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Abstract. Products generate a large amount of information during their lifecycle. Small and medium enterprises often lack an efficient management of such an amount of information. Several tools of product lifecycle management have been developed in the last years to address this issue, but they are rarely exploited by companies, especially SMEs. The aim of our work is to present a semantic platform to integrate data along the whole product lifecycle to allow semantic search and knowledge reuse. The integration of data is realized with a reference PLM ontology, containing the main concepts and relations to describe a PLM. This ontology has a modular structure, so that it can be easily extended to describe concrete product lifecycles. An example of a real application of the semantic platform in an industrial case is reported.

Keywords. PLM, manufacturing, knowledge management, information retrieval, semantic model, ontology, semantic search, UML, OWL, RDF.

Biographical notes.

Giulia Bruno is a post-doc researcher at Politecnico di Torino from 2009. She holds a Ph.D. in Information and System Engineering and a Master of Science in Computer Engineering from Politecnico di Torino. Her research activity is focused on data mining, ontologies, knowledge management and system modelling in the industrial domains. She has been involved in several national and European research projects in the fields of data analysis. She is also working in collaboration with healthcare sanitary agencies to analyse patient flows.

Roman Korf received the Master of Science in Artificial Intelligence in 2003 at the University of Edinburgh. He had been research associate at the University of Potsdam in the area of knowledge management and business process management where he had been working in national funded research projects and lecturing. He has experience in more than 15 European and national funded research projects experience in fields of artificial intelligence, semantic technologies, grid computing, cloud computing, knowledge management and location based services especially in industrial context. He has been senior researcher and principle investor in research projects at ontoprise GmbH and

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Joachim Lentes is head of department and member of the management board at the Fraunhofer Institute for Industrial Engineering IAO and lecturer for Mathematical Methods for Production Planning at the University of Stuttgart. He is project manager of the Fraunhofer Innovation Cluster Digital Production. He is involved in EC-funded research since 2002 and initiated projects like amePLM and DREAM, which he also coordinated. His main research areas are the integrated engineering of products and production systems, especially by semantics, as well as strategies for next-generation development and production.

Nikolas Zimmermann holds a Diploma in Mechanical Engineering from the University of Karlsruhe. He is senior researcher at the University of Stuttgart and gained a lot of experience concerning ontology-based support in the engineering domain; over 3 years he was working as a researcher in the amePLM project and over 12 months he was working as a research assistant at the Institute for Product Development in Karlsruhe. Furthermore he is responsible for the Digital Engineering Lab at Fraunhofer IAO and was involved in numerous projects for industrial customers.

1. Introduction

The process from the idea of a new product over its development and production to the market is typically fragmented across different functional units, but requires input and activities from experts from a variety of disciplines using different methods and tools. This leads to a high coordination effort to synergize work and information transfer, to sub-optimal decisions, and unused knowledge as well as experiences. This results in an unnecessary extension of time-to-market and time-to-production of new products and in a loss of competitiveness of companies. To tackle these challenges for engineering in small and medium sized manufacturing companies, the amePLM (advanced platform for manufacturing engineering and PLM) project is based on a set of ontologies that serves as an interoperable model and integrating element for an open engineering system. Furthermore, the usage of an ontology-based approach advances the information provision in activities during product creation.

An essential advantage of the application of ontologies in product development is knowledge sharing. Bradfield and Gao determined three main problem categories for knowledge sharing in the new product development (NPD) process of a manufacturing company: inappropriate information about the knowledge in the NPD process, multilingualism as well as multidisciplinary, and insufficient information provision to users (Bradfield and Gao 2007). By means of an ontology-based approach, knowledge sharing in NPD may be facilitated. Lutters et al. (2000) worked to apply information management based on an ontological approach on design and engineering processes under special consideration of manufacturing, i.e. process planning and cost estimation. Lemaignan et al. (2006) designed an upper level manufacturing ontology (MASON), and Young et al. (2007) showed the benefits of applying ontologies to support knowledge sharing in PLM with a focus on manufacturing processes. Giménez et al. 2008 defined a product ontology to model complex product (the PRONTO ontology). By using a product ontology as pivotal element, Panetto et al. (2012) introduced an approach to support interoperability in Product Data Management (PDM). Matsokis and Kiritsis (2010) developed an ontology of concepts and rules to support PLM, emphasizing the product and its role in closed-loop PLM (the Semantic Object Model, SOM). Raza et al. (2009) tested an approach building up on existing work by usage of ontologies for knowledge management. Barbau et al. 2012 defined a semantic model supporting the representation of product geometry concepts, taken from of the Standard for Exchange of Product model data (STEP/ ISO 10303) and the NIST Core Product Model (CPM). Furthermore the work of Fiorentini et al. (2013) using ontologies to model the engineering data of nuclear power plants to leverage interoperability with external information systems showed the potential of an ontological approach.

Previous ontologies mainly focused on the product structure, geometry and generic information (El Kadiri and Kiritsis, 2015). Thus, their main aim is to grant interoperability among systems rather them to improve knowledge search and reuse. On the contrary, our aim is to firstly define a general PLM ontology able to link the pieces of knowledge generated during different lifecycle phases, and then to incrementally specify the general concepts to represent specific industrial domains. Thus, we did not need a very detailed representation of product information, but only of the key elements of interest for the user to allow an easy finding and reusing of knowledge. For this reason, we analysed previous models existing in literature, and we kept only the concepts that were relevant for our purpose. Since we were not interested in storing all the geometry information deriving from STEP, we did not consider PRONTO and OntoSTEP. We reused the part of the SOM and MASON model representing the physical product, its characteristics and the manufacturing operations, while we add other part related to the product lifecycle. Further input we used during the development of the software solution and its underlying ontological data model were, among others, an ontology for engineering mathematics (Gruber and Olsen 1994), work concerned with the area of design in the product lifecycle (Bernard et al. 2014) and with the digital factory (Kádár et al. 2013 and Efthymiou et al. 2015). The principal applicability of ontology-based approaches to PLM as in the platform amePLM has been shown by Lentes et al. (2013) and Bruno et al. (2014), but there still is a potential for improvement in automated information provision in PLM to reduce manual efforts for information management and retrieval.

