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# Supporting Linked Engineering Data Management of Smart Product Systems through Semantic Platform Services

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**Abstract.** The increasing industrial relevance of connected smart product systems, enhanced individualized customer requirements, regulatory boundary conditions as well as advanced value networks and volatile international markets determine a new level of engineering complexity. Current engineering processes are enabled by a large number of IT applications, which are partially orchestrated by product lifecycle management solutions. Considering the dramatically increasing complexity, the IT applications are often not adequately connected as a whole, leading to interruptions in the process chains and finally resulting in quality problems, time expenditure, and additional costs.

To support seamless engineering processes, a sufficiently linked information system structure is necessary. Due to the often-existing best-of-breed solutions and historically grown IT infrastructures, the direct point-to-point coupling of IT systems among each other requires disproportionately high efforts. As an approach to improve the existing situation, integration platforms utilizing loose coupling of individual heterogeneous engineering IT applications by semantic web technologies could be used to create a comprehensive, linked engineering data structure.

This paper presents a conceptual IT-Service approach that utilizes this linked data structure to address problems in the area of information retrieval, data exchange, and data quality. A fundamental service function enables easy access to the information scattered throughout the whole organization. This approach could contribute to a high level of transparency within the company's internal processes and relationships between data across individual engineering IT applications. The proposed concepts for IT platform services facilitate the exchange of data between different software applications and the standardized checking and documentation of data quality.

**Keywords:** Semantic Services, Linked Engineering Data, Smart Products, Product Lifecycle Management

## 1 Introduction

Smart products, which are composed of a multitude of interdisciplinary subsystems and including smart connected IT services based on the Internet of Everything [1] confront engineers with fundamentally new challenges. Also, increasing demand for customer-specific individualization determines a strong increase in the number of product variants. Consequently, interdisciplinary engineering in globally distributed dynamic value networks requires enhanced communication throughout all phases of the product lifecycle.

Product Lifecycle Management (PLM) approaches try to address this problem by managing business processes and associated data, which are generated by a large number of individuals using software applications distributed over the entire product life cycle [2]. Due to the high amount of existing best-of-breed solutions and historically grown IT infrastructures, many software applications are not linked to the PLM infrastructure, which in turn causes disruptions in the process chains through missing interoperability.

The conceptual approach for a basic set of platform-based IT services presented in this paper utilizes linked engineering data to support cross-product-lifecycle and interdisciplinary collaboration. To define basic needs for these IT-Service concepts, an engineering process requiring a high degree of interdisciplinary cooperation due to a large amount of data and specific engineering knowledge involved is exemplarily considered. This exemplary use case scenario includes a Noise, Vibration, and Harshness (NVH) simulation of the powertrain from a modern hybrid vehicle.

Based on the generalized needs derived from the use case scenario, a concept for three IT services addressing information retrieval, data exchange, and data quality has been developed using our metadata repository for semantic product lifecycle management SP<sup>2</sup>IDER, which has been developed in our research group since 2016 [3].

## 2 Use Case Scenario and Needs for Conceptual IT Services

Considering the problem-solving cycle of systems engineering, simulation is a part of the search for solutions and involves the four steps of mission definition, model structure building, simulation runs, and solution recommendation [4]. The use case scenario of Noise, Vibration, and Harshness (NVH) processes includes Multi-Body Simulation (MBS), Finite Element Method (FEM) and Statistical Energy Analysis (SEA), which are used in combination to investigate vibrations and noises caused by oscillations [5]. These simulation methods, nowadays are part of the methodical standard repertoire in the automotive industry, which is especially crucial for new challenges in the context of the electrification of the drivetrain [6].

The simulation process begins with the mission definition. In the considered use case, there is suddenly a higher torque requested to accelerate a hybrid vehicle (Tip-In) where in consequence the internal combustion engine is started by engagement to the electric motor. A proper tuning of the electrical and mechanical components as well as

a capable control system are necessary. Otherwise, an unexpected, noticeable longitudinal shake in the vehicle could occur [7]. After the mission has been defined, the engineer is responsible for acquiring the necessary data for the simulation model. An MBS simulation is carried out for the low-frequency examination, which requires the locations and masses of the components for the model assembly. However, the engineer responsible for this task is not necessarily aware of which software application the data can be found in. Studies like [8, 9] show that engineers today spend over 50% of their working hours searching for information.

