocols for asynchronous communication with the various COGITO applications. The support of asynchronous messaging protocols offers many benefits and brings challenges such as concurrency and synchronisation issues. The service orchestration is needed to ensure that the business-logic operations of the DTP are running smoothly and that the available computing resources are allocated correctly. As shown in Figure 3, we use Docker and Docker Swarm to provide basic capabilities such as flexibility, scalability, and reliability.

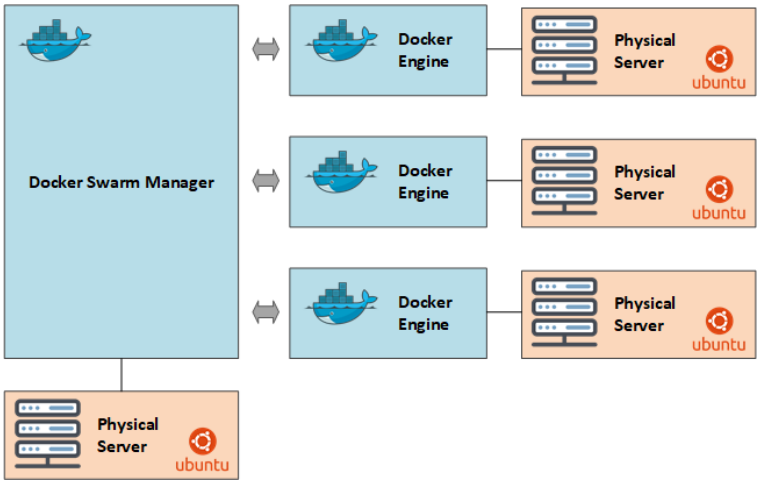

Figure 3 Use of Docker Swarm in COGITO's DTP

The primary responsibility of the orchestration layer is to deploy the components on the available physical computational nodes efficiently. This deployment method uses Docker, a lightweight virtualisation system that does not require Virtual Machine (VM) hypervisors running on hardware. The Docker images facilitate the portability and distribution of workloads in a standardised manner and allow developers to package the software components and dependencies into reusable and scalable units.

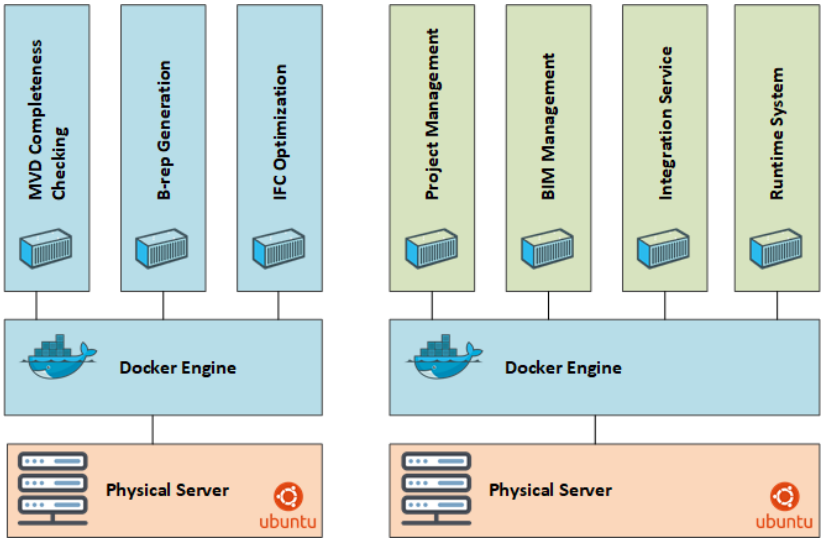

Figure 4 DTP's service orchestration

The distribution model of the DTP follows the Software as a Service (SaaS) approach, deployed on a private and containerised cloud computing environment hosted on dedicated physical servers. This approach ensures that the allocation of the hardware resources can be centrally managed using simple instructions. As shown in Figure 4, the Data Post-processing Layer components require multiple running instances, while the Data Ingestion Layer and Data Management Layer components have fewer requirements.

3 Authentication Layer

The Authentication Layer is responsible for storing and managing user accounts and their roles, enabling the DTP to register and authenticate the users of the COGITO solution. It provides an Authentication and Authorisation Infrastructure (AAI), allowing the DTP to manage the access of the different stakeholders/users of the various COGITO software applications by assigning various functionalities such as registration, authentication, and authorisation to an external open-source identity provider.

3.1 Identity and Access Management

The AAI solution used in the DTP relies on the open-source identity and access management solution named Keycloak[1]. This solution is an industry-standard implementation for identity and access management supporting various protocols such as OpenID Connect and SAML 2.0. The OpenID Connect protocol enables Single Sign-On (SSO) and cross-domain identity management. Keycloak offers a REST API to handle the authentication protocol requests and a Graphical User Interface (GUI) to facilitate user registration, login, profile management and administrative operations.

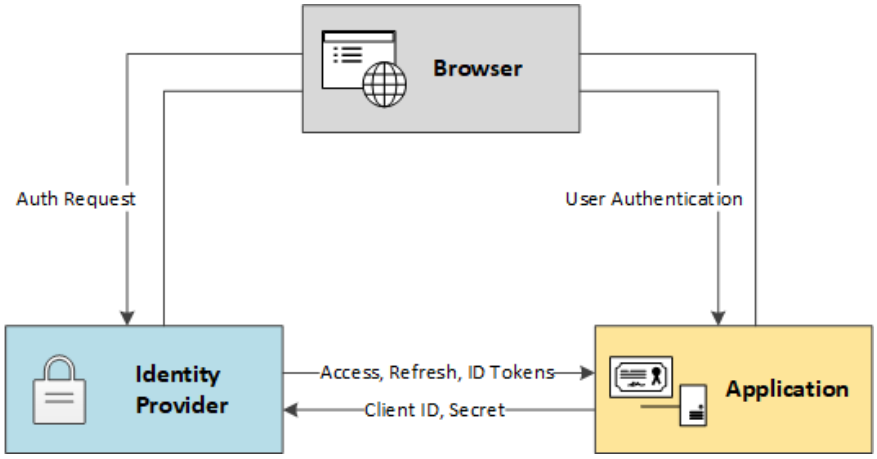

Figure 5 User authentication process in COGITO solution

Figure 5 shows the authentication process using the OpenID Connect protocol. Keycloak is the central system for managing profiles and the overall authentication process. The browser is used for the communication between COGITO's web-enabled applications and Keycloak. In case of a protected resource or endpoint request, the COGITO application forwards the user session to Keycloak's login page for the authentication request. Then, the COGITO application identifies itself using the Client ID and a secret key is generated from the Keycloak Admin Console. After successful authentication, Keycloak provides the Access, Refresh, and ID tokens to the COGITO application. The application can use these tokens to retrieve the assigned roles of the authenticated user and apply access policies.

3.2 User Roles

Within Task "T2.1 Elicitation of Stakeholder Requirements" and its primary outcome "D2.1 Analysis of Digital Tools Market and Prevailing Regulatory Frameworks," the main stakeholders of the COGITO project have been identified following a User-Driven Innovation (UDI) methodology [5]. These stakeholders are the end-users of the various COGITO applications. Thus, the identified roles have been introduced in the Authentication Layer using the Keycloak Admin Console. Core roles that have been added in the Keycloak database are the following: Project Manager, Site Manager, Quantity Surveyor, Foreman, Worker, Quality Manager, Surveyor, Health Safety and Environment (HSE) Manager, HSE Supervisor and HSE Trainer.

When a new user registers to COGITO`s DTP, the Project Management component provides access to the GUI for project creation and assignment of the user into existing projects.

[1] Keycloak Identity and Access Management https://www.keycloak.org

3.3 Interface Specification

As mentioned in the previous section, Keycloak is a central management system for managing user-profiles and the user authentication process. It provides two primary endpoints to interact with the COGITO applications: a) the Keycloak Authentication API granting access to users based on user credentials such as username and password and b) the Keycloak Admin REST API allowing administrator users to access all features provided by the Admin Console GUI.

The COGITO applications use the Authentication API for authenticating users. The authentication process has the following steps: First, the COGITO application redirects the user to Keycloak for performing the authentication process. If the authentication is successful, the Keycloak redirects the user back to the COGITO application. Next, the COGITO application performs a second request for retrieving the Access, ID, and Refresh Token.

On the other hand, the Keycloak Admin REST API is used by some COGITO components and admin users for interacting with the Keycloak backend. It supports various requests such as getting roles, getting users, getting users with a specific role, and assigning a role to a user.

The specification of the APIs and detailed instructions about their usage will be available in the final version of this deliverable.

4 Data Ingestion Layer

The Data Ingestion Layer includes software components responsible for project creation, BIM data consistency validation, and ontology population. The software components can be grouped into three operational blocks based on their characteristics and functionalities: a) Project Management, b) BIM Management, and c) Knowledge Graph Generation. These blocks include components, which can act as standalone services. Figure 6 displays a generalised view of the architecture of the Data Ingestion Layer with its three blocks and their members.

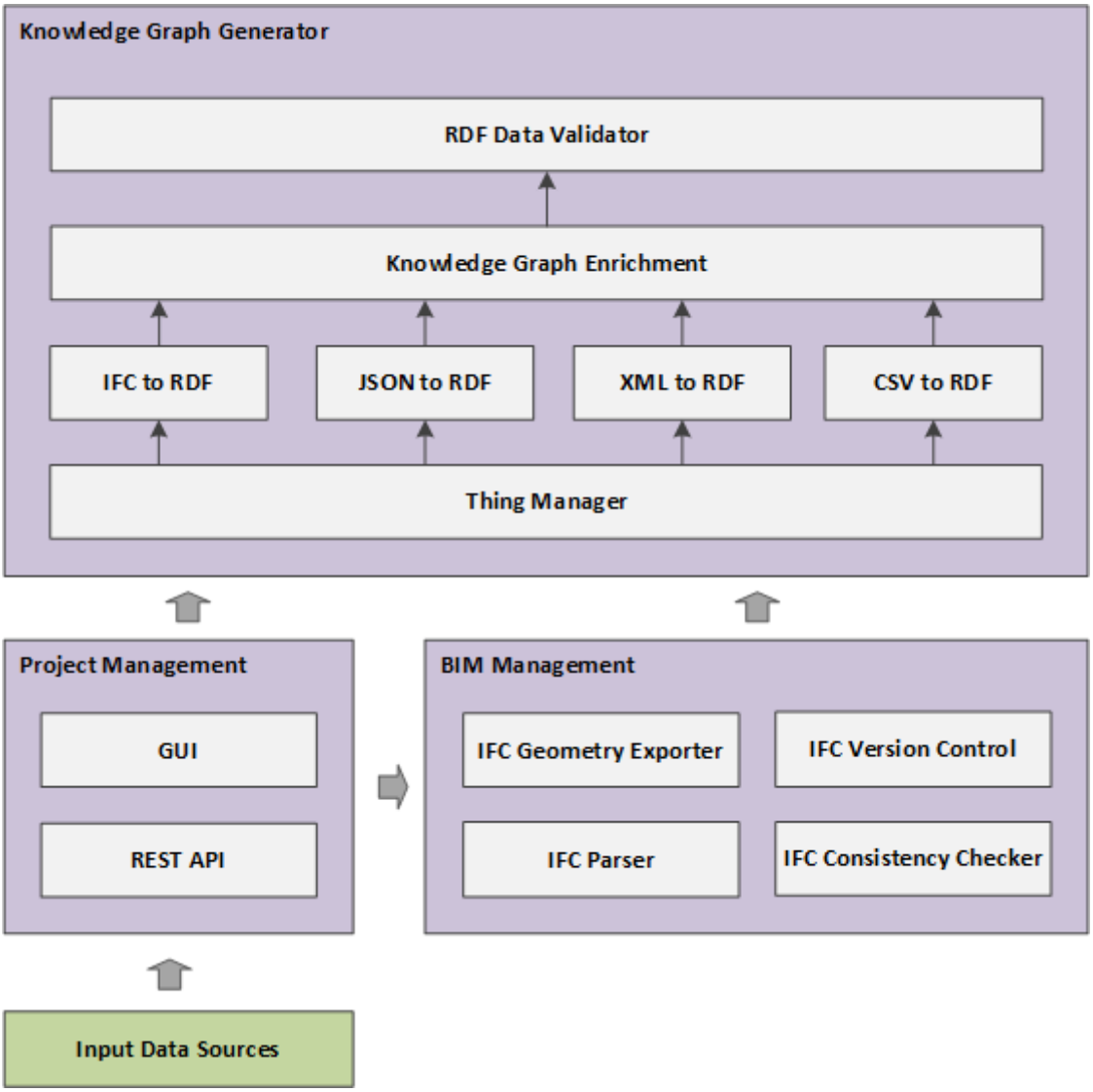

Figure 6 Data Ingestion Layer architecture

These three operational blocks and their respective components are described in detail in the following subsections.