The rest of the paper is organized as follows. Section 2 describes the semantic platform for PLM knowledge structuring and reusing, whereas Section 3 illustrates the structure of the ontologies at the basis of the platform. Section 4 shows how the developed semantic platform can be used for semantic search and information reuse. Section 5 reports the usage of the amePLM platform in an industrial use case. Finally, Section 6 draws conclusions and states future works.

2. Advanced platform for Manufacturing Engineering and PLM (amePLM)

The principal architecture of the overall amePLM solution is briefly shown in Fig. 1. It is based on an ontology that serves as an interoperable model and integrating element for an open engineering software system, called the amePLM platform. Based on this platform, several methods were implemented as modules to realize tools to assist product and process development, analysis, virtual testing, simulation and optimization based on heuristic methods. Such modules operate with the knowledge that is structured by means of the ontology.

The usage of an ontology-based approach enables the application of domain-neutral problem solving methods to specific engineering activities. Aim of the presented solution is not the integration of all existing data or information into the ontology, but to interface towards external information systems like databases, Product Data Management (PDM)-systems, Customer Relationship Management (CRM)-systems, or Enterprise Resource Planning (ERP)-systems by the use of mapping processes, thereby facilitating especially read-access to existing data and information to realize proper information provision to engineers. The open engineering software platform is built upon existing tools and libraries, specifically on Open Source Software systems. The ontology represents on the one hand the knowledge of the product lifecycle (PLC), and on the other hand the domain specific knowledge of the business domain.

The aim of the developed amePLM platform is to capture, interrelate, reuse and exchange knowledge along the PLC. Compared with commercial PLM systems, the amePLM platform is a more open and extensible solution, where new modules can be easily added to solve new problems and cover additional domains. Differently from fully fledged heavy solution where the customer needs to pay for 90% functionality it does not use, by using open standards and an open platform we intended to provide service on demand to SMEs. We can theoretically interconnect with any system used by knowledge workers along the PLC by extending the platform with these additional modules. The ontology functions as a central schema for capturing and exchanging knowledge amongst the modules. This could be somehow compared to data warehouse systems, where a central schema is used to integrate knowledge from different, heterogeneous sources. However, in data warehouse systems the schema is usually static and cannot easily be extended. Ontologies give us the flexibility to add additional aspects of the PLC or modules used within the PLC without having to change the overall schema. Our solution provides added-value compared with available PLM systems as it combines features from PLM with knowledge management which are enabled by the intrinsic "understanding" the system has on the subject matter and related activities of the user based on its founding semantic data model, the set of ontologies.

The following sections give details on the ontology structure and the semantic infrastructure to manage it.

Fig. 1. Principal architecture of the amePLM solution

3. Ontology in amePLM

Two kinds of ontology are considered in the amePLM solution: a PLM ontology and domain specific ontologies. Knowledge created and shared by engineers and other knowledge worker using the amePLM modules along PLC is structured accordingly to the PLM ontology, and relationships between the knowledge artefacts are continuously established. The PLM ontology covers the general elements of the PLC, and it is a high level ontology applicable in every industrial domain. The PLM ontology can be extended to generate a use-case PLM ontology to specialise some concepts and include additional classes or attributes, depending on the use-case PLC specific requirements. Domain specific ontologies on the other side represent knowledge within the application domain. They are used to further specify the knowledge artefacts and their content, and they are used for the semantic tagging of documents to allow their semantic search and reuse.

3.1 PLM ontology

The PLM ontology was developed by firstly defining the basic concepts needed to represent the information to manage the product lifecycle: the model produced at the end of this process contains the basic concepts and their relationships. Then, by analyzing the industrial cases of interest, the basic concepts are further specialized. New concepts can also be added to this structure to represent additional information of companies. In order to show the ontology model, we exploited the UML formalism (Fowler and Scott 2000). Particularly, we used the UML class diagrams, as they are frequently used to visualise part of the OWL class structure (Fiorentini et al. 2007, Giménez et al. 2008, Eckstein et al. 2010, Matsokis and Kiritsis 2010, Chungoora et al. 2012, Imran and Young 2015). This section describes the general PLM ontology, while Section 5.1 shows the procedure to derive the specific concepts for an industrial use case.

The set of high level concepts needed to represent the product lifecycle management knowledge of a company are the following (Bruno et al. 2014, Bruno et al. 2015).

- *Production item*: either a Product or a Product component. Each product can be made of several components, and the same component can be used by different products. Each component can be in turn be composed by other components.
- *Characteristic*: a material, a functional characteristic or a physical characteristic (e.g., height, length, width, weight, etc.) which refers to a production item.
- *Customer*: the reference person of a company of who ordered a product.
- *Project*: the term used by a company to indicate the collaboration with a customer for the developing of a new product; each project refers to one product and is connected with one customer.
- *Activity*: an action executed during the lifecycle of a product by one or more resources,
- *Information item*: an electronic source of information, which is identified by a URL such as a file, a decision, a simulation or an optimization. Depending on its content, a file can be product-related, if it refers to one or more production item, or resource-related if it refers to one or more

resources. A decision is linked with other two concepts, the stage of the decision and the tool exploited to take the decision.