Once the necessary data is found, it has to be transferred into the simulation application. In the considered use case scenario, non-existing connections between the data management application like PLM and simulation application lead to uncontrolled data exchange, e.g. via e-mail. As a result, it is no longer possible to trace the development stage on which the data is based and a large source of potential errors is created. Since the accuracy of a simulation is correlated directly with the quality of the input data [10], data quality assurance is crucially important. However, the scope and complexity of the data make manual data quality monitoring unfeasible for the responsible engineer.

As soon as the data is available in the simulation application, the engineer builds up the simulation model. When the assembly is completed, the correctness of the model can be checked. For this purpose, either known historically test data or, if available, physical experiments are used. Now that the pre-processing is completed, the actual calculation and solving of the simulation takes place. In subsequent post-processing, the results of the simulation must be interpreted and evaluated with the help of in-depth specialist knowledge. The simulation model and results are then incorporated into a simulation data management (SDM) solution to enable reusability. However, simulation applications often are not necessarily connected to an SDM solution. As a consequence, the simulation models and results are often only persisted locally.

A detailed analysis of the mentioned use case scenario lead to following needs developing conceptual IT services for the semantic engineering platform SP<sup>2</sup>IDER:

- N1 Software application can be linked with a low as possible effort
- N2 Data can be retrieved from different source systems centrally
- N3 Data can be exchanged between different source systems
- N4 Data Quality can be determined and monitored

### **3 Current State of Linked Engineering Data Management Solutions**

Product Lifecycle Management and Enterprise Resource Planning (ERP), existing over decades, have been applied to a multitude of use cases across the product lifecycle. However, these solutions often coexist as separate information technical and organizational ecosystems within the corresponding departments of a company [11]. As a result, these solutions typically manage data such as requirement data, product models, and source code, supplemented by numerous authoring software applications, which are specific to a particular life cycle phase or engineering discipline. The data from these software applications could be managed in a single, consistent data model across the

whole product lifecycle. In reality, however, there are often several redundant and inconsistent data models that are often synced manually or using ad hoc processes [12]. Smart, connected products further increase the data management effort by providing more and more data from the product use phase. This also enables new data usage scenarios (e.g. availability-oriented business models) that would not be possible without a coherent view of both product instance-specific and generic product development data. However, for these use cases, the data must be gathered, prepared, and made available across the whole product lifecycle and different departments [13]. Also, processes often require access to data which is scattered across a variety of software applications, which in turn requires knowledge about the existence and structure of all data sets. This need for data and process integration has led to several industrial IT solutions supporting the mentioned use case scenarios. Solutions can be classified according to their strategy for providing a unified view of data from different source systems. Systems like Intercax Syndeia [14] enable the synchronization of several databases. Similarly, platforms like eQube BI [15] or the Semantic Data Management Integration Platform [16] add an additional layer on the top of existing systems to enable centralized access to all required data. In all approaches, a unifying data model or ontology provides the required information for mapping the data. These approaches are primarily based on data integration rather than the processes using the data. Also, the mentioned approaches are only considering particular areas of the product lifecycle and have to be tailored to exactly address the problem.

The Open Services for Lifecycle Collaboration (OSLC) provide a decentralized approach towards data integration by using open web technologies based on linked data instead of integration or synchronization [17]. According to the principles of linked data, the data is represented by URIs that refer to objects. Information about these objects is provided in the form of RDF [18]. OSLC currently provides just a small core and several specific application profiles that could undermine interoperability. Using OSLC for data integration requires all connected systems to support the required profiles in a compatible way, which will be a challenge for such solutions in the short term. Similar approaches like OPC-UA exist in the context of manufacturing and production [19].