4.1 Project Management

The Project Management component provides a standalone web-based application responsible for creating a new project, assigning users, and loading data from the other COGITO applications. It is responsible for supervising the running services and informing the COGITO users about the progress and the corresponding results.

4.1.1 Architecture

The Project Management component is deployed as a Spring Boot application and is the primary input interface of the DTP. Spring Boot is built on top of the Spring Framework, enabling an easy way to set up, configure and run services and web-based applications. It provides an API and includes several indicators to inspect the health of the running processes, memory usage, error logging and more.

The proposed software implementation uses modern web technologies to deliver a rich Graphical User Interface (GUI) for user interaction and configuration, including web-sockets to synchronise the backend services with the front-end elements. It uses the Apache Tomcat web server and software packages provided by the BIM Management component to load, handle, and visualise IFC data. The Data Post-processing Layer may generate some of the required data.

The Project Management component provides authorised access to COGITO users and other COGITO applications through the Authentication Layer. The web application is based on the Model-View-Control (MVC) design pattern and uses web-sockets implementing the Streaming Text Oriented Messaging Protocol (STOMP). Figure 7 shows the interactions of the main components involved in the GUI and REST API backend for the element.

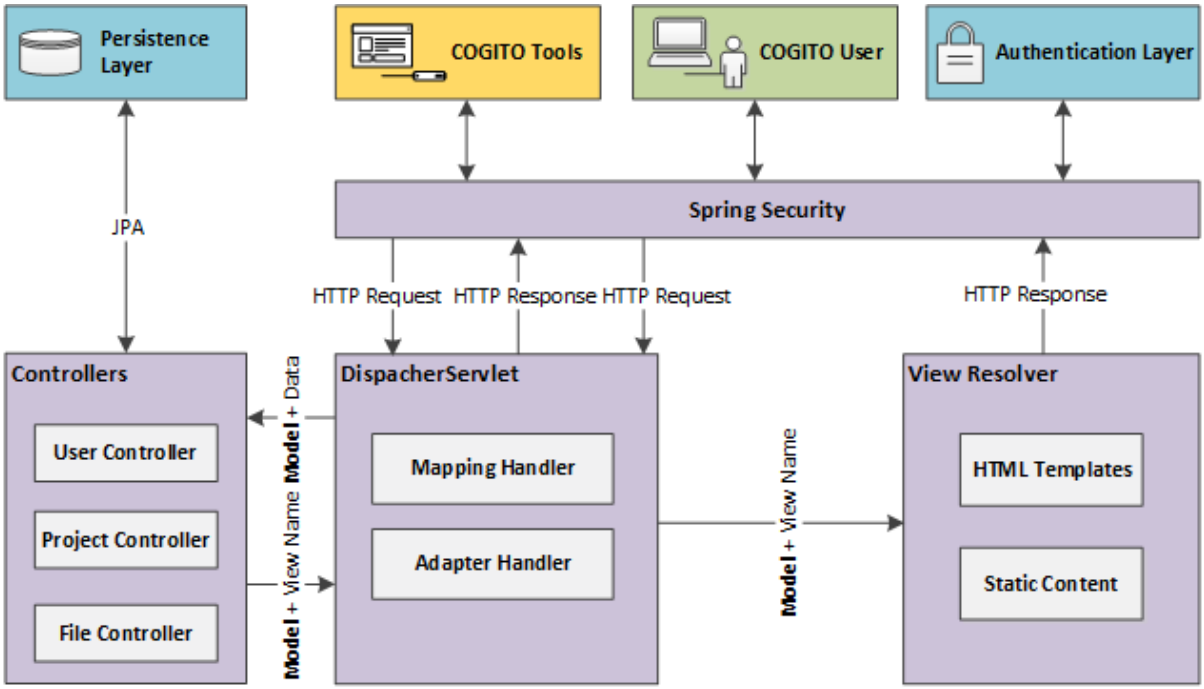

Figure 7 Backend architecture of Project Management component

As shown in Figure 7, the Spring MVC framework comprises four main parts:

- The **Dispatcher Servlet** to forward incoming client requests to specific controllers based on the URL pattern configuration of the Mapping Handler.
- The **Model** contains the data of the request; the data can be a single object or a collection of objects.
- The **Controller** collects through an API or using Dependency Injection (DI) the data from the Persistence Layer and stores them in the Model object; and
- The **View Resolver** combines the Model object with the corresponding HTML template to render the page and then forwards the response back to the client.

The Project Management component uses the Spring Security Framework with the embedded Spring Keycloak Adapter to manage the access policies of the COGITO users. Spring Security uses the tokens provided by the Authentication Layer to grant access to users and other COGITO applications for accessing protected data through the REST API.

As mentioned previously, the backend implementation of the Project Management component uses a relational database located in the Persistence Layer for storing all project data and meta-data. Moreover, it includes an AMQP adapter for enabling asynchronous communication with the Data Post-processing Layer through the Enterprise Service Bus (ESB) of the Messaging Layer. Figure 8 illustrates the stack diagram of the Project Management component that contains the following subcomponents:

- **Spring Core** is the foundation component of the Spring Framework. It supports application development using Dependency Injection (DI) and Inversion of Control (IoC).
- **Spring JDBC** is a component of the Spring Framework responsible for connecting to the Project Database and executing SQL queries. Spring JDBC provides an abstraction for handling database connections, preparing SQL statements, and handling potential exceptions.
- **Spring Java Persistence API (JPA)** is a component of Spring Framework that automates the creation and population of relational databases using the Object-Relational Mapping (ORM) specification. It supports the Create, Read Update and Delete (CRUD) operations of the Data Access Objects (DAO) of the Project Management component.
- **Spring Security** is a component of Spring Framework that manages the authentication and authorisation operations of the Project Management component. The Keycloak Spring Adapter uses Spring Security to grant access to registered users and other COGITO applications.
- **Spring Model View Control (MVC)** provides a framework for creating web applications using the Model View Control design pattern. It supports the main concepts of modern web applications and offers extensibility through the integration of external frameworks.
- **Thymeleaf** is a template engine used for implementing the front-end components, which constitutes the View part of the MVC design pattern.
- **Spring Java Messaging Service (JMS)** provides a framework for the asynchronous communication of the Project Management application with the ESB of the Messaging Layer using the AMQP protocol.

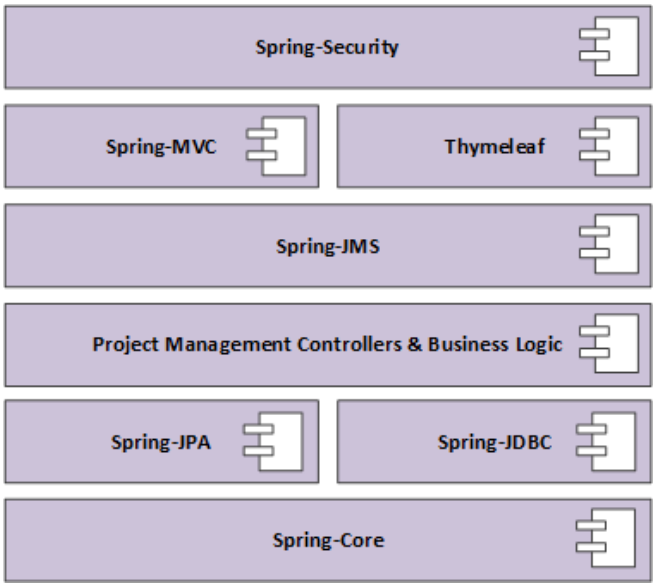

Figure 8 Stack diagram of Project Management component

It is worth mentioning that all involved technologies and frameworks to develop the Project Management component are based on open-source projects. In the final version of this deliverable, we will report the complete list of software frameworks and their version and licences.

4.1.2 Interface Specification

The Project Management component provides a REST API allowing the various COGITO applications to interact with the DTP for project creation, user assignment, uploading files and more. Some of the fundamental functionalities provided are listed in Table 1.

The endpoints and the detailed specifications of the above API will be provided in the final version of this deliverable "D7.2 Digital Twin Platform Design & Interface Specification V2".

Table 1 Project Management API functionalities

Functionality	Protocol	API/Method	Endpoint Description
Create project	HTTPS	REST/POST	Allows the creation of a new project. This request supports attributes such as ID, Name, Description, Location and more and it is available for limited user roles.
Edit project	HTTPS	REST/POST	Allows the editing of an existing project. This request supports overwriting the project attributes.
Delete project	HTTPS	GET	Allows the deletion of a project. This request is available for limited user roles.
Assign user to a project	HTTPS	REST/POST	Allows to add new user to a project. This request is available for limited user roles.
Remove user from a project	HTTPS	REST/POST	Allows to remove a user from a project. This request is available for limited user roles.
List all users	HTTPS	REST/GET	Allows to list the registered users. This request is available for admin users and trusted applications.
List all projects	HTTPS	REST/GET	Allows to list the created projects. This request is available for admin users and trusted applications
List user's projects	HTTPS	REST/GET	Allows to list the projects of a user.
List project's users	HTTPS	REST/GET	Allows to list the users of a project.

4.2 BIM Management

The BIM Management component can handle BIM models that conform to the Industry Foundation Classes (IFC) standard[2]. This component is responsible for parsing IFC data and loading the corresponding objects into the key-value database of the Persistence Layer. It is responsible for serialising/deserialising, querying, updating, and merging the IFC data. Furthermore, it performs asynchronous requests to the Data Post-processing Layer for complex BIM-related operations such as MVD completeness checking, IFC optimisation and B-rep geometry generation.

4.2.1 Architecture

The BIM Management component is deployed as a Spring Boot application and is responsible for providing the backend infrastructure and the endpoints for handling BIM models. It contains software libraries for serialising/deserialising, validating, querying, and updating the IFC data. These software libraries are widely used within the various layers of the DTP. For the implementation, we use Java with a minimum number of external dependencies.

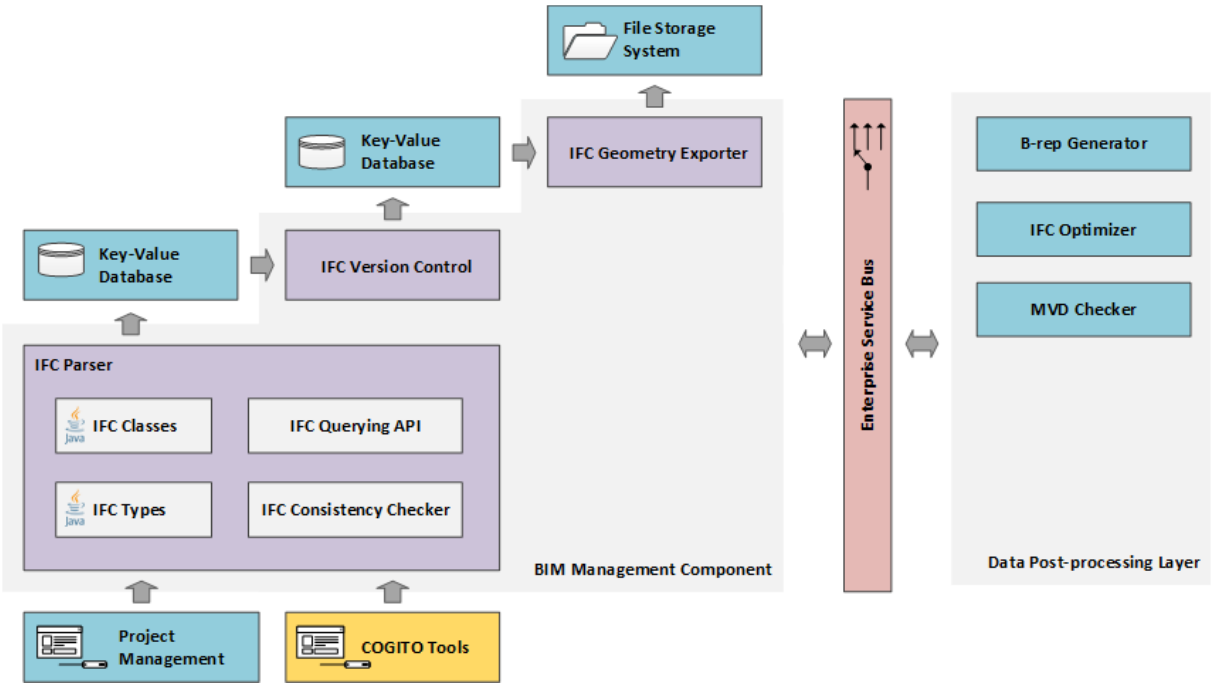

Figure 9 High-level architecture of BIM Management component

As shown in Figure 9, this component is responsible for handling the IFC data coming from the Project Management component and coordinating the asynchronous executions of the services provided from the Data Post-processing Layer. The Data Post-processing Layer consists of three services, the MVD Checker, the IFC Optimiser and the B-rep Generator. Depending on the complexity of the BIM model, these services require more time to perform their business logic operations. For instance, the B-rep Generator is used to generate triangulated B-rep solids of the structural and non-structural building elements, which are optimised for web-based graphic viewers, avoiding verbosity.