- *Workspace*: is a collection of information items which are opened by a responsible person during an activity of the product lifecycle. The storage of the workspace is needed because in case of recognition of the similarity of the current project with a previous project, the workspace previously stored can be opened, thus saving time for the user in searching the relevant documents and information items.
- *Resource*: an entity that is involved in the execution of an activity. It can be of two kind, Person or Machine.
- *Role*: the role of a person denoting his/her skills in the company.

Fig. 2. UML class diagram of the PLM ontology.

Regarding the relationships between concepts, the Production item is associated to the Characteristic class to store the characteristic of the item. A Characteristic can be a Material, a Functional characteristic or a Physical characteristic. In this latter case the characteristic is linked to the unit used to compute it. The Product class is linked to the Project class, and the Project class is linked to the Customer class to store the customer involved in each project. The Product class is associated with the Activity class to store the activities of its lifecycle. To keep trace of the resources involved in the activities, the Resource class is linked to the Activity class. For each Person, the Role he/she has in the company is known; furthermore the roles that can execute each activity are stored. The Workspace is linked with the Information items which it contains and it produces, with the Activity it refers to and with the responsible person. As said, an Information item can be further specialized in file, decision, simulation and optimization. Fig. 2 shows the UML class diagram of the PLM ontology.

3.2 Domain-specific ontology

The generic ontology as introduced above was enriched by adding concepts deriving from industrial use-cases and the resulting ontologies were integrated in a coherent way to facilitate re-usage over different industrial branches. The resulting model is formalized using the Web Ontology Language (OWL) as a standard notation for the specification of ontologies. Furthermore Simple Knowledge Organisation System (SKOS) is used to enable semantic searches. SKOS is providing a model for expressing the basic structure and content of concept schemes such as thesauri, classification schemes, subject heading lists, taxonomies, folksonomies, and other types of controlled vocabulary (W3C 2009). This formalism is widely used within natural languages processing (NLP) to semantically enhance text and served as a good basis for the amePLM project. The SKOS model represents concepts and relations, that can be specialized towards specific ontologies for industrial applications as demonstrated in the example of the industrial pilot case below.

4. Intelligent information layer (IIL)

The semantic infrastructure of the amePLM solution is called *Intelligent information layer* (IIL). It functions as a semantic middleware for knowledge created, shared, preserved and extended along the product lifecycle and which is used by amePLM engineering modules, other applications as well as knowledge workers. As illustrated in Fig. 3, the IIL consists of two main parts: (a) the *semantic backend*, i.e., a semantic meta-data repository and reasoner and (b) the *semantic search*, i.e., a semantic content enhancer and semantic search component.

4.1 Architecture of the IIL

The semantic backend is based on the semantic web framework Apache Jena (Jena 2015). It is open source, provides a wide range of APIs to manipulate and reason with RDF (W3C 2014) and OWL (W3C 2004) ontologies. For querying and manipulating ontologies within the reasoner Jena provides SPARQL 1.1 (W3C 2013) interfaces. SPARQL querying can therefore perform also on knowledge inferred by the reasoner (Hitzler et al. 2009). The semantic backend as part of the IIL provides APIs and web-services that abstract from the Jena API for modules of the amePLM platform and the intelligent software agents. Knowledge created by the amePLM engineering modules is stored within the PLM ontologies (Section 3.1). Software agents establish relationships between these knowledge artefacts. The semantic backend provides a tool to browse through these knowledge structures using SPARQL queries. In this sense the semantic backend provides a structured and formal way to explore knowledge along the PLC. The reasoning capabilities of the semantic backend are used in order to infer new conclusions form the interconnected knowledge within the semantic backend. These characteristics make it an ideal tool to provide this knowledge to applications like the engineering modules and reuse the just created knowledge in the information lifecycle within the PLC.

Fig. 3. Architecture of the IIL of the amePLM platform.

The second pillar of the IIL, the semantic search component is based on Apache Stanbol (Apache Software Foundation, 2010) and Elasticsearch (Elastic 2015). The former is a framework for semantic content management, while the later is a distributed full-text search engine based on Lucene (Apache Lucene 2012). The Stanbol enhancer enables the IIL to automatically enhance knowledge artefacts (e.g. documents and web-pages) created and used within the PLC. This is done based on the domain specific ontologies (Section 3.2). In contrast to the PLM ontology, which represent the PLC logic, which has commonalities amongst different branches, the domain specific ontologies represent the knowledge of the business domain. The process of the enhancement is sometimes also referred to as semantic tagging or semantic annotation (Oren et al. 2006, Uren et al. 2006). The annotations are then used within the semantic backend as meta-data and enhance the knowledge structure. Additionally these enhancements are stored for semantic search using the semantic index of Apache Stanbol. The later stores the enhancements within Lucene and therefore allows efficient and enhanced knowledge retrieval.

Within a more recent development we included Elasticsearch as a second semantic search engine. While the information retrieval (search) within the semantic backend and the semantic search based on Apache Stanbol is based on the knowledge structure, the Elasticsearch strategy within amePLM additionally provides efficient full text search based on the document content. The full text search is semantically enriched by the domain specific ontologies using an amePLM extension for Elasticsearch (Gormley and Tong 2015). This enhances the conventional full text search by expanding and contracting the queries using e.g. synonyms and semantic hierarchies (taxonomies), as described in Section 4.2.

An intelligent agent layer uses the functionality of both layers and combines the PLM knowledge and the domain related knowledge which can be used by the engineering modules. Using the 3D workspace of the platform (the knowledge capturing component in **Fig. 1**) the process of browsing and exploring knowledge within the PLC is supported by intelligent agents searching the semantic backend, evaluating metrics like similarity of projects and documents, or automatically enhancing documents using the semantic enhancement functionality of the IIL.

The IIL is implemented in the extensible component based framework OSGi (OSGi 2015). Being additionally based on open standards like RDF, OWL and SPARQL provides an easy way to extend the platform with additional engineering modules and even enables the integration with existing PDM and PLC software. The platform independent access of knowledge is realized using web-services.