There is no general common consensus on comprehensive IT solutions which could serve as the primary source of information in these models. Based on the previous examples this could either be PLM, ERP, an IoT platform, a common dashboard that connects to all these platforms or a common data model that is deployed across different systems and synchronized automatically. However, the analyzed approaches show several trends: Building on (open) standards enables interoperability, graph-based representations allow the modeling of highly connected data and the various source systems are largely being left intact. Other aspects like the question of whether to synchronize, to add a central system or to link data in a decentralized architecture, do not seem to have been addressed yet by obvious solutions. Additionally, all the mentioned approaches are built on the assumption that data is available and correct. Managing data in a realistic industrial scenario requires processes for managing and requesting access rights to data as well as ways to ensure the consistency and quality of data objects stored in the various IT systems.

## 4 Conceptual Framework for Semantic Platform Services

To address the basic needs analyzed in section 2, a capable Linked Engineering Data Management solution is mandatory and serves as a prerequisite for the needs N2, N3, and N4. Previous research projects also show that effective collaboration requires data exchange across systems [20] as well as a holistic view on all relevant aspects of the system in question [21]. Additionally, redundant data stored and often inconsistent data across multiple systems have to be handled systematically.

To address these challenges, the Semantic Product and Process Information and Digitized Engineering Repository (SP<sup>2</sup>IDER) platform has been developed since 2016 by a team of researchers at the Chair of Virtual Product Engineering at the University of Kaiserslautern in Germany [3]. The approach is based on loose coupling of source systems to a central core using lightweight application-specific wrappers built on open web technologies. Similar to OSLC, the concept is based on RESTful API and Linked Data but in contrast offers a superordinate (data) layer to provide a comprehensive knowledge base. A code generator for the wrappers allows new source systems to be connected to the core with manageable effort, thus ensuring interoperability.

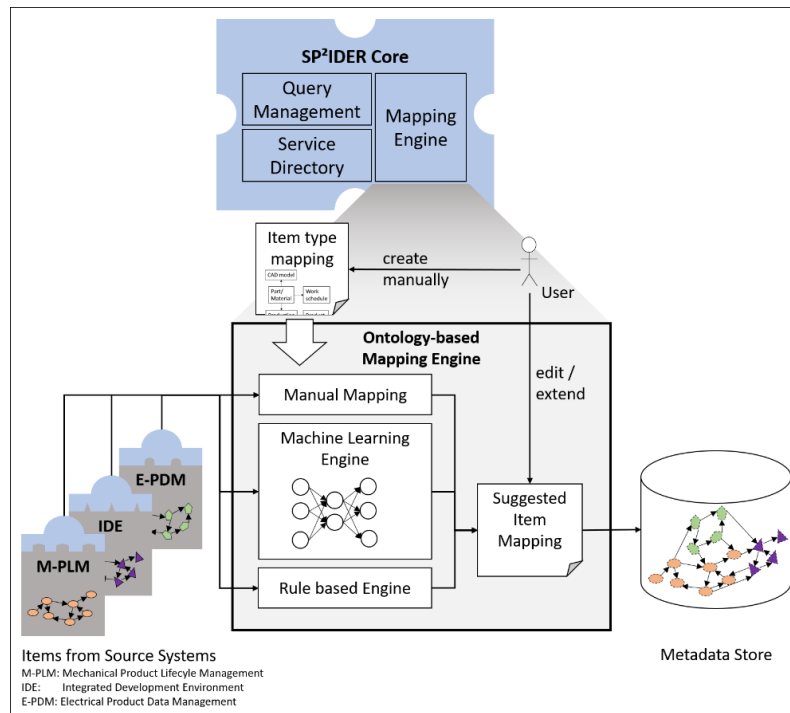


Fig. 1. SP<sup>2</sup>IDER Data Mapping Engine according to [3]

The SP<sup>2</sup>IDER Metadata Store does not store deep copies of data objects, but instead, it stores only metadata about the objects in a graph repository. Due to the possibility of

performing create, read, update, and delete (CRUD) operations by HTTP methods, the core can fetch required data through the wrappers on the fly.