4.2.2 EXPRESS Schema Compiler for Java

The EXPRESS Schema Compiler is a library developed in Java EE using the Java Code Model framework for generating the IFC Java classes and IFC types directly from the EXPRESS schema. The compiler can parse all available IFC releases successfully, from IFC2x3 to IFC4x3. Figure 10 illustrates how IFC classes and IFC types are generated automatically from the IFC EXPRESS schema.

[2] buildingSMART International https://buildingsmart.org/

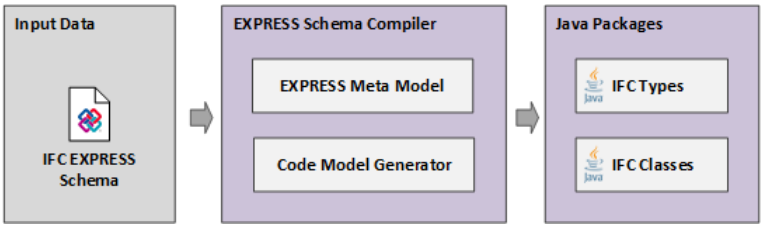

Figure 10 IFC Java Classes Generation using the EXPRESS Schema Compiler

Firstly, the compiler transforms the EXPRESS data into in-memory objects using an internal data model representation. Then, it applies a set of transformation rules to instantiate the corresponding Java Code Model objects. In the end, the Java Code Model framework generates the IFC classes and IFC types and classifies them based on the name of the IFC schema in different packages.

4.2.3 IFC Java Library

The IFC Java Library, aptly named IFC Library, uses the IFC classes and IFC types generated from the EXPRESS Schema Compiler to efficiently parse the STEP data and instantiate the representation of the BIM model in-memory. The current version of the implementation can handle the most frequently used IFC releases, from IFC2x3 to IFC4x3.

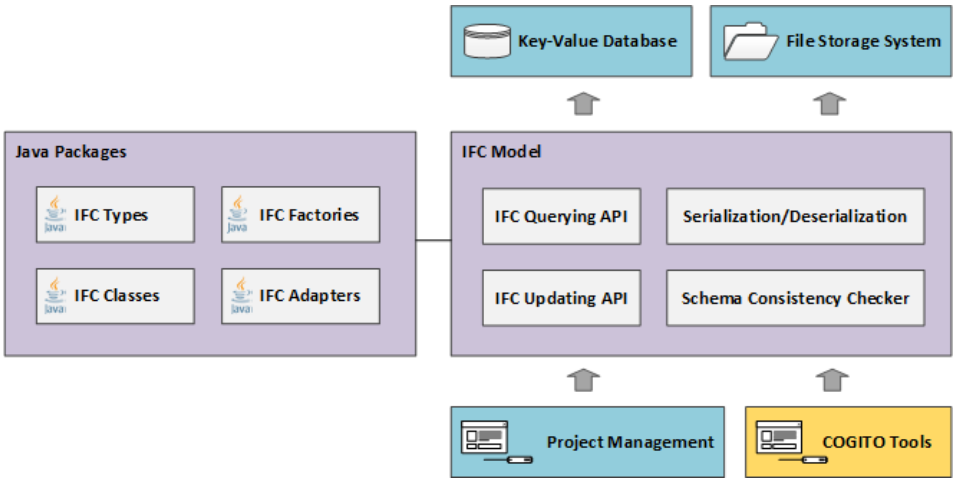

Figure 11 IFC Implementation for Java

As shown in Figure 11, the IFC Library provides an API that offers useful functionalities for handling the loaded objects. It supports an API for querying and updating the IFC objects and some advanced features such as initialising the inverse relations by adding an object to the corresponding collection of the inverse connected instance of another entity. The initialisation of the inverse relations in the objects is automatically archived by calling the inverse() method, as shown in Table 2.

Table 2 Example of inverse relations provided by the IFC Library

IfcElement

```
public IfcElement(){
   ...
   this.hasOpenings = new ArrayList<IfcRelVoidsElement>();
}

public void inverse(){
}

public List<IfcRelVoidsElement> getHasOpenings() {
   return this.hasOpenings;
}
```

IfcRelVoidsElement

```
public IfcRelVoidsElement(){
}

public void inverse(){
   if(this.element != null && this.element.getHasOpenings() != null){
      this.element.getHasOpenings().add(this);
   }
}
```

In the above example, using the *inverse()* method, it is possible to retrieve the *IfcRelVoidsElement* object from the inverse method *getHasOpenings()* of the *IfcElement* object. This functionality is widely used by the MVD completeness checking service.

4.2.4 IFC Consistency Checker

Within the COGITO solution, building information exchange among the different components is based on the openBIM standard IFC ISO 16739:2018. In IFC standard, the data are stored in ASCII form using the STEP format, the structure of which is defined according to the corresponding EXPRESS schema provided by buildingSMART International. The IFC Library includes a schema compliance checker for validating the STEP data against the EXPRESS schema of the standard. The schema compliance can perform validation across various datatypes, classes and restrictions in numerical values and collections.

4.2.5 IFC Geometry Exporter

The efficient processing of the IFC data consists of separate operations performed by individual libraries written in different programming languages. The deserialisation of IFC is easier using high-level programming languages such as Java or C#, while geometric operations are more efficient in low-level languages such as C or C++. As shown in Figure 12, the IFC Geometry Exporter component uses the IFC Library to parse the IFC data and generate an XML file that contains the geometric representation of the building elements and their related local coordinate system data. The generated XML conforms to an XSD schema which follows the geometric subset of the IFC4 Design Transfer View (DTV) specification, including the geometric extensions for IFC4x3.

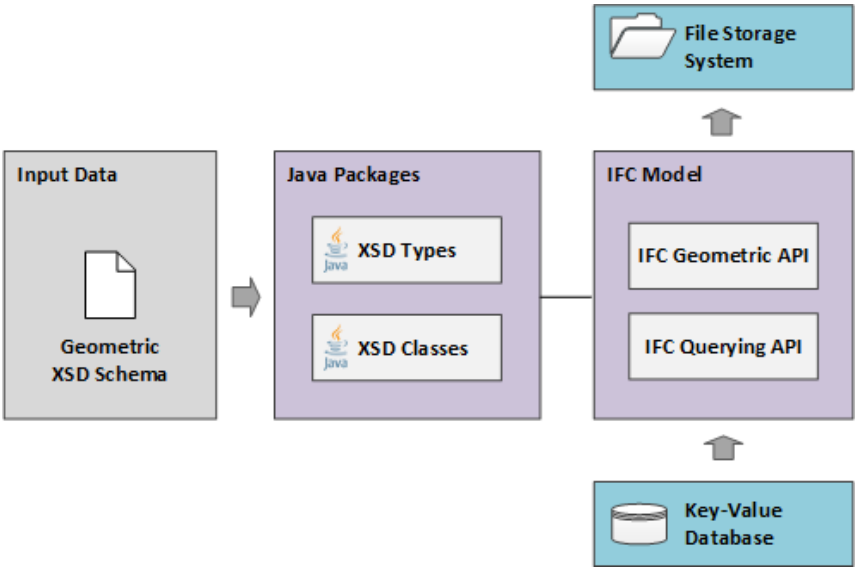

Figure 12 IFC Geometry Exporter component

4.2.6 IFC Revision Control

The BIM Management component can handle both the geometric and the semantic information included in the IFC data. In the IFC schema specification, the objects may reflect a final state, but they also may reflect a transient state. For instance, the SafeConAI application identifies zones in the BIM model where specific types of hazards can occur [6]. After identifying the zones, the tool enhances the BIM model with safety information by revising the existing IFC objects.

In a scenario where multiple applications update the IFC model simultaneously, the IFC schema supports local copies of the modified objects. The included revision scheme identifies changes declared on a per-object basis instead of identifying changes in the text. An IFC object is considered as modified when: a) any of the direct attributes changes; b) any referenced resources change; and c) items are added or removed from any collection. Each IFC object is marked with a change action within this revision scheme, indicating if the IFC object was added, modified, deleted, or not changed.

The COGITO applications can use this revision scheme to track the changes that might have occurred to the IFC objects during the last active session. In this case, the BIM Management component will know how various COGITO applications affect an IFC object. Figure 13 illustrates a scenario where various external tools update the original IFC. The BIM Management component is responsible for filtering and merging the updated IFC objects according to the latest changes.

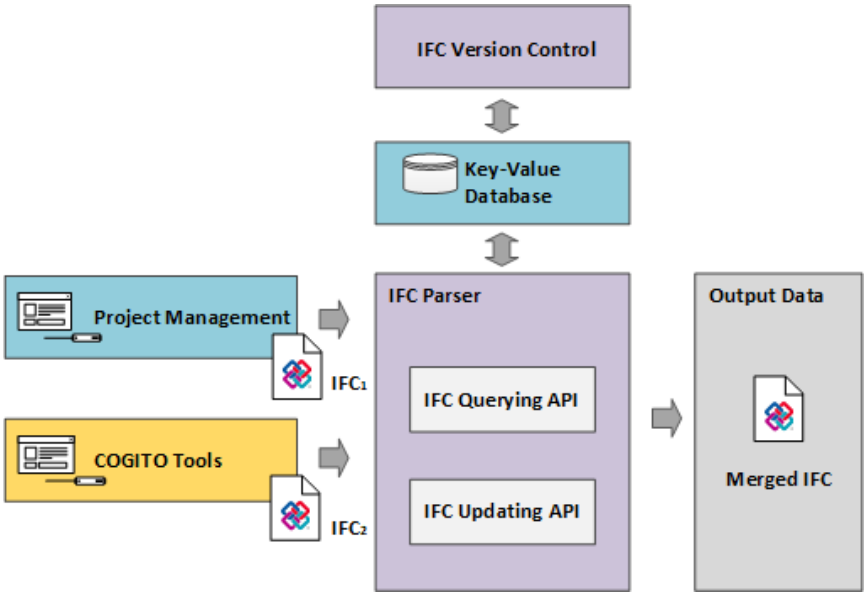

Figure 13 IFC Revision Control component

The process is as follows: First, the BIM authoring tool creates an IFC open for modifications. The IFC exporter should set the ChangeAction attribute of the IfcOwnerHistory to NOCHANGE to establish a baseline. With this annotation model, the BIM Management component can identify the upcoming modifications. Next, when a COGITO application updates the information of an existing IFC object, it should set the ChangeAction to MODIFIED and the OwningApplication to the application identifier. On the other hand, when it adds or deletes an IFC object, it should set the ChangeAction to ADDED or DELETED accordingly.

Moreover, the COGITO applications are responsible for updating the LastModifiedDate attribute to the time of modification. Thus, when the BIM Management component receives modified IFC data, it can determine which objects have been added, modified, and deleted and either merge or reject these changes, as necessary.