4.2 Exploitation of the IIL to browse and search the PLM knowledge

The following section describes the use of knowledge within the amePLM platform utilizing the IIL. This is done based on a small example. In this example a new customer project has been initiated. The project manager needs to staff the project. To do so the project manager needs to map the requirements of the customers project with the skills of the employees of the department or company. The requirements where gathered within the initial phase of the project using specific modules of the amePLM platform. These requirements where transformed by software agents into instances of the amePLM ontology. The profiles (CVs) of employees are managed as PDF files within the document management system. They were semantically enhanced (Fig. 4, right side) and linked with the domain ontology using the semantic search component of the IIL. The profiles are associated with the concepts of the employees within the PLM ontology within the Semantic Backend (Fig. 4, left side).

Having the association of the profiles and the automatically tagged profiles as well as the project requirements now allows software agents to map the requirements and the employees and find ideal candidates for the project. Usually the project manager would use a dedicated user interface for this task and the technical complexity would be hidden from the user. However, for demonstration purpose we intend to show the SPARQL query. Let's say the requirements on the project are "Green Field Plant Design" and "Lean Methods". In our example (Fig. 4) Paul has experience in "5S" and "Lean Six Sigma" methodology but not directly in "Lean Methods". However, "S5" as well as "Lean Six Sigma" are sub-classes of "Lean Methods". Thus, following the OWL sub-class reasoning, we could infer that if Paul has experience in "S5" and "Lean Six Sigma" he has some experience in "Lean Methods".

Fig. 4. Example of an associated and tagged profile.

In our SPARQL query this is respected with the "rdfs:subClassOf" statement.

```
PREFIX amePLM: <http://www.amePLM.org/PLM#>
PREFIX dOnt: <http://www.amePLM.org/domainOnt#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?employee
WHERE {
      ?employee rdf:type amePLM:Person.
      ?profile rdf:type amePLM:Profile.
      ?employee amePLM:hasProfile ?profile.
      ?profile amePLM:hasMetadata ?metadata1.
      ?profile amePLM:hasMetadata ?metadata2.
      ?metadata1 rdf:type  dOnt: GreenFieldPlantDesign.
```

```
      ?metadata2 rdf:type ?type.
      ?type rdfs:subClassOf* dOnt:LeanMethods.
}
```

This example shows the potential of using automatically tagged documents and the association with PLC knowledge. Adding additional information like the information about project involvement of employees can further refine the results by including the availability of employees. This procedure can be easily adapted to other use-cases than to staffing, e.g., the mapping of project requirements with production processes.

Within a more complex example additional OWL axioms the added value of using the reasoning capabilities of the semantic backend are clearer. However we think that this would go beyond the scope of this article. We therefore refer to the semantic web literature (Hitzler et al. 2009).

5. Industrial use case

In our initiative, five different companies with different pilot cases were addressed. The pilots were concerned with different stages of the product lifecycle and their linkage. In the following, we introduce the company and case, the derivation of the company-specific ontology based on the generic ontology shown above, the domain-specific ontology and taxonomy for the case, and the resulting information retrieval solution thereby highlighting its benefits.

One of the industrial pilots realized in amePLM regards a company specialising in the design and manufacturing of sophisticated electro-mechanical medical devices, aimed at the critical care respiratory market. Its point of strength compared to the competitors is the use of higher cost technologies which are more effective, such as a vibrating mesh technology. It is necessary that the company has a comprehensive technical knowledge about the effects that the main input parameters have on the relevant output parameters. The products considered are built around aperture plates, finely perforated parts cut out of wafers which are slices of a well-defined material.

In the use case, the focus is on an initial stage in which wafer and the Aperture Plate (AP) are carried for the design and manufacture. AP is an integral part of the product and the most critical component. Within the design phase, different actions are conducted in order to change mixture and plating of the raw material and process the wafers and measure the quality of the material. Each run of the design process is called a trial. Within the trials several parameters are adjusted in the different design steps in order to enhance the quality of the aperture plate. In order to adjust these parameters, knowledge of previous trials like the parameter adjustments and their effect on the quality of previous trials is needed.

There are many complex factors, during the production steps that need to be monitored, such as the size of the holes, the quality of their construction on both sides of entrance and exit of the material and the surrounding wafers. The large number of process steps and the multiple positions require a constant tracking and engineering studies along the development cycle, both AP and final products themselves. This requires a high level of integration between the various workflows and information flows. For production and delivery, wafers are aggregated into lots.

Information technology support is required for several activities as for example for the optimal use of the testing machine by planning, for the optimization of the product logistics, for reporting and analysing results from the trials and for the decision-making process based on the outputs of former trials. The company needs to keep track of the product, in which the AP is finally used and where it is provided, among others based on relevant data from the product lifecycle. Typically, the APs from a particular wafer have similar characteristics. Normally, APs from any given wafer can be used in any product, whereby APs from some wafers may not be suitable for particular products. So, it is required to keep track of wafers, APs and the products their used in as well as the respective manufacturing and quality data, so that the information can be reconstructed.

The concrete pilot case considers the occurrence of a product failure during the usage phase. Based on the lot identifier, the manufacturer has to check manufacturing processing and quality data from earlier phases of the product lifecycle urgently, to decide if other products of the respective lot may be affected by a quality issue or if there are other reasons for the product failure, like a non-intended usage of the product. In the concrete case, an engineer had to spend around an hour to get a comprehensive view on the respective product lot based on distributed information available on the servers of the manufacturer company.

The scope of the application of an amePLM-based solution and PLM ontology in this case is to support the retrieval of information of previous trials and the documents and information related to a current trial during the design phase, i.e. manufacturing process and quality data. As the data that has to be examined is distributed in a bunch of large files in the form of spreadsheets, the domain-specific ontology has to enable the quick and error-free provision of manufacturing and quality data for the manufacturing lot.