Managing the unified metadata model requires the unification of synonymous objects and identical objects stored in different source systems. These are data objects existing in different source systems representing an identical logical unit, for example, a part which is held in a PLM system for product development processes and in an ERP system for economic business or manufacturing processes. Responsible for this task is the SP<sup>2</sup>IDER mapping engine as shown in figure 1. Identical objects from different source systems can be merged into one graph node using a combination of imperative rules, probabilistic mappings using machine learning algorithms which are subsequently checked by the user, and manual mapping to cover exceptions. The merged graph nodes contain the necessary metadata to enable processes like information retrieval or data exchange requests. Beside the mapping engine, the SP<sup>2</sup>IDER core includes a query management as well as a service directory thus supporting workflows.

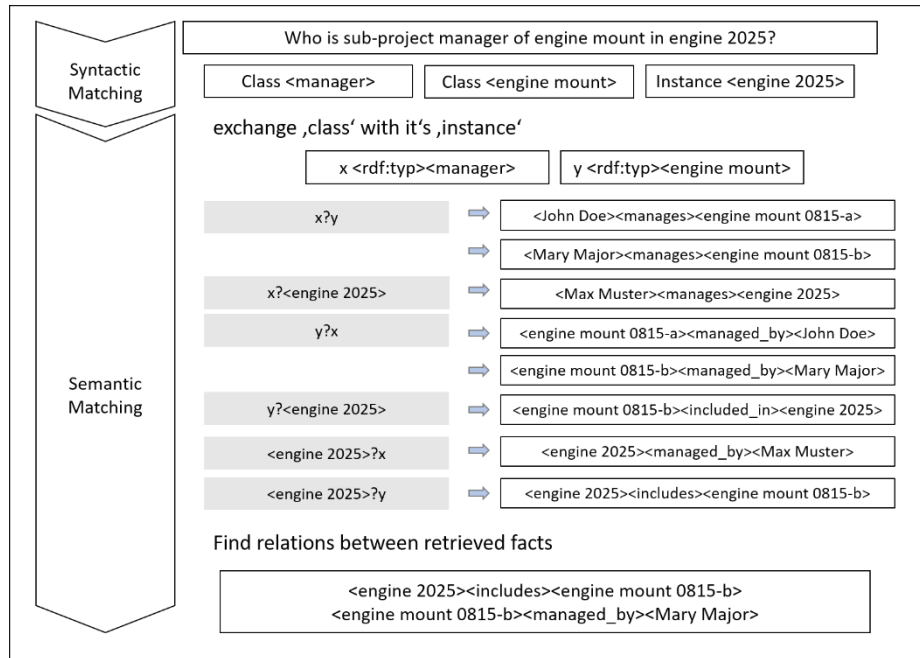
Based on the technological foundations of the SP<sup>2</sup>IDER platform, we propose three conceptual IT services that are introduced in the following.

#### 4.1 Information Retrieval

A keyword-based search approach, which is used at a high level of maturity by internet search engines, is often not sufficient to find the correct information across different engineering IT systems due to problems like different naming conventions or hierarchies [22]. The **information retrieval service** proposed in this paper will use semantic search technologies as a solution to this problem by utilizing knowledge described in a formal and machine-interpretable way.

This approach will enable the user to submit queries for which he lacks explicit knowledge in keyword-based search queries. For instance, search queries such as "Who is the sub-project manager of engine mount in project engine 2025?" will be possible with the fitting knowledge-base. Thus, easy access to the information scattered across the value network will be achieved. Prerequisite for this type of search is a formal representation of knowledge. The service therefore will utilize the semantically enriched, graph-based metadata model provided by the SP<sup>2</sup>IDER Metadata Store. This metadata model is built by SP<sup>2</sup>IDER out of the data from every connected source system and will be expanded with every newly attached system. The model consisting out of two layers: the data type level providing classes and their relations and the data object level providing instances and their relations. Using the mapping engine described at the beginning of this chapter, the metadata model represents the relations of data across the connected source systems and provides the needed machine-interpretable knowledge base. That allowing to incorporate connections between the data objects in question across all connected source systems and tracing located information as well as relations back to a single source system. Thus, retrieving primarily metadata, SP<sup>2</sup>IDER can additionally fetch further detailed information if required, by supporting HTTP methods like 'get' through the wrapper on each source system.