4.3 Knowledge Graph Generation

The Knowledge Graph Generation (KGG) component is responsible for generating, validating, and storing RDF graph data. As shown in Figure 14, it supports the transformation of heterogeneous data payloads coming from the different applications composing the COGITO project in several formats such as IFC, JSON, XML and CSV. The generated and validated RDF data will be merged into a unified knowledge graph which will conform to the semantic representation of the construction digital twin. This semantic representation will be the main provider of information from which the different applications can consume and exchange data.

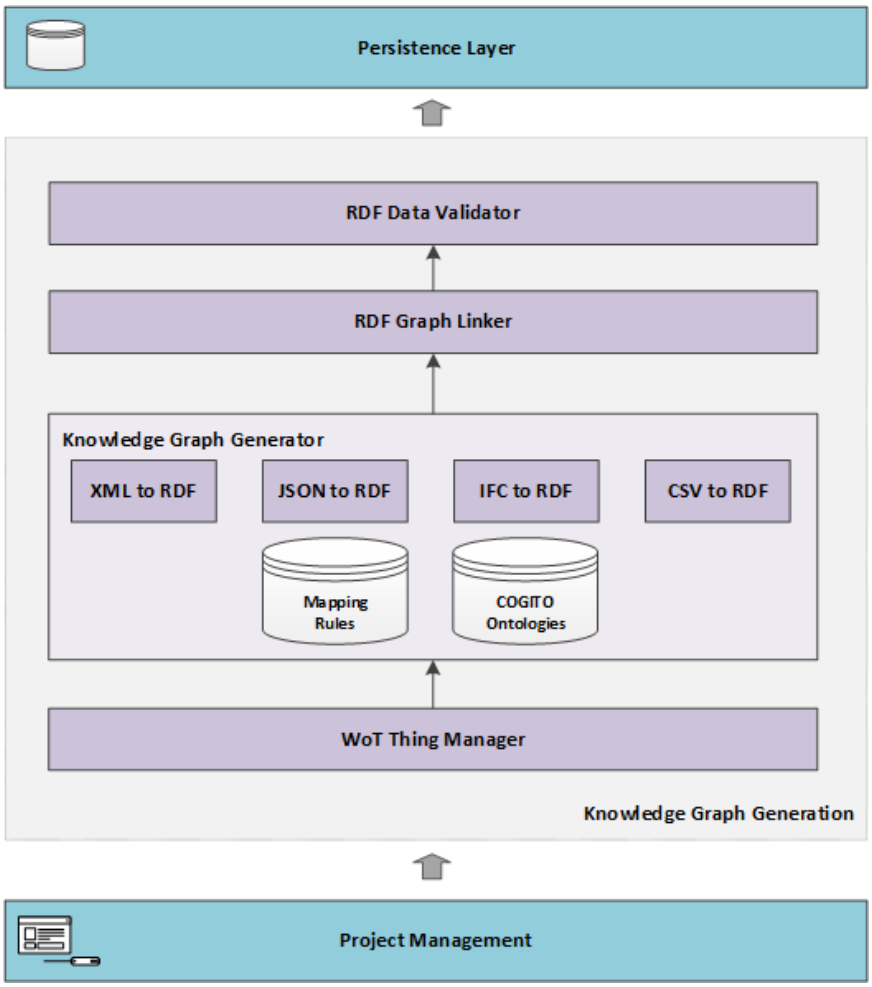

Figure 14 Knowledge Graph Generation

4.3.1 Architecture

Figure 15 shows the architecture of the KGG component, with the following modules: The Thing Manager, the Knowledge Graph Generator, the RDF Data Validator, and the RDF Graph Linker. In the RDF graph generation pipeline, each subcomponent is a standalone micro-service.

The Project Management component sends files to the **WoT Thing Manager** for their storage in the DTP. The Thing Manager is responsible for routing those files inside the system according to the type of information handled or the desired operation mode.

The **Knowledge Graph Generator** will receive the files from the Thing Manager and transform them to RDF data according to the ontologies defined in the project.

The **RDF Data Validator** will perform a series of validation checks to ensure the RDF data complies with the schema, with no missing values or incorrect data types.

Finally, the **RDF Graph Linker** is responsible for creating the connections between new and existing RDF data to generate a unified knowledge graph representing the different aspects of the project. The Data Persistence Layer stores this knowledge graph in a graph database (triple store). According to the data type pushed to the system, original files can also be stored in dedicated databases. Apart from the ingestion and transformation of data, the KGG also allows data retrieval from the knowledge graph or the original files.

The communication between the sub-components will be established utilising a dedicated network and internal APIs. The Thing Manager will be the only external interface from the KGG component to other components of the Data Ingestion Layer or COGITO applications.

The services are deployed independently as containerised backend applications using the Docker compose technology. The Flask micro framework with the Gunicorn HTTP WSGI server for handling the requests in production. The main programming language used for the development of the component is Python. In the following sub sections, we will provide further details for each subcomponent.

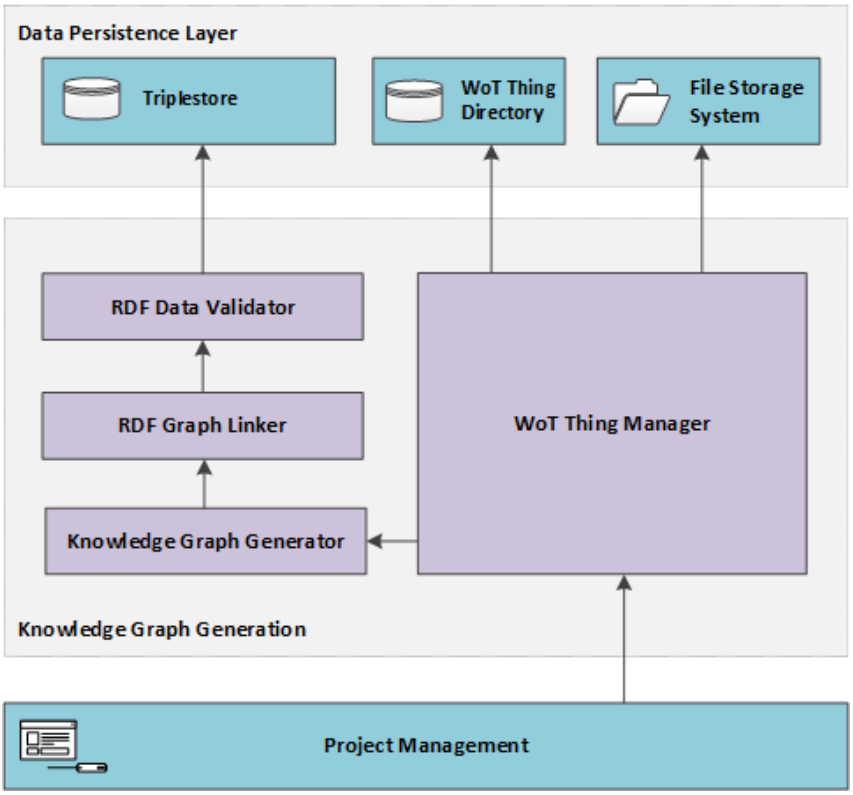

Figure 15 Architecture of the Knowledge Graph Generation component

4.3.2 Web of Things (WoT) Thing Manager

The WoT Thing Manager is responsible for orchestrating the flow of information inside the KGG component. The KGG component gets invoked externally when the RDF graph needs to be (re-)generated. Predefined configurations or the request parameters will activate the corresponding services to store or retrieve data correctly. The manager is also in charge of creating the descriptions for the different data resources needed. Those data resources represent the various components of the construction site, such as workers, equipment, machinery, spaces, building elements, etc. We follow the WoT Thing Description specification for their representation, which provides a set of standard metadata for defining those objects. Figure 16 provides a small example of the Thing Description used to model a location tracking device.

```
{
      "id": ""id": "urn:dev:wot:com:example:servient:tracking-device",
      "name": ""name": "MyTrackingDevice",
      "security": [{"scheme": "basic"}],"security": [{"scheme": "basic"}],
      "properties": {"properties": {
              "status": {"status": {":{
                      "type": "string",
                      "forms": [{""forms": [{"href": "coaps://dt.cogito.io/device/status"}]
              }},
              "battery": {"battery": {":{
                      "type": "integer",
                      "forms": [{"forms": [{"href": "coaps://dt.cogito.io/device/battery"}]
              }},
              "altitude": {"altitude": {":{
                      "type": "real",
                      "forms": [{"forms": [{"href": "coaps://dt.cogito.io/device/altitude"}]
              }},
              "longitude": {"longitude": {":{
                      "type": "real",
                      "forms": [{"forms": [{"href": "coaps://dt.cogito.io/device/longitude"}]
              }},
              "latitude": {"latitude": {":{
                      "type": "real",
                      "forms": [{"forms": [{"href": "coaps://dt.cogito.io/device/latitude”}]
              }}
      },},
      "actions": {"actions": {
              "alarm-on": {"alarm-on" : {
              "forms": [{"forms": [{"href": "coaps://dt.cogito.io/device/alarm/on"}]
              }},
              "alarm-off": {"alarm-off" : {
              "forms": [{"forms": [{href": "coaps://dt.cogito.io/device/alarm/off"}]
              }}
      },},
      "events":{"events":{": {
              "low-battery":{"low-battery":{
                      "type": "boolean",
                      "forms": [{"forms": [{
                              "href": "coaps://dt.cogito.io/device/low-battery",
                              "subProtocol": "LongPoll"
                      }]}]
              }}
      }}
}
```

Figure 16 Location Tracking Thing Description Example

The WoT Thing Description (TD) gives information about the different ways we can interact with the resources. Those interactions, called in the specification interaction affordances, are classified into three categories:

- Property Affordance: Provides information about certain internal states or properties of the thing we are modelling. The states can be read-only or writable. For instance, we can retrieve the device's current location by reading the properties of longitude, latitude, and altitude.

- Action Affordance: This allows the manipulation of the state of the thing or the triggering of an internal process. Examples of this type of interaction include the on or off actions of a sound alarm of a wearable location tracking device.
- Event Affordance: This type of interaction affordance pushes subscribers' event data, such as low battery notification.

For each type of interaction, the TD provides information concerning the endpoints needed to interact with the real resource, the access method, the protocol, etc. For the specific case of the resources in a construction project, we could have the thing description of the workers on the construction site. Those TDs can provide endpoints to access the notification devices of the workers and alert them in case they are near a dangerous zone.

The Thing Manager will generate those TDs automatically from the data upload by the COGITO application based on the ontologies developed for each domain. The thing descriptions created will be stored in a special component called the Thing Directory, which will perform the persistence of the TDs.

The Thing Manager is implemented as a backend service, provided as a containerised application using the Docker technology for its easy deployment. The main framework used for the implementation of the service has been the Flask micro-framework.

4.3.3 Knowledge Graph Generator

The Knowledge Graph Generator is responsible for transforming heterogeneous data provided by the different COGITO applications into RDF graph data. This component ensures that the graph data generated is aligned with the ontologies developed for each domain. The administrators of the Knowledge Graph Generator define the mappings files for each domain or application before we can proceed with the execution of the respective transformation. We define the mapping rules to perform the data transformation using RML (the RDF Mapping Language). The processed data is then sent to the other services of the data ingestion layer to validate the data, perform the appropriate links to the existing graph, and store the data in the proper graph database in the data persistence layer.

In particular, the RDF Data Generator offers the following capabilities:

- Mapping of the ingested data to the respective COGITO ontologies: Mapping files will be created to align the concepts from the data provided by the applications and concepts from ontologies developed for the different domains of the project.
- Transformation of the ingested data to the respective COGITO ontology: Using the previously created RML mapping files, the Knowledge Graph Generator derives the transformation rules needed to convert the original data into RDF graph data automatically.

The module will be implemented as a backend service with two layers:

- The Business Logic Layer contains the logic behind the execution of the transformation rules. The Flask micro web framework and Helio will be used for the development. Helio is a framework that allows the translation of data into RDF and the publication of RDF data as a Linked Data Service.
- The Data Access Layer stores the mapping files and additional internal configuration files. This DAL layer will utilise a Postgress database.