5.1 Specification of the PLM ontology

The specification of the PLM ontology to manage the use case application is shown in Fig.5. It is an extension of the general PLM ontology, i.e., it uses concepts of the PLM ontology, specializes concepts of it and extends the PLM ontology by adding new concepts based on the use-case specific requirements – therefore, concepts of the original, generic ontology are in white colour, whereby new, added concepts have a darker background colour. In this specific case, the Product entity is related to the Trial entity to link the trials related to a product. A Product is composed by an Aperture Plate, representing the component of interest for the pilot case, and by additional parts. The aperture plate derives from a lot, which in turns derives from a wafer produced by a contractor. Thus, the Lot entity is connected to the aperture plates it generates, and the Wafer entity is connected with the Lot entity. The Contractor entity is connected with the Wafer entity. A wafer is composed by a specific material and has a plating of a different material. Thus the Wafer entity is connected with the Material entity to store these two relations.

The concept to model activities of the lifecycle is related to the product, and therefore to the aperture plate and the lot, respectively. The activities modelled for the specific pilot case cover specifically the lifecycle from the design to the production of the product. The design activities consist in the design of the manufacturing parameters for a specific trial. The production activities are of three kinds: manufacturing, assembly and testing. Manufacturing activities in the pilot case can be annealing, doming or braising. Testing activities can be detailed in optical density testing and micro inspection testing. For each test, the obtained results are stored.

Parameters to be stored depend on the manufacturing activity performed. For example, for an annealing activity, the time, the temperature and the number of repetitions are stored, while for the doming activity only the depth is relevant.

The ontology was implemented in OWL by using the Protégé ontology editor (Fig. 6).

Fig. 5. Specification of the PLM ontology for the use case.

Fig. 6**.** Implementation of the use case PLM ontology in Protégé.

5.2 Domain-specific ontology

In the pilot case, the company stores manufacturing and quality information in electronic spreadsheets, each consisting of several sheets with thousands of lines. Consequently, there is the need for a mean to bridge the gap between the amePLM solution and the electronic spreadsheets, which are continuously updated "living" documents in a typical office-document format (i.e. Microsoft Excel). To automate the input of the information contained in the spreadsheets into the semantic data base of amePLM, ontologies in the form of taxonomies are used in the standard SKOS format. With the taxonomy, it is defined how the information elements in the spreadsheets are translated into ontological elements, which are declared in the amePLM-set of ontologies as introduced above. Thereby for each relevant spreadsheet-element a relation to exactly one concept or its attributes of the target ontology has to be defined. For this, in the taxonomy keywords and their synonyms are defined as *skos:concept* with the respective labels and used as keys to identify relevant columns in the spreadsheets.

Fig. 7. Excerpt of a taxonomy supporting the transformation of manufacturing and quality data in the pilot case.

One of these keywords, in this case lot identifiers as Lot_Number with its synonyms, is defined as key "input" element for the identification of relevant rows and the corresponding ontological concepts. Furthermore, in the taxonomy an arbitrary number of "output" elements and their synonyms can be defined, which are considered as attributes to the main concept, i.e. the lot id in this case. Essential for the transformation is that for all ontology concepts which are concerned, related *skos:concept* elements have to be defined whose local *rdf:about-attribute* of the *owl:NamedIndividual*-element directly corresponds to the local name of the respective ontological concepts and relations. By means of an adapter agent, the original information contained in the spreadsheet files is transferred into the ontological data model of the amePLM-software by using the SKOS vocabulary serving as taxonomy. In this way, data found in the spreadsheets, e.g. about the concrete product, contractors, batch quantities for individual processes and their quality rates are translated into instances of the corresponding concepts of the data model provided by the PLM ontology, thereby populating the ontology with real world information. Based on this step, further semantic processing inside the amePLM-solution is possible, as highlighted for the case of information retrieval in the next section. To ensure the accurateness of the data model, the adapter agent continuously monitors the respective spreadsheet files and updates the information in the ontological data model where needed. A simplified excerpt of the taxonomy used in the case of the retrieval of lot-related information is provided in Fig. 7.

5.3 Information retrieval

By means of the transformation mechanism described above, the semi-structured data in spreadsheet files can be provided in the ontology for further semantic processing. In the industrial pilot case, an engineer has to get insight in manufacturing and quality information by means of a request he gets per mail based on a product failure. Consequently, an additional software component of the solution is a retrieval agent consisting of several components: one to parse the text of an email to extract a lot identifier, which is in this case a six-digit number out of a given range, and one component to retrieve all concepts with the given lot number as a Lot_Number property including all their other properties from the from the semantic data model in the IIL as introduced above. For the properties which are concepts themselves, so: object properties, all properties are retrieved, too. Furthermore one software component acts as a user interface to browse an email text and to display the output generated by means of a pretty-printed excerpt of the ontology, as shown Fig. 8 with anonymized data. By means of semantic processing, the agent is able to identify data contained in the populated ontology which is relevant for the user, and the identified data is presented to the user without any further need for action.

For this pilot case, a solution was developed with the amePLM system, which enables the transformation of available external semi-structured information into the semantic data model of the amePLM-software system and the subsequent semantic processing, in this case by means of the comprehensive retrieval of information related to a given lot identifier. By application of the amePLM-based solution, the time needed for manual information retrieval in the high amount of distributed files on the servers of the manufacturing company could cut down from one hour, over several minutes when using Microsoft's advanced search tools, to zero by the amePLM-solution, as basically a kind of Just-in-Time information provision was implemented by means of the amePLM-solution. The user gets the information he needs without any manual effort, but triggered by a software agent reading the email the user gets.