**Fig. 2.** Procedure of semantic information retrieval service by a statement-based approach

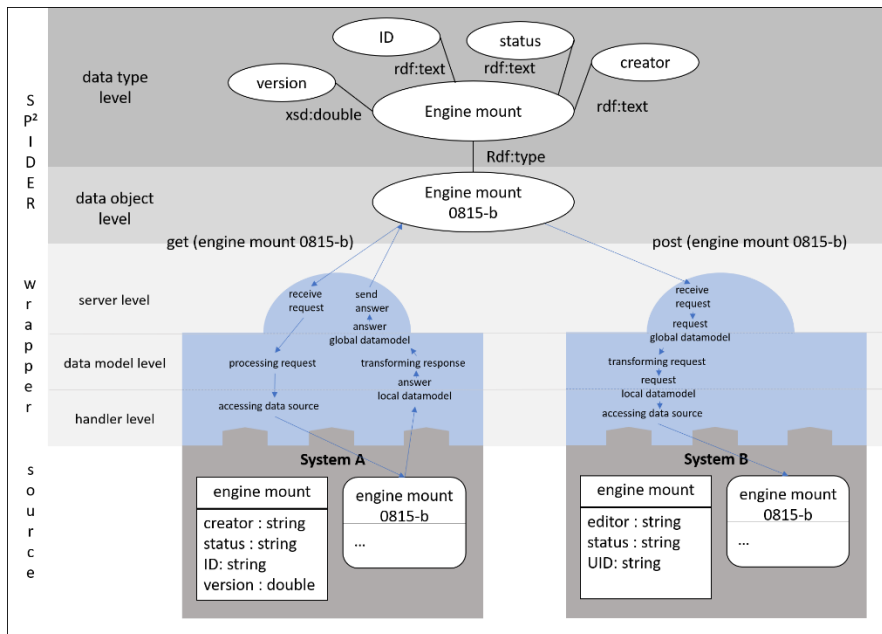
According to Dengel [23], semantic processing can take place in three different phases: in query processing, the search algorithm itself, or the processing and presentation of the results. There are different methods like reasoning, traversing on graphs, or statement-based approaches available for semantic-based search algorithms. Concerning SP<sup>2</sup>IDER, we recommend a statement-based algorithm due to the graph-based metadata model. Because of the wide range of users informal, natural language free-text search queries are intended. The query will be first subjected to a syntactic comparison with the textual content of the knowledge base to identify any fitting concepts (see Fig. 2 syntactic matching). Concepts can be classes, instances, or properties from the SP<sup>2</sup>IDER metadata model. Subsequently, semantic processing will take place by exploring the ontological context of the concepts found and searching for related instances [23]. Therefore, SPARQL-Queries are built out of <subject, predicate, object> triples where subjects and objects being classes or instances and predicates being properties retrieved in the previous step (see Fig. 2 semantic matching). While a traditional retrieval only exploits the syntactic matching, the here proposed approach uses the machine-interpretable relations within the metadata model to consider the meaning of the search terms and provide fitting, precise results. The search result is finally presented to the user in a way that facilitates the transparency and traceability of the information and its structure.

Besides, an explorative search will be provided based on the retrieval results. Therefore, the user can limit or generalize the search result by using facets. The selected retrieval results will be visualized in a graph, in which the search results are nodes and

the relations between them are edges. This provides the user with a clear overall view of the information structure across the boundaries of individual software applications and organizational units.

## 4.2 Data Exchange

The conceptual approach for data exchange addresses the problem of transferring data defined in one system deploying a certain source schema to an instance of another system in a target schema [24]. Computer science has been dealing with this problem for quite some time and coming up with context-specific application protocols bundled under the ISO 10303 accompanied by the data modelling language EXPRESS [25]. But due to the increasing number and diversity of the software applications in recent years, the complexity is rising. As well as in the case of data integration, the problem of data exchange arises from the management of data persisted in heterogeneous formats [24].