4.3.4 Knowledge Graph Linker

The Knowledge Graph Data Linker or Identity Link Detection component will be responsible for linking different resources belonging to different knowledge graphs. When two resource descriptions refer to the same real-world entity, such as the same person, or identical items, it is possible to establish a link reflecting this identity relationship. This way, heterogeneous data provided by the various COGITO applications can be linked, obtaining greater effectiveness. Potential advantages of the linked data approach include improved *precision* and *robustness* by cancelling possible errors in the data; *efficiency* in terms of time and space, minimising the search time between different resources; and *versatility*, applying to various datasets

and domains. The positive benefits of this linked data approaches will be evaluated in the context of the COGITO applications.

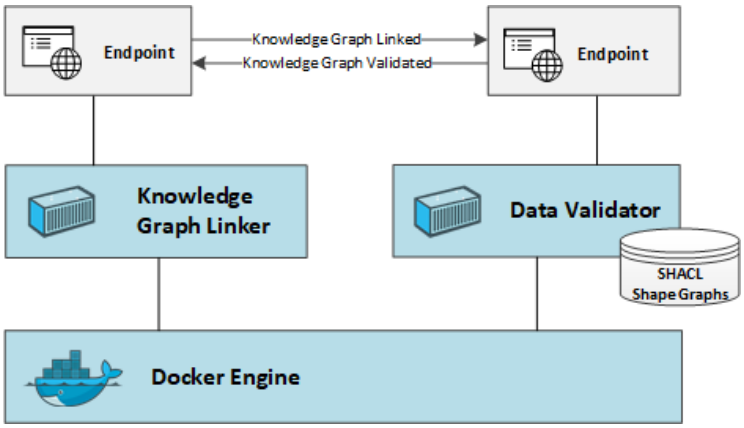

Figure 17 Knowledge graph linking process

Figure 17 shows the interaction between the Knowledge Graph Linker and the RDF Data Validator through the provided endpoints. The process carried out is as follows:

- The knowledge graph validated by the RDF Data Validator is received.
- Existing data within the knowledge graph are linked through linking processes described in the Knowledge Graph Linker service.
- Once the existing data within the knowledge graph is linked, the network is forwarded to the RDF Data Validator to validate the created links.

4.3.5 RDF Data Validator

The RDF Data Validator aims to detect, through the validation process, the different possible errors that may exist within the previously generated knowledge graph. A recent development, the Shapes Constraint Language (SHACL) can help achieve this.

SHACL is a language for validating RDF graphs against a set of requirements provided as shapes and other constructs expressed in the form of an RDF graph (shapes graphs). SHACL shape graphs are used to validate the data graph, and they can be a description of the data graphs that satisfy a set of conditions or requirements. RDF graphs that pass validated against a shapes graph are called "application profiles".

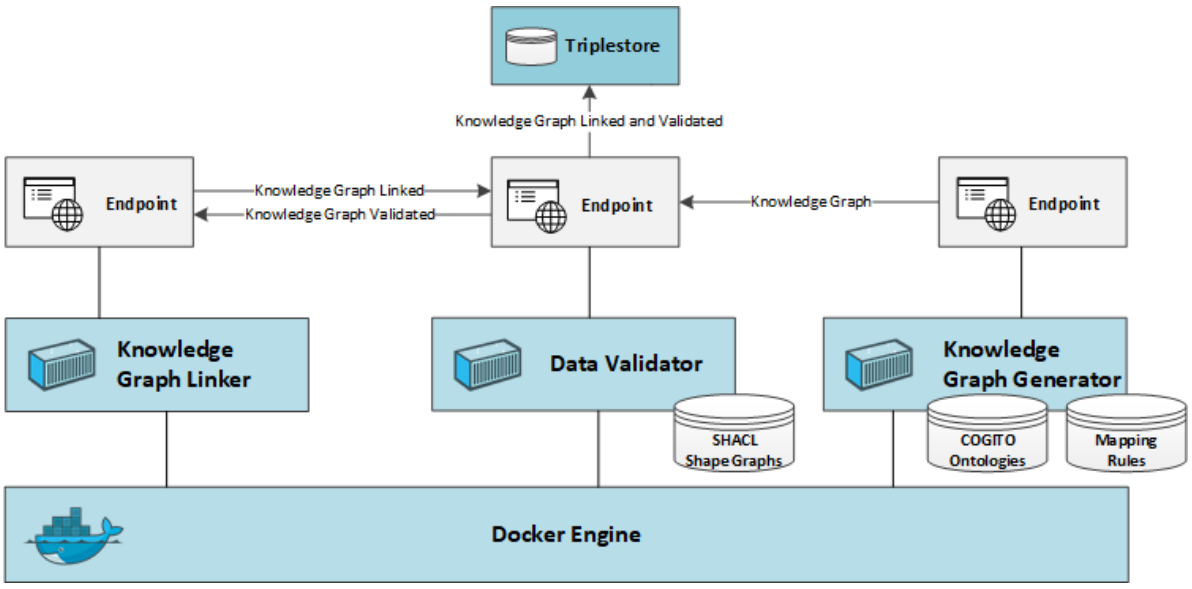

Figure 18 RDF Data Validator architecture

Figure 18 presents the architecture of the RDF Data Validator, where the generated knowledge graph is received by an endpoint that is connected to the Knowledge Graph Generator endpoint. In turn, the container belonging to the RDF Data Validator has a database in which all the SHACL Shapes are stored, which are subsequently used for the validation of the received knowledge graphs.

The process carried out within the architecture has as follows:

- The knowledge graph generated by the Knowledge Graph Generator is received.
- The SHACL Shapes in accordance with the received knowledge graph are selected from the described database.
- The validation process of the knowledge graph is performed with the use of the SHACL Shapes.
- The validated knowledge graph is sent to the next container, in this case, the one belonging to the Knowledge Graph Linker.
- When the linking process is finished in the Knowledge Graph Linker container, the linked knowledge graph is sent back to the validation container and validated again, following steps 2 and 3, to validate the links created in the linking process.
- Once the validation process is finished, the knowledge graph is stored in a Triple store, in this case, a Virtuoso SPARQL Endpoint.

5 Data Persistence Layer

The Data Persistence Layer of the DTP contains different types of datastores for storing structured data. Based on the architecture specification of the platform, the Persistence Layer consists of a) a file storage system for storing files generated by other COGITO applications, b) a relational database for storing project and user data, c) a key-value database for storing IFC objects, d) a time-series database for storing IoT sensor data and e) a triplestore for storing COGITO's knowledge graph(s). The following subsections describe these datastores and their functionalities.

5.1 File Storage System

The File Storage system provides a file storage solution enabling other COGITO applications to access shared files. It supports file system semantics and a permission model applying access policies such as role-based access control on the registered users. The proposed software implementation includes a REST API for accessing and managing files stored on a DTP cloud provider.

5.2 Project Database

The Project database includes various tables and relationships representing a relational data model which stores the information required by the Project Management component. The tables related to users and user roles are populated and synchronised by the Identity Provider of the Authentication Layer, as shown in Figure 19.

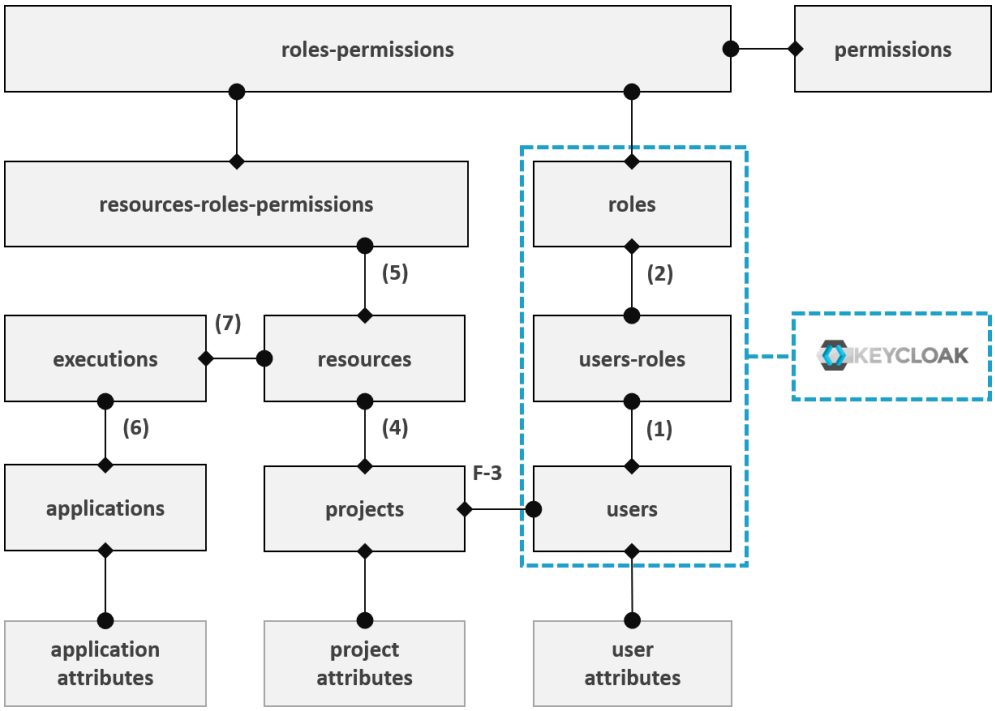

Figure 19 Relational data-model of the Project Management component

The GUI and the REST API use the information stored in the Project database and the relationships among the different tables to support core functionalities of the Data Ingestion Layer, which are described as follows:

1. Storing user accounts defined by Keycloak in the Authentication Layer.
2. Storing user roles defined by Keycloak in the Authentication Layer.
3. Assigning user accounts to a specific COGITO project.
4. Storing meta-data of the uploaded files and assigning them to a specific COGITO project.
5. Applying access policies to the uploaded files using a permission scheme connected with the user roles.

6. Monitoring the various COGITO applications and the progress of their executions.
7. Applying access-policies on the output resources of the executions of the various COGITO applications.

The Project Management component uses the Spring Java Persistence API (JPA) and the Hibernate framework, for automatic deployment of the Project database. In this context, Java classes represent the tables, while the fields inside the classes represent properties and the relations between different tables. The Spring JPA framework supports all types of relations such as one-to-one, many-to-one, one-to-many and many-to-many. When using this approach, the relational database can bet transparently managed from Java, increasing the abstraction level of the persistence layer.

The Project Management requires a connection to a MySQL server. MySQL server is a Relational Database Management Systems (RDBMS) that supports multi-tenancy. The Hibernate framework utilises the MySQL dialect to access the Project database for performing transactional operations and queries. The Spring JPA entirely manages the generation and execution of the SQL queries used mainly for providing the necessary information to the GUI and the REST API.

5.3 Key-Value Database

As mentioned in a previous section, the IFC Library provides an object-oriented representation of the IFC model. The STEP-data are parsed and loaded in memory using the IFC Java classes generated by the EXPRESS Schema Compiler. Based on their scope, the generated IFC Java classes implement various interfaces to achieve the desired level of abstraction. The IFC EXPRESS schema contains a set of different data types for storing IFC data described as follows:

- **ENTITY** is equivalent to the Java class. It can be defined as an abstract or concrete class, including attributes, and implementing various interfaces.
- **ENUMERATED** is equivalent to the Java Enum. It represents a group of unchangeable STRING values.
- **SELECT** is equivalent to the Java interface. It defines a choice or an alternative between different options.
- **SIMPLE** is equivalent to the Java basic data types such as Integer, Double, Boolean and String.

The IFC Library defines a set of high-level interfaces to handle the above data types, as shown in Figure 20.