Fig. 8. User interface for the automated information retrieval in the pilot case

6. Conclusions

In this paper we have described an approach to structure knowledge, the asset of engineering companies, along the product lifecycle (PLC). The aim of the amePLM approach is to support engineers and other users involved within the product lifecycle to create, share, retrieve, and preserve knowledge amongst different stages of the PLC.

The amePLM solution differs in several aspects from current approaches. We focus on an extensible, open and modular solution of managing knowledge along the PLC by adapting semantic technology.

A central knowledge repository based on open-sources software (e.g., Apache Jena, Apache Stanbol, Elasticsearch) providing interfaces based on open standards (e.g., SOAP and REST web-services, SPARQL endpoint, OWL, XML, JSON) is functioning as semantic middleware for engineering modules and other applications used by different actors along the PLC. The modularity of the implemented platform allows a customised solution by providing a light weight subset of the platform functionality and therefore particularly targets SMEs.

The management of information artefacts along the PLC is done by using the amePLM ontology via semantic annotation of information as well as by tagging them semantically by using the domain ontology. This allows us to interlink knowledge of different stages of the PLC based on the semantic links by utilizing OWL reasoning (e.g., sub-class/super-class reasoning) or by OWL and SKOS reasoning via the semantic tags. Additional semantic interlinking can be achieved via formulation of rules or queries using SPARQL. And the combination of search technology (Elasticsearch) and semantics (amePLM extension) provide semantic search via semantically enriched search indices. Heuristics utilizing data mining algorithms additionally provide metrics on the knowledge within the semantically enriched knowledge supporting actors along the PLC like managers and engineers during design time, planning, production, marketing and sales.

The platform is not intended to replace existing systems like PDM or CAx applications since people are used to their systems of preference. We rather see amePLM as a system that can integrate these systems as additional engineering modules and incorporate their knowledge into the amePLM knowledge space. Within the pilots defined within amePLM the prototypical realisation of the platform has already shown its potentials. Besides the application scenario presented in this work, the PLM ontology was specified in other four different industrial cases, thus proving its validity in a broad context. Particularly, they addressed the following aspects: the design and manufacturing of a mandrel, the manufacturing of a telecommunication filter, the balancing of a production line, and the incident management for a service provider.

The extension of the platform functionality will include the following four main points: the integration of third party apps into the 3D workspace, the addition of new workflow apps to integrate further project management functionality and additional engineering tasks into the PLC, the integration of existing data sources (e.g., database, PLM systems, etc.), and the integration of third party engineering modules and other applications into the IIL.

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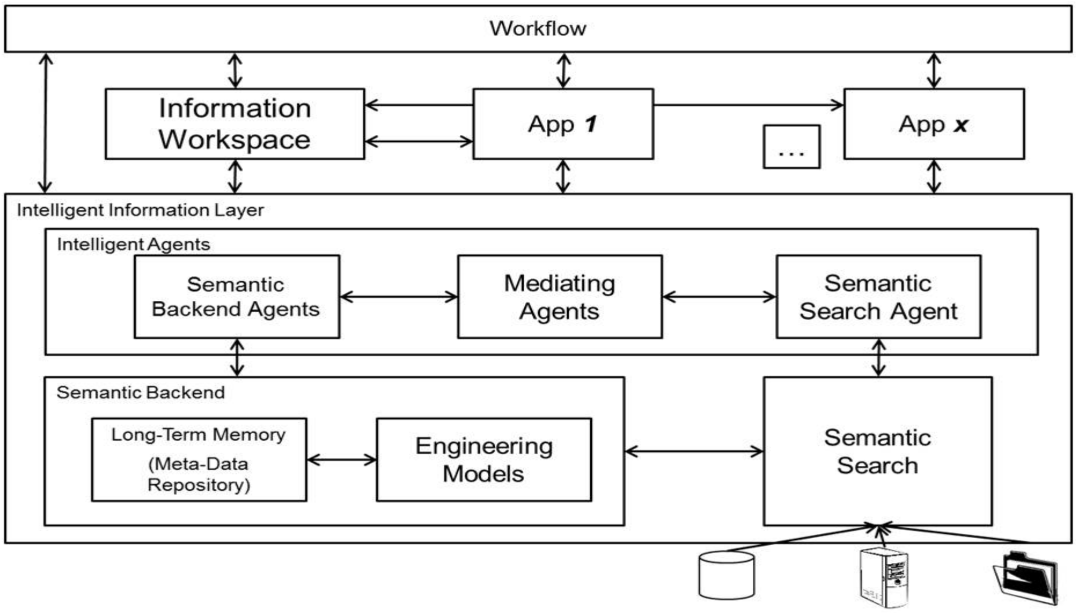