**Fig. 3.** Procedure of data exchange service between two source systems connected to SP<sup>2</sup>IDER

In times of digitized engineering processes strongly driven by computer-aided technologies (CAx), data exchange has become dramatically more crucial. The downstream processes require data from the previous steps, associated with a costly, centrally coordinated data provision [10]. A linked engineering data management solution like SP<sup>2</sup>IDER proves to be a promising technical basis for enabling seamless engineering using a comprehensively controlled data exchange. Since the source and target schemata as well as relationships are known by SP<sup>2</sup>IDER through the metadata model and CRUD operations are supported by HTTP Protocols and a REST API wrapper on top

of the source system, a **data exchange service** is possible without much additional effort.

After a successfully executed information retrieval like described in section 4.1, this service will enable the user to transfer the retrieved data object into an instance of a desired connected source system. A data object can take any form known to SP<sup>2</sup>IDER. For example, it can be a geometric model from a PLM system as well as a single data set from an SQL database. By using the graph-based metadata model, a compatibility check is carried out to determine whether the selected data object can be transferred to the desired target schema. Therefore, the data type level of the metadata model is used to check whether the corresponding class of the source system instance exists in the target system. If the exchange is possible at the schema layer, the service will check whether a matching instance exists in the target system. In case of matching, the user can decide to update the instance data or not. In the other case, a new instance in the target system is created and the data is transferred. The service therefore will fetch the data using an HTTP get method towards the source system and creates the new instance with an HTTP put method in the target system (see Fig. 3). If the instance already exists and the user confirmed the update, an HTTP post method will be used.

### 4.3 Data Quality

An important step to master data quality in the long term is measuring and monitoring the data quality to create transparency. Despite its high relevance, it has not yet been possible to find generally applicable and accepted metrics for measuring data quality [26]. Most approaches originate from the Total Data Quality Management by Wang [27] where data quality is considered over the entire life cycle of data. For this purpose, the steps following the Plan-Do-Check-Act cycle of defining, measuring as well as evaluating quality and finally taking appropriate measures for a sustainable increase in quality are continuously carried out.

The complexity and amount of data make an automated checking of the quality necessary. For this reason, we propose a **data quality service**, which will measure data quality by using executable rules. The rules can range from rather simple tasks like checking if values range in an interval to complex mathematical examinations of a simulation result. Depending on the data and use case, the rules can vary significantly, whereby we recommend the six primary dimensions for data quality assessment by the DAMA [28] as a guideline for the rule development. The rules will be embedded into executable processes, which allows the modeling of triggers and subsequent events along with an implementation of the rule logic. The processes will be developed in Business Process Execution Language for Semantic Web Services (BPEL4SWS), which extends BPEL 2.0 by the ability to use semantic information for describing activity implementations [29]. The independence from the interface description thus achieved in conjunction with the data mapped in ontologies will enable semantic reasoning and reusability of the process models. As an appropriate engine, we propose a customized version of the open-source Apache ODE to fit the BEPL4SWS extensions.

Every user, data producer as well as data consumer, can define quality checking rules and associated processes within a dedicated development environment. This allows to

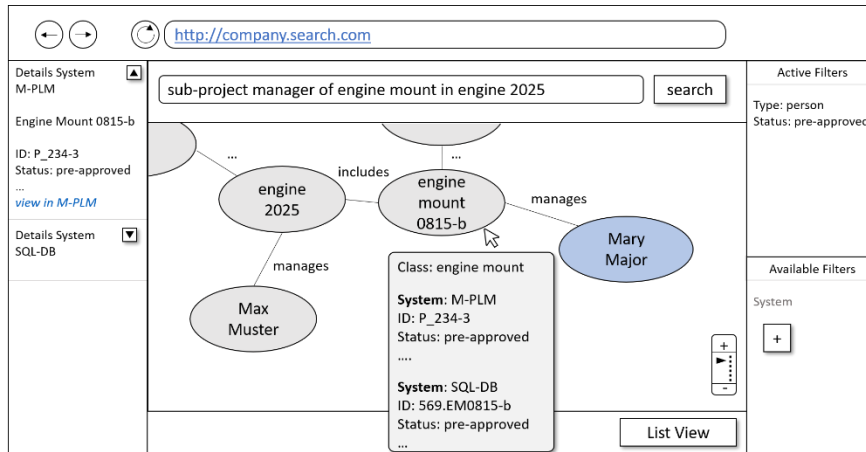
address the intrinsic interest of the data producer in high-quality results of his work as well as the quality requirements from the perspective of the data consumer. The usage of the XML-based BPEL4SWS for rules and processes facilitates the application of an intuitive, graphical development environment like a customized Eclipse BPEL Designer. The process containing the rule has to be associated with a certain data class and is always executed when an instance of this class is transferred via the service presented in section 4.2. After development, the processes have to be approved and activated by a central reviewing instance.