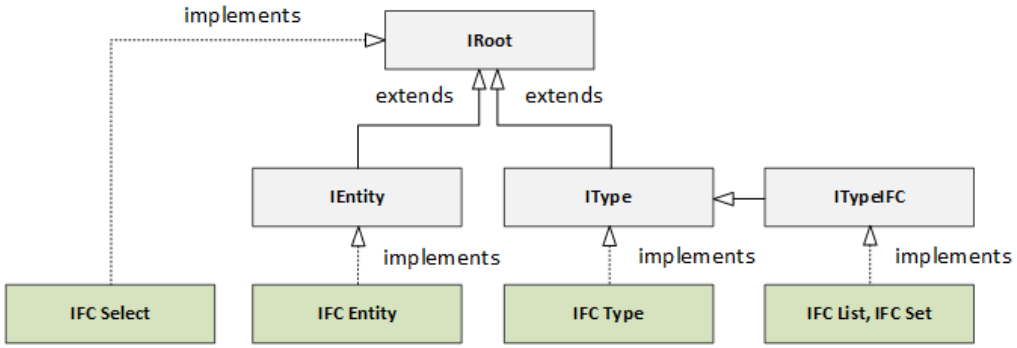

Figure 20 High-level interfaces defined in the IFC Library

The IFC parser of the BIM Management component includes a HashMap collection to store the key-value pairs of the loaded IFC data in memory. Each key contains the EXPRESS Id, and the corresponding value contains the IFC object that implements the IFC Library's high-level interfaces. After parsing the IFC, the BIM Management component stores the collection of the key-value pairs in Redis DB. Redis DB provides a distributed and high-performance key-value database system that offers additional functionalities than the Java HashMap collection, such as remote instances, persistence, concurrent read/write and more.

5.4 Timeseries Database

For storing location tracking data coming from sensorial IoT devices installed on workers and machinery located in the construction site, the Persistence Layer of the DTP provides a time-series database based on InfluxDB. This database is optimised for storing high-volume data produced from the various IoT devices. The IoT Data Pre-Processing tool feeds the datastore with timestamped location tracking data identified by a unique Tag ID. The Worker Order Definition and Monitoring (WODM) tool is in charge to assign workers and machinery to the registered IoT devices. Through the SPARQL API Wrapper, the Data Management Layer queries the knowledge graph to retrieve the Tag IDs. Then, it performs a second request through the Timeseries API Wrapper for retrieving the corresponding time-series data.

5.5 Graph Database

The Graph Database will store the RDF data generated by the Knowledge Graph Generation component. The RDF data will be stored under different namespaces (graphs) on different domains. The graph database will include the graph network representing the various aspects of the construction digital twin. The Graph database will support read, update, write and delete operations through its SPARQL endpoint. This endpoint will not be accessed directly by the applications or by the WOT Thing Manager performing predefined SPARQL queries. However, this data will be linked utilising common concepts in the models.

The triple store is deployed independently as a Docker container and will be implemented using the Virtuoso[3] database.

5.6 Thing Description Directory

The Thing Description Directory is a persistence service that contains the Thing Descriptions (TD) created by the Thing Manager component in the Knowledge Graph Generator. The directory will support the discovery, creation, retrieval, update and deletion of TD's. The Thing directory uses the WoT Hive implementation, compliant with the W3C Web of Things Directory standard specification. The RDF4J triplestore will be used.

[3]Virtuoso Universal Server https://virtuoso.openlinksw.com

6 Data Management Layer

The Data Management Layer consists of a) a set of API wrappers for interacting with the Data Persistence Layer, b) an actor-based runtime system for hosting modules used for synchronising the various data coming from the Data Persistence Layer, and c) message adapters and web services for interacting with the various COGITO applications. Figure 21 shows the interactions between the components included in the Data Management Layer and the COGITO applications.

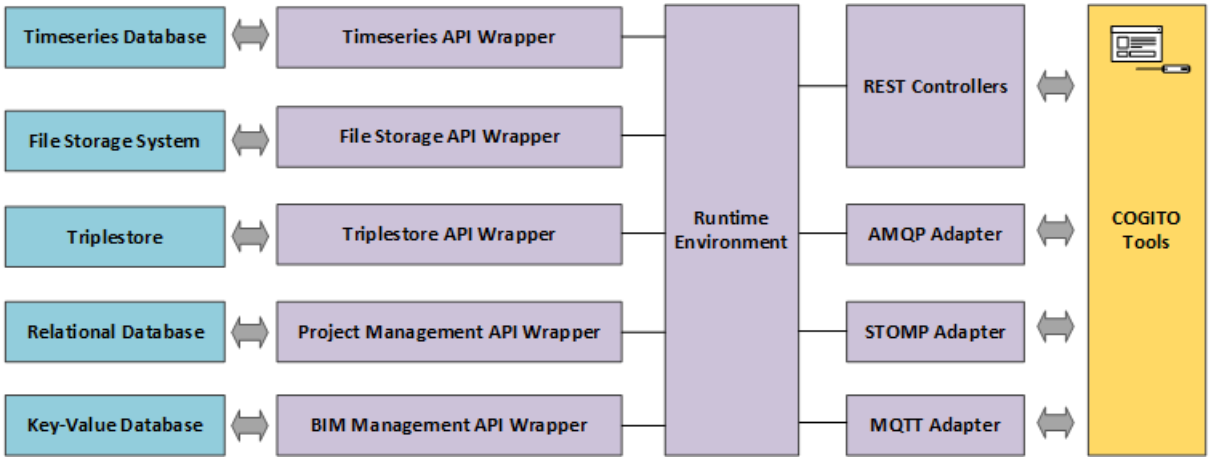

Figure 21 Data Management Layer architecture

The Data Management Layer is responsible for performing and supervising data query operations, ensuring that data have been correctly retrieved from the Persistence Layer and efficiently delivered to their destinations. It includes a set of API wrappers for abstracting the interfaces between the datastores of the Persistence Layer and the various COGITO applications. Furthermore, the embedded actor-based runtime environment orchestrates the data processing operations, ensuring that the data coming from different datastores are synchronised and harmonised before being forwarded to the data consumers through the available adapters.

6.1 API Wrappers

For interacting with the Persistence Layer, the Data Management Layer contains a set of Java packages (API wrappers) that encapsulate collections of different API requests to facilitate the reusability and minimise the relevance of the expertise in the development of the various modules. The final list of DTP's API wrappers is presented in Table 3.

Table 3 DTP's API wrappers

Name	Description
Project API Wrapper	This package contains methods to facilitate the interactions with the Project Management component. The responses are JSON data.
BIM API Wrapper	This package contains methods to facilitate the interactions with the BIM Management component. The responses are OBJ, IFC or JSON data.
Timeseries API wrapper	This package contains methods to facilitate the retrieval of dynamic data from the location tracking system or from the historical Timeseries DB.
Files API wrapper	This package contains methods to facilitate file manipulation of cloud-based storage systems.
RDF API wrapper	This package contains methods to facilitate the interaction with COGITO's knowledge graph. It provides a list of preconfigured SPARQL queries.

6.2 Runtime Environment

The actor-based runtime environment is a lightweight container for hosting modules deployed to synchronise data responses from the Persistence Layer and harmonise the data before being delivered to the final destinations. It is based on the open-source project Akka[4] which provides a toolkit and a runtime environment for simplifying the construction of concurrent and distributed applications. In other words, Akka is a powerful reactive high-performance framework optimised for running on the Java Virtual Machine (JVM) that can handle multiple queries simultaneously and respond to COGITO applications through the available adapters.

6.2.1 Architecture

The proposed architecture includes a set of system actors for executing the internal data requests sequentially using the API wrappers of the Data Management Layer. This solution implements a conceptual model to deal with concurrent asynchronous data requests and enables the communication between primitive software units, named actors. An actor is an extensible program-code template that uses the available API wrappers for interacting with the Persistence Layer, executes its business-logic operations and forwards the results to other actors by producing asynchronous messages.

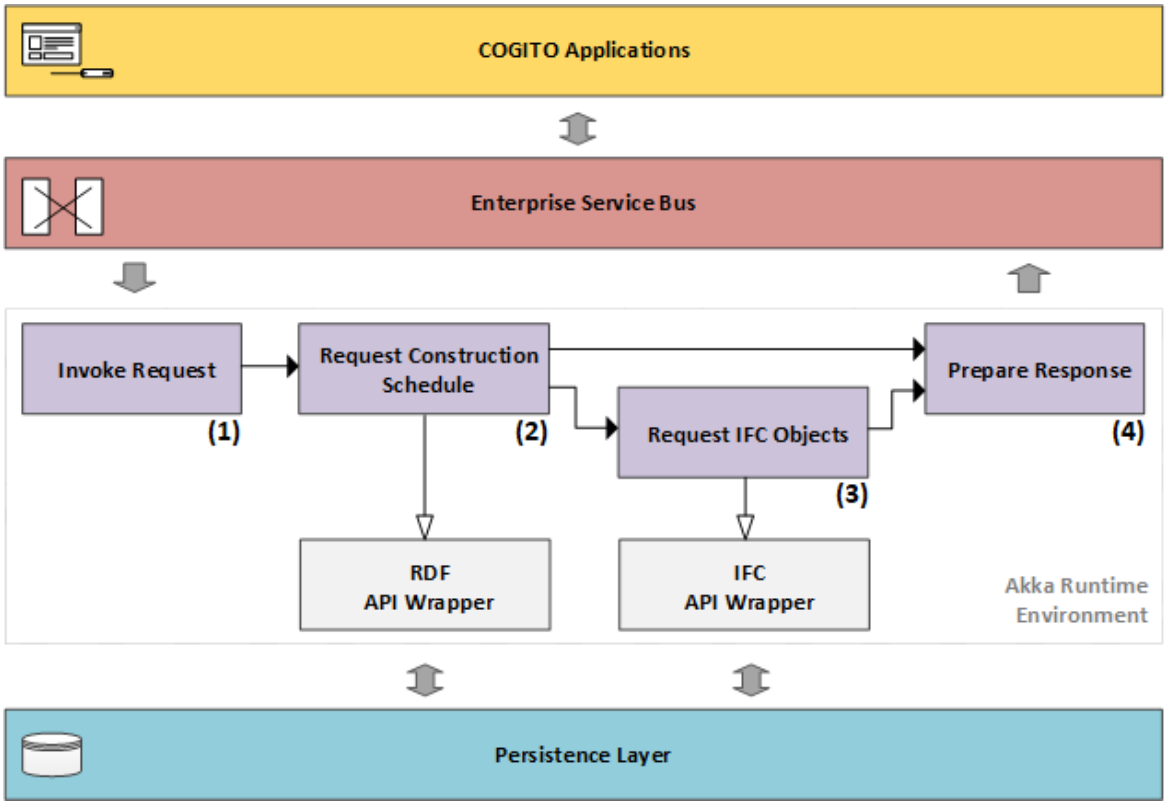

Figure 22 Example of actors' deployment in the Akka Runtime Environment

By way of example, see Figure 22. The involved actors are wired together in a sequence for handling the complex request of querying 4D BIM data from the DTP. First, a system actor **(1)** handles the incoming request and triggers the executions of the following actors **(2,3)** for retrieving the construction schedule and the corresponding IFC objects. These actors use the API wrappers for interacting with the Data Persistence Layer. Next, the last actor **(4)** is responsible for synchronising, merging, and delivering the results to the correct destination through the ESB.

This is one way of creating responses to complex queries. Such actors can be created and re-used depending on application needs and information requirements.

[4] Akka Actor Model https://www.akka.io

6.3 Interface Specification

Based on the work performed in "T2.4 COGITO System Architecture Design" and the corresponding deliverable "D2.4 COGITO System Architecture V1", the main data exchange requirements between the DTP and the various COGITO applications have been identified [6]. Within COGITO, the multiple tools can be categorised as follows:

- **Data Pre-processing** tools are responsible for a) pre-processing raw visual and location tracking data, b) annotating the processed data, and c) storing the data into DTP's Persistence Layer.
- **Health and Safety** tools are responsible for generating hazards mitigation measures and producing warning notifications to the on-site crew for their proximity to hazardous areas.
- **Workflow Modeling and Simulation** tools are responsible for monitoring and optimising the construction processes.
- **Quality Control** tools are responsible for comparing the as-designed and as-built data and detecting potential defects.
- **Visualisation** tools are responsible for retrieving data from the DTP and visualise it to support on-site and off-site activities of relevant stakeholders and training of the workers.

As shown in Table 4, the COGITO applications with their high-level data exchange requirements are grouped into the identified categories.