Fig. 1. Principal architecture of the amePLM solution

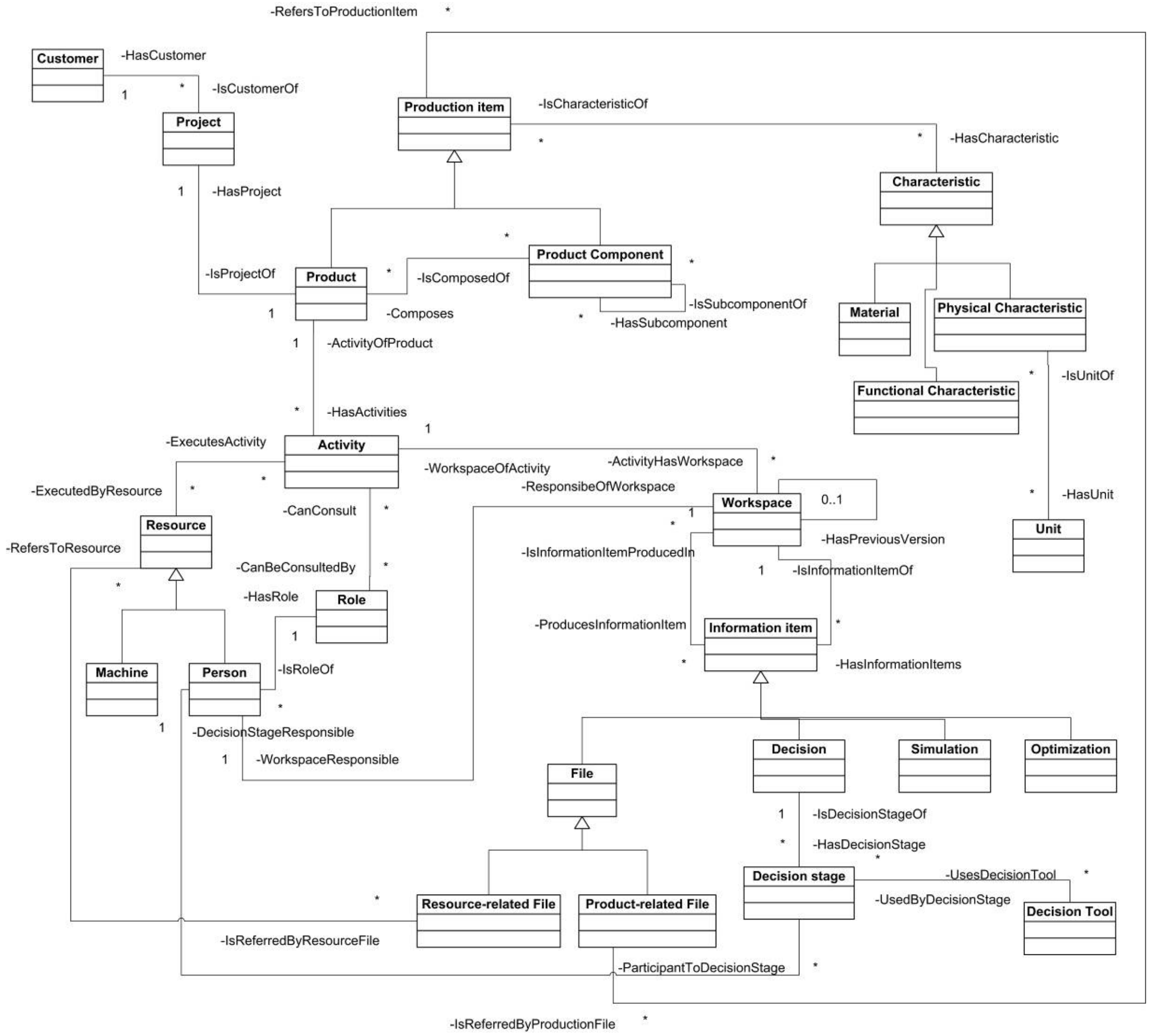

Fig. 2. UML class diagram of the PLM ontology.

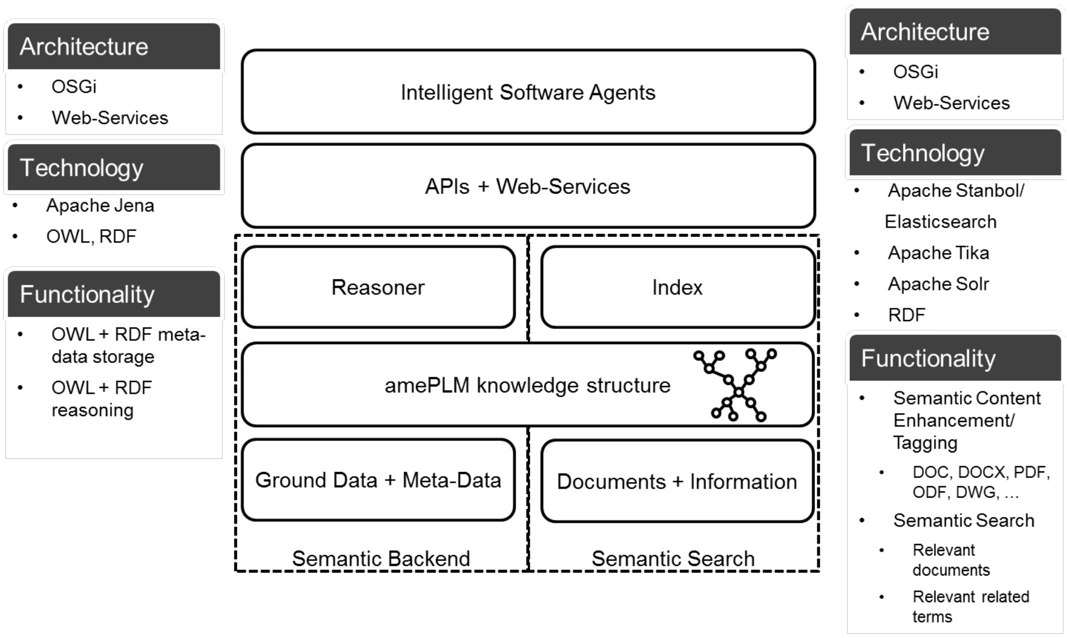

Fig. 3. Architecture of the IIL of the amePLM platform.