Whenever the data exchange service sends a get request to a source system, a quality check will be initiated. Therefore, the quality service will determine the class of the instance to be exchanged and cache all rules associated with that class. Subsequently, the cached rules will be executed with the data instance as input and the results will be logged. Finally, a quality report consisting of every executed rule and the corresponding result will be generated. The data consumer thus always will receive a quality report for his data with the help of which he can evaluate the given data quality. As a simple aggregated quality index, the percentage of failed rules will be provided. The user will be able to drill down to single rules and results and browse or filter the report. This transparency enables conscious handling of the data and if needed taking appropriate measures to improve quality in the long term.

## **5 Use Case Study including the Semantic Platform Services**

The presented IT-service concepts have been applied in the use case scenario introduced in section 2. Supporting the considered use case by the proposed IT services, a significant difference can be noted in retrieving the required data. Instead of searching for data in an unstructured and haphazard way, the engineer uses the information retrieval service, which provides a central user interface to search for data from different source systems (see figure 5 step 1).

Figure 4 provides an early graphical user interface mockup of the information retrieval service. According to the search string and the active filters, the data is visualized in the form of a graph, which transparently shows the relation between the concerning project, a single part, and the responsible manager. In the example shown, the engineer is looking for the manager responsible for a component, the engine mount, of the engine 2025 project, e.g. to clarify any detailed questions. This shows the superiority of the semantic search, which determines the concrete engine mount of the project and the corresponding manager using the semantic network within the SP<sup>2</sup>IDER Metadata Store. Beside the relation, further meta-information for the retrieved data will be given as well as a jump-off point to respective source systems.



**Fig. 4.** Mockup of the Information Retrieval Service

Once the required data has been found, the information retrieval service offers a starting point for the data exchange service. The mass and location of the engine mount required for the simulation were found in the company's M-PLM system. Because both, the M-PLM and the simulation tool, are connected to SP<sup>2</sup>IDER, the exchange service can transfer data between the systems after a compatibility check is carried out (see figure 5 step 2). In the course of this process, the third service automatically checks the data quality. The assigned rules check, for example, whether the stiffness of the engine mount is within a plausible range. The engineer receives a quality report for his data, which contains the executed test rules and the respective test results (see figure 5 step 3). It is now up to the engineer to evaluate whether the quality of the data is sufficient for his purpose or not. If there is a sufficient data quality, the model building and simulation run processes can follow. Finally, the models and results are incorporated into an SDM solution. Assuming that the SDM solution is connected to SP<sup>2</sup>IDER, the data exchange service enables the direct transfer of models and results into the SDM (see figure 5 step 4).

With regard to the Linked Engineering Data Management solutions introduced in chapter 3, we try to assess the performance increase for the engineering process of this use case. The superordinate layer, provided by the metadata model of SP<sup>2</sup>IDER, provides the necessary foundation for the services presented in this paper. In contrast to commercial solutions, SP<sup>2</sup>IDER offers a flexible open-source platform that enables easy connection of source systems throughout the entire product life cycle as well as the development of further specialized services if needed. In contrast, completely decentralized approaches do not have this superordinate layer and therefore do not provide the knowledge base needed for services like the information retrieval. The services themselves promise to significantly shorten process runtimes and at the same time create a consistent quality standard through transparency and documentation. The time required to gather information will be shortened by the information retrieval service. Furthermore, a largely independence from individual knowledge carriers in the

information retrieval will be achieved. The data exchange service reduces the manual steps for data exchange to a minimum and thus reduces potential sources of error. In addition, the data quality service reveals quality problems in the data at an early stage in the process and documents the present quality. Thus, it is possible to take measures in time and avoid carrying problems further down the process, which in turn leads to the repetition of larger, time-consuming process sections or poor decisions.