Table 4 Data exchange requirements of COGITO applications

Categories	COGITO Tools	Input Data	Output Data
Data Pre-processing tools	IoT Data Pre-processing	-	▪ Timestamped measurements of location tracking devices (**longitude, latitude, altitude, tags**)
	Visual Data Pre-processing	▪ Authentication Tokens ▪ Semantically linked data (**geometric representations of building elements, building element objects, task objects**) filtered by (**camera location, time range**)	▪ Annotated imagery datasets. (**building element objects, images**) ▪ Annotated point clouds. (**building element objects, point cloud datasets**)
Health and Safety	VirtualSafety	▪ Semantically linked data (**geometric representations of building elements, building element objects, geometric representations of H&S elements, H&S elements, tasks**) filtered by (**time range**)	▪ Training KPIs for workers (**actual resource objects, performance metrics objects**)
	SafeConAI	▪ Authentication Tokens ▪ Semantically linked data (**geometric representations of building elements, building element objects, task objects**) filtered by (**time range**)	▪ Semantically linked data (**geometric representations of H&S elements, H&S elements**)
	ProActiveSafety	▪ Semantically linked data (**geometric representations of building elements, building element objects, geometric representations of H&S elements, H&S elements, tasks**) filtered by (**time range**) ▪ Timestamped measurements of actual resources (**longitude, latitude, altitude, actual resource objects**)	▪ Notification (**actual resource objects, safety warning objects**)
Workflow Modeling and Simulation	WODM	▪ Authentication Tokens ▪ Semantically linked (**actual resource objects, tags**) ▪ Semantically linked data (**as-planned resources ,task objects, building element objects**)	▪ Semantically linked data (**actual resource objects, task objects, building element objects**)
	WOEA	▪ Authentication Tokens	-

	PMS	▪ Authentication Tokens ▪ Initial data (**as-planned resources**) ▪ Initial linked data (**building element objects, construction schedule**) ▪ Timestamped measurements of actual resources. (**longitude, latitude, altitude, actual resource objects**) ▪ Semantically linked data (**geometry quality control objects, building element objects**) ▪ Semantically linked data (**visual defect objects, building element objects, images**) ▪ Semantically linked data (**geometric representations of H&S elements, H&S elements**) ▪ Defect Notification (**building element objects, images, type of remedial works**) ▪ Hazard Notification (**building element objects, images, type of mitigation works**)	▪ Semantically linked data (**as-planned resources, task objects, tag objects, building element objects**) ▪ Semantically linked data (**actual resource objects, task objects, tag objects, building element objects**)
Quality Control	Geometry QC	▪ Semantically linked data (**geometric representations of building elements, annotated point clouds**) filtered by (**time range**)	▪ Semantically linked data (**geometry quality control objects, building element objects**)
	Visual QC	▪ Semantically linked data (**geometric representations of building elements, tasks**) filtered by (**camera location**)	▪ Semantically linked data (**visual defect objects, building element objects, images**)
Visualisation	DigiTAR	▪ Authentication Tokens ▪ Semantically linked data (**geometric representations of building elements, building element objects, geometric representations of H&S elements, H&S elements**) filtered by (**AR glasses/tablets location**) ▪ Semantically linked data (**geometry quality control objects, building element object**) ▪ Semantically linked data (**visual defect objects, building element objects, images**)	▪ Defect Notification (**building element objects, images, type of remedial works**) ▪ Hazard Notification (**building element objects, images, type of mitigation works**)
	DCC	▪ Authentication Tokens ▪ Semantically linked data (**geometric representations of building elements, building element objects, geometric representations of H&S elements, H&S elements, tasks**) filtered by (**time range**) ▪ Semantically linked data (**geometry quality control objects, building element object**) ▪ Semantically linked data (**visual defect objects, building element objects, images**) ▪ Timestamped measurements of actual resources. (**longitude, latitude, altitude, actual resource objects**)	-

To meet the diverse data needs of the various COGITO applications, the Data Management Layer asynchronously bridges the different data stored in the Persistence Layer via a set of dedicated interfaces. Table 5 shows the identified interfaces of the DTP with their high-level specifications. These interfaces have been processed and merged based on the type and applied filters.

Table 5 DTP's external interfaces

Type	Data Exchange	Protocol	API	Data Type
Input Data	Timestamped measurements of location tracking devices (**longitude, latitude, altitude, tags**)	MQTT	-	JSON
	Annotated imagery datasets. (**building element objects, images**)	HTTPS	REST	JSON
	Annotated point clouds. (**building element objects, point cloud datasets**)	HTTPS	REST	JSON
	Training KPIs for workers (**actual resource objects, performance metrics objects**)	HTTPS	REST	JSON
	Semantically linked data (**geometric representations of H&S elements, H&S elements**)	HTTPS	REST	IFC
	Semantically linked data (**as-planned resource objects, task objects, building element objects**)	HTTPS	REST	BPMN
	Semantically linked data (**actual resource objects, task objects, building element objects**)	HTTPS	REST	BPMN
	Semantically linked data (**geometry quality control objects, building element objects**)	HTTPS	REST	JSON
	Semantically linked data (**visual defect objects, building element objects, images**)	HTTPS	REST	JSON
	Defect Notification (**building element objects, images, type of remedial works**)	AMQP	JMS	Images, JSON
	Hazard Notification (**building element objects, images, type of mitigation works**)	AMQP	JMS	Images, JSON
Output Data	Authentication Tokens	HTTPS	REST	JSON
	Semantically linked data (**geometric representations of building elements, building element objects, task objects**) filtered by (**location, time range**)	AMQP	JMS	OBJ, IFC, JSON
	Semantically linked data (**geometric representations of building elements, building element objects, geometric representations of H&S elements, H&S elements, task objects**) filtered by (**location, time range**)	AMQP	JMS	OBJ, IFC, JSON
	Timestamped measurements of actual resources (**longitude, latitude, altitude, actual resource objects**)	HTTPS	REST	JSON
	Semantically linked (**actual resource objects, tags**)	HTTPS	REST	JSON
	Semantically linked data (**as-planned resources ,task objects, building element objects**)	HTTPS	REST	JSON
	Initial data (**as-planned resources**)	HTTPS	REST	JSON
	Initial linked data (**building element objects, construction schedule**)	HTTPS	REST	JSON
	Semantically linked data (**geometry quality control objects, building element objects**)	HTTPS	REST	JSON, BCF
	Semantically linked data (**visual defect objects, building element objects, images**)	HTTPS	REST	JSON, BCF
	Semantically linked data (**geometric representations of H&S elements, H&S elements**)	HTTPS	REST	IFC
	Defect Notification (**building element objects, images, type of remedial works**)	AMQP	JMS	Images, JSON
	Hazard Notification (**building element objects, images, type of mitigation works**)	AMQP	JMS	Images, JSON
	Semantically linked data (**geometric representations of building elements, annotated point clouds**) filtered by (**time range**)	AMQP	JMS	Point Cloud, JSON

The endpoints and the specification of the identified interfaces will be reported in the final version of this deliverable "D7.2 Digital Twin Platform Design & Interface Specification V2".

7 Messaging Layer

The Messaging Layer is responsible for transmitting data asynchronously between the Data Management Layer and the various COGITO applications. Since the COGITO applications will be implemented using different technologies and communication protocols, a system that provides the infrastructure compatible with these technologies is required. For this purpose, an Enterprise Service Bus (ESB) is deployed, which enables the integration of different communication protocols.

The ESB supports event-driven and service-oriented communication approaches and offers an integrated solution allowing bi-directional communication between the DTP services and the COGITO applications. The ESB provides a native integration environment using multiple technologies and protocols for the connectivity of the applications and supports both synchronous and asynchronous communication patterns. As shown in Figure 23, the ESB consists of a) a message broker implementation for establishing asynchronous remote connections between producers and consumers and b) an integration framework for configuring message routers, translators, and endpoints.

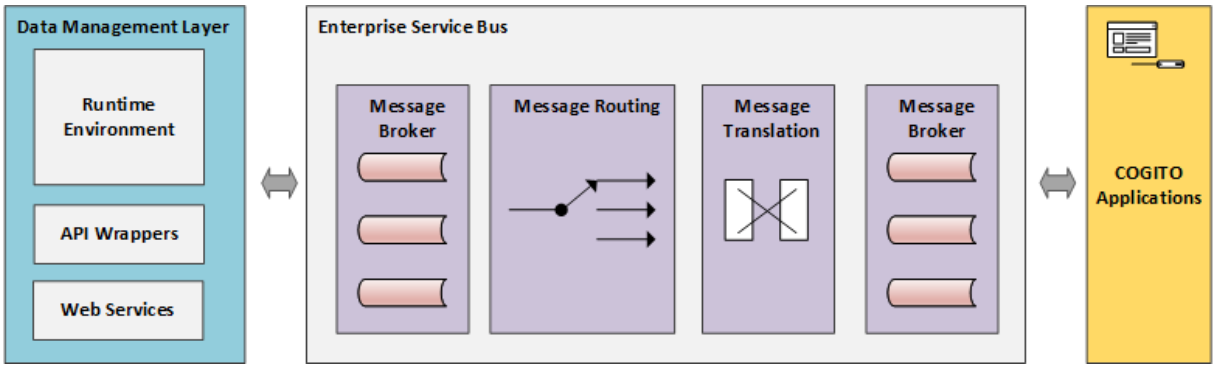

Figure 23 Enterprise Service Bus architecture

The ESB includes an Active MQ message broker, which supports communication over secure connections using various protocols such as Advanced Message Queueing Protocol (AMQP), Streaming Text Oriented Messaging Protocol (STOMP) and Message Queue Telemetry Transport (MQTT). The primary reason for using a message broker is to increase the performance and reliability of the DTP. Supposing that any data consumer happens to be offline for a short period due to connectivity issues, the message broker could continue accepting messages by storing them into the embedded queues.

Furthermore, the ESB includes the Apache Camel integration framework, which offers advanced message routing patterns based on the message payload's content. There are cases where the producers do not know the exact channel that the message to the consumer will get, but the producer sends the message to the ESB, determining how to deliver the message to the consumer.

In addition, if the COGITO applications do not agree on the format of the messages, Apache Camel (the framework used for the ESB) includes a set of filters for converting message payloads that contain the same conceptual information from one form to another.

8 Data Post-processing Layer

The Data Post-processing Layer comprises components for handling time-consuming processes such as IFC optimisation, MVD model checking and B-rep geometry generation. These components are modular, and additional can be included in an extensible manner. They contain a set of low- and high-level libraries to perform their business logic operations. The low-level libraries support multithread processing and exchange information with the high-level libraries through the Java Native Interface (JNI) programming framework.

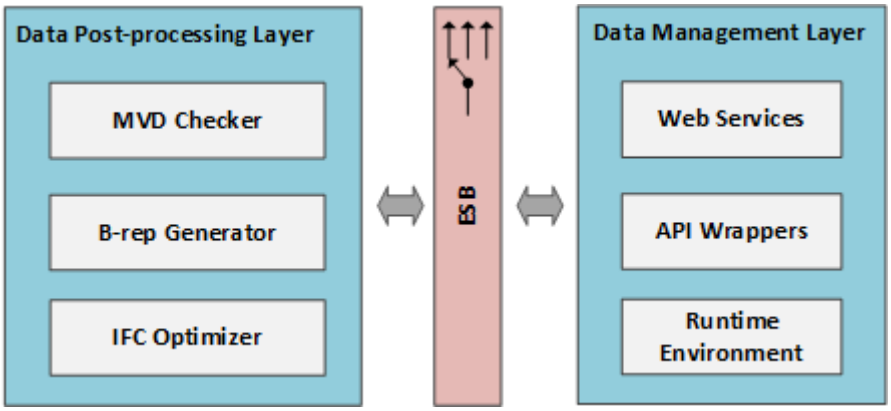

Figure 24 Data flow between Data Post-processing Layer and the Data Management Layer

The components are packaged as Software as a Service (SaaS) applications and deployed in a private cloud computing infrastructure. In the proposed architecture design, we defined the following components as a basis of the first implementation of the Data Post-processing Layer.

- **The Model-View Definition (MVD) Checker** helps the BIM Manager to validate IFC files in terms of data completeness and semantic consistency against predefined rules following the MVD specification. This component reports the detected issues using machine-readable data storage formats such as JSON and XML.
- **The B-rep Generator** reads the geometric information generated from the IFC Geometry Exporter to generate triangulated B-rep solids of the structural and non-structural elements. This component exports the geometric information using open formats such as OBJ and glTF.
- **The IFC Optimiser** performs lossless compression of an IFC file to speed up loading and data transformation processes. This component generates a new IFC with reduced file size.

As shown in Figure 24, each of these components exchange information asynchronously through the ESB using data structures which conform to openBIM standards. The integration framework of the ESB controls the biding between the components of Data Post-processing Layer and Data Management Layer.

8.1 Architecture

The three main components of the Data Post-processing Layer are deployed as lightweight standalone Spring Boot applications, following the microservice architecture design pattern. Because they don't have GUI and persistence, some Spring Framework components such as Spring MVC, Spring JPA, and Spring Security are not included in the final packages. Instead, a looser of coupling is used through the Spring JMS component, enabling asynchronous communication between the Data Post-processing Layer and the Data Management Layer. Security in message passing is assured through various encryption protocols and the connection credentials defined by the message broker of the ESB.

A methodology for achieving a significant reduction in the executions times is the separation of their business logic operations into two groups a) high-level operations such as IFC data handling using high-level programming environments such as Java, and b) low-level geometric operations such as B-rep generation and mesh triangulation using low-level programming environments such as C/C++.

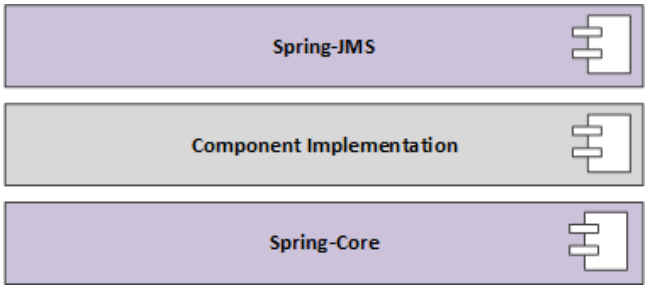

Figure 25 Stack-diagram of Data Post-processing Layer components

Each component of the Data Post-processing Layer provides an API including several indicators to inspect the health of running processes, memory usage, error logging and more. Figure 25 illustrates the stack diagram of these components.

8.2 Model View Definition (MVD) Checker

The IFC specification includes a multi-domain information model for capturing building data such as geometry, materials, components, properties and more. To support specific data exchange requirements between different tools and processes, only a subset of the IFC specification is required in terms of user entities and properties. The Model View Definition (MVD) specification allows the definition of reusable Concept Templates and Rules to describe the data exchange requirements precisely. Along with the maintenance of the IFC specification, buildingSMART has published the following general-purpose Model View Definition schemes:

- **IFC Reference View** mainly used by tools and services that do not require geometry modifications. The geometric representation is optimised for analysis and display purposes but excludes the parametric geometry definitions.
- **IFC Design Transfer View** supports the editing of geometric representations of structural and non-structural building elements. It is the preferred MVD in COGITO solution because it enables the enrichment of the BIM model with new properties and geometric objects.

The DTP provides the MVD completeness checking component to help COGITO users validate the BIM model's completeness against predefined concepts using the mvdXML specification. For instance, completeness checking is essential to ensure that each structural building element of the IFC model has a property used to create the semantic link between the element and the construction schedule.

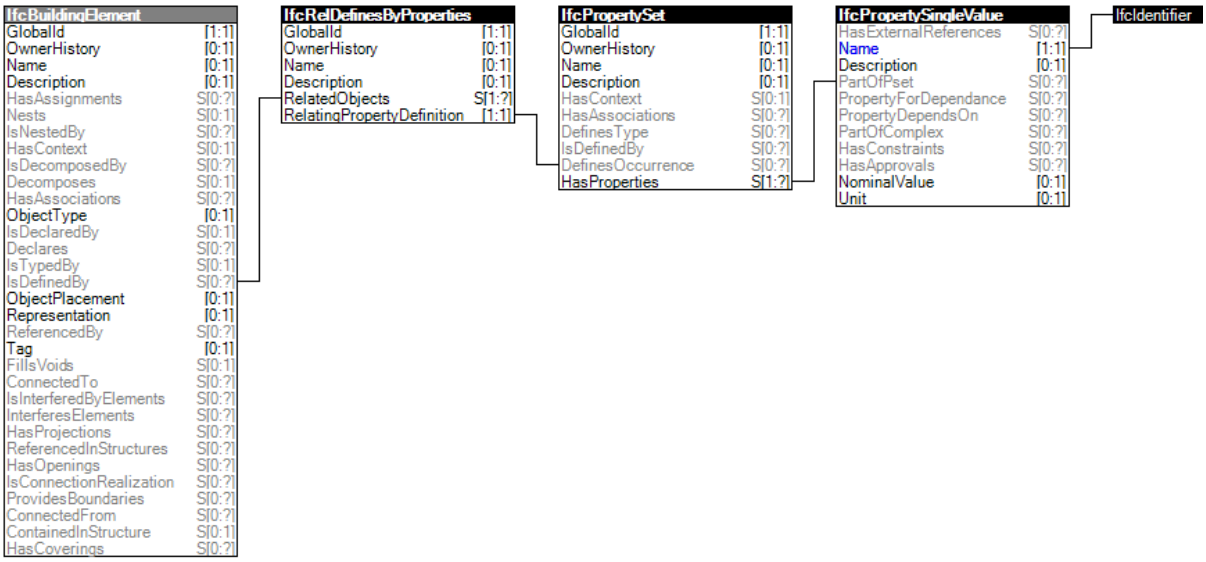

Figure 26 Example of a concept template for validating IFC properties

As shown in Figure 27, three steps are needed to achieve automatic MVD validation of a BIM model: a) The creation of the mvdXML file using the IfcDoc tool; b) The application of the concept rules on the IFC objects using the algorithms provided by the IFC Library, and c) The generation and the visualisation of the error reports.

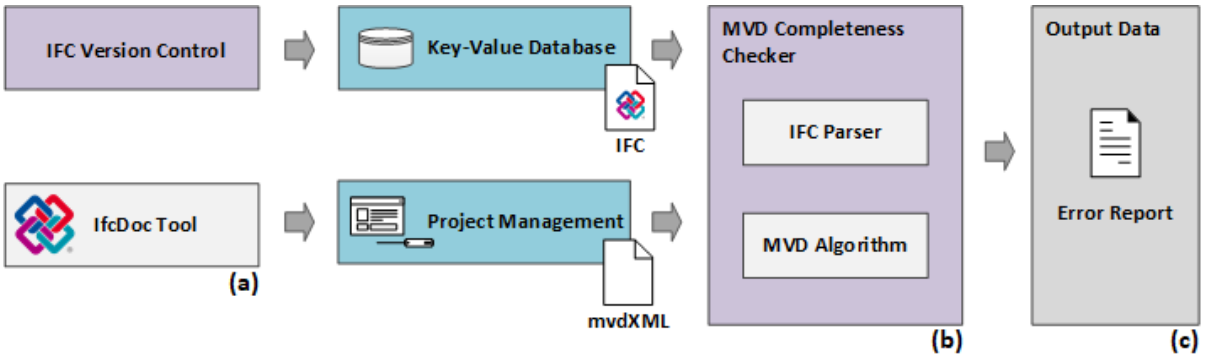

Figure 27 MVD model checking process

BuildingSMART International has developed IfcDoc to improve the computer-interpretable implementation of the IFC specification. The user can create custom definitions and assign new concepts to them. Each concept contains a) a connection to an IFC entity, b) an additional concept to filter the instances by validating the applicability of the relational diagram, and c) the rules along with their parameters and logical operations.

8.3 B-rep Generator

The IFC data have geometric representations which are not in a graphics-friendly format. Therefore, the B-rep Generation component of DTP transforms the IFC geometric data into triangulated Boundary representations, which are optimised for graphic viewers, avoiding verbosity and without losing critical information. In this transformation process all geometric representations of the structural and non-structural building elements are transformed into 3D triangle surface sets in a two-step conversion process. In the first step, the IFC Geometry Exporter exports the geometric information in XML format. Then, in the second step the geometry data are loaded into and processed by the B-rep generation component using the JNI programming interface. The output of the B-rep generation component (the generated B-rep objects), are exported in an optimised graphic data format such as OBJ and glTF, containing triangulated polygon surfaces.

The B-rep generation component transforms the geometric representation of every element in the input IFC data file into a triangulated surface set. Suppose the geometric representation of the element is parametric. In that case, the B-rep generation component applies all the necessary geometric operations to transform it to a boundary representation first (set of outward-oriented polygon surfaces) and then applies a triangulation process to every polygon surface to create a final triangle set. Multiple parametric geometric descriptions are supported for every element in the BIM file, including extruded area solids, half-space solids, and CSG boolean operations on these descriptions of finite depth. If the element has a non-parametric description, then only a triangulation process is applied on its boundary polygonal surfaces to transform them into a triangle set.

8.4 IFC Optimiser

The IFC exportation plugins of the BIM authoring tools perform the serialisation of the IFC objects and generate the final IFC using the STEP data format. The generated IFC data often contain duplications of the same information. The IFC Optimisation component performs lossless compression of IFC data to speed up loading and data transformation processes such as the B-rep Generation and Knowledge Graph Generation. It uses the IFC objects loaded by the BIM Management component and performs the following steps: a) converts the content of each object into a hash value, b) reduces the size of the generated hash table by removing the duplications, and c) updates the references of the removed entries in the remaining entries.

9 Conclusions

This deliverable introduced and analysed in detail the software architecture of COGITO's DTP. The DTP plays a central role to COGITO's architecture, as it is responsible, not only for performing user management tasks but also for handling and processing all incoming data traffic and for converting COGITO's input data to suitable data formats for all COGITO applications.

The DTP has been divided into six layers each serving a specific functional purpose:

- The *Authentication Layer* to perform user management tasks according to the open-source project Keycloak's specification.
- The *Data Ingestion Layer* includes operational blocks for transforming the incoming data into ontology graphs and other necessary COGITO data structures.
- The *Data Persistence Layer* provides data storage functionality.
- The *Data Management Layer* responds to COGITO applications data requests, synchronising the multiple parallel responses to data queries from these applications in a fast and efficient manner.
- The *Messaging Layer* coordinates data transformation operations and the responses to data queries from other COGITO applications.
- The *Data Post-processing Layer* to perform ETL and model checking operations on COGITO's BIM data.

A top-down approach was used to describe each component thoroughly, starting from an overview of operational blocks to a detailed description of software components. We also described data exchanges among these layers.

Many components of the above layers (Data Post-processing Layer, Data Ingestion Layer, Data Management Layer) can act as standalone services enabling parallel executions in a highly containerised environment following a Service-Oriented Architecture (SOA) pattern. This is an efficient design approach, achieving minimum response time to queries of variable processing load. Furthermore, the communication among the different subcomponents of the DTP layers is performed efficiently, transparent, and well-structured using an appropriate message routing scheme by the Messaging Layer components.

The components of this initial design are not final, and they are expected to adapt to future updates and new requirements of the other COGITO tools and applications. All the necessary changes will be performed in a timely fashion and will be reported in the final version of this deliverable.

The final version of this deliverable "D7.2 Digital Twin Platform Design & Interface Specification V2" is expected to be released on M24 and will include the detailed technology stack used for the implementation of the components developed within "T7.1 Digital Twin Platform Design & Interfaces Specification" and "T7.2 Extraction, Transformation and Loading Tools (ETL) & Model-Checking". Furthermore, it will provide the detailed specification of the external interfaces used for the interaction the various COGITO applications.

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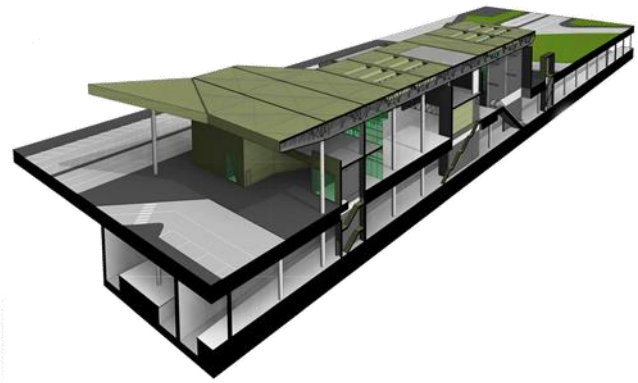

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