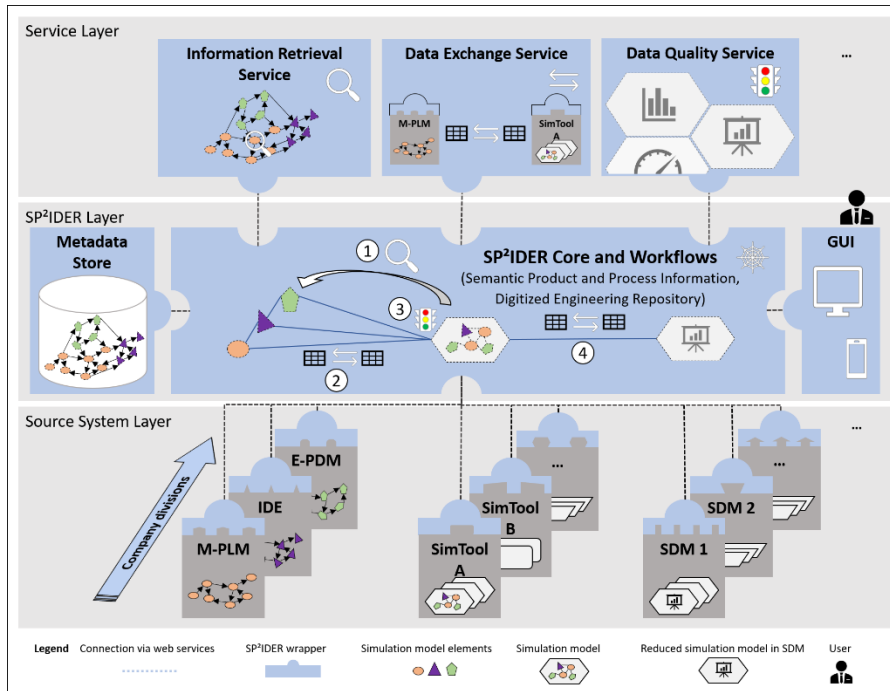


Fig. 5. The SP<sup>2</sup>IDER system architecture with Semantic Platform Services

## 6 Conclusion

To enable semantic engineering management IT services are introduced. Based on a linked engineering data management solution like SP<sup>2</sup>IDER, we designed three IT services as a conceptual solution. A semantic search service allows the retrieval of information scattered through many software applications and departments. Based on this, a second service enables the exchange of data across the boundaries of individual applications. Using a data quality service, data quality can be measured and monitored, and thus more transparency is achieved.

The potential of such a combined solution of a linked engineering data management and IT services is huge, as the need for findable high-quality data spreads all over the product life cycle. Potential use case scenarios include e.g. engineering change management. With the help of SP<sup>2</sup>IDER and connected IT services, the impacts of a design change can easily be traced into downstream processes. Engineers can find change-

affected items at an early stage and trigger the necessary adjustments allowing simultaneous engineering and shorter lead times. Especially disruptive and unpredictable changes from external triggers require a solid knowledge base concerning product and process information for an effective collaboration even in heavily fragmented and decentralized engineering activities. Another possible scenario is the development of a new product. Hence many new product development projects are based on previous product generations, SP<sup>2</sup>IDER and the connected IT services allow for the search of life cycle data from previous product generations, saved inter alia in so-called digital twins. This enables the engineers to learn from data and adjust their designs accordingly. During the new product development, engineers can use a platform like SP<sup>2</sup>IDER and the connected IT services to gather the necessary information for the initial configuration of a digital twin (see [30]).

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