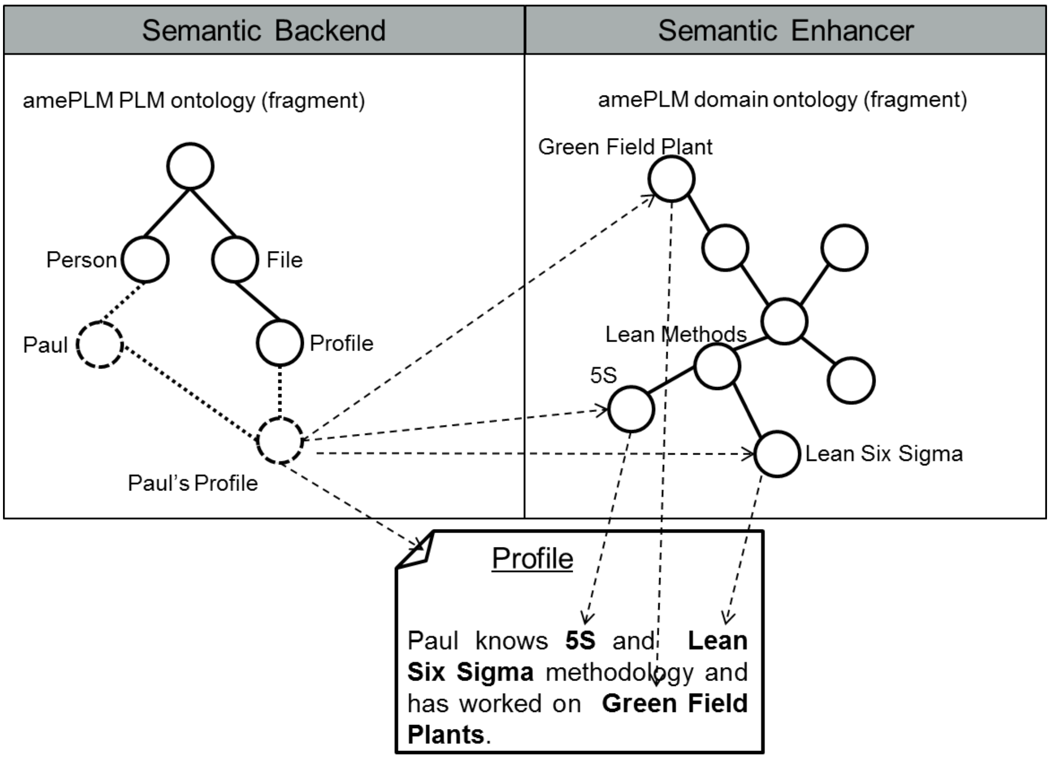

Fig.4. Example of an associated and tagged profile.

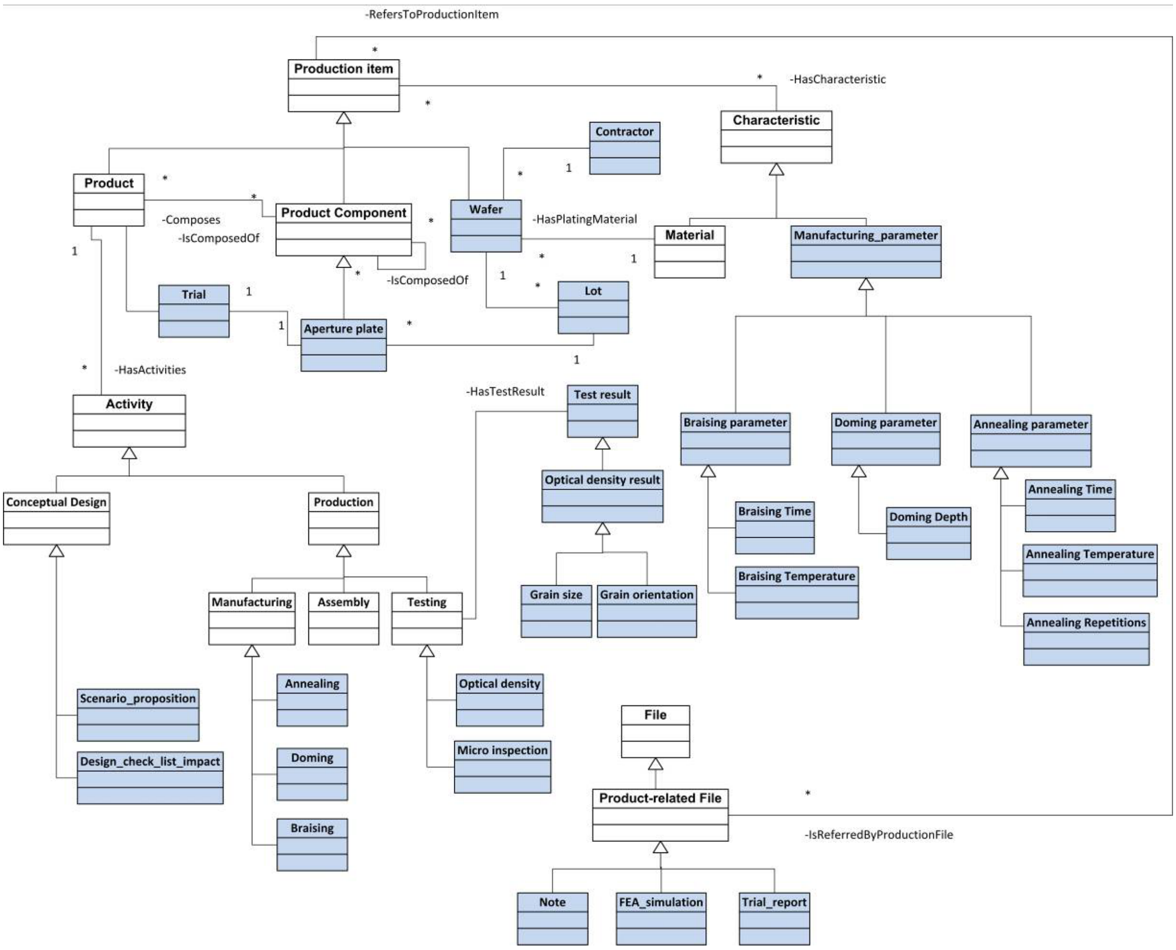

Fig. 5. Specification of the PLM ontology for the use case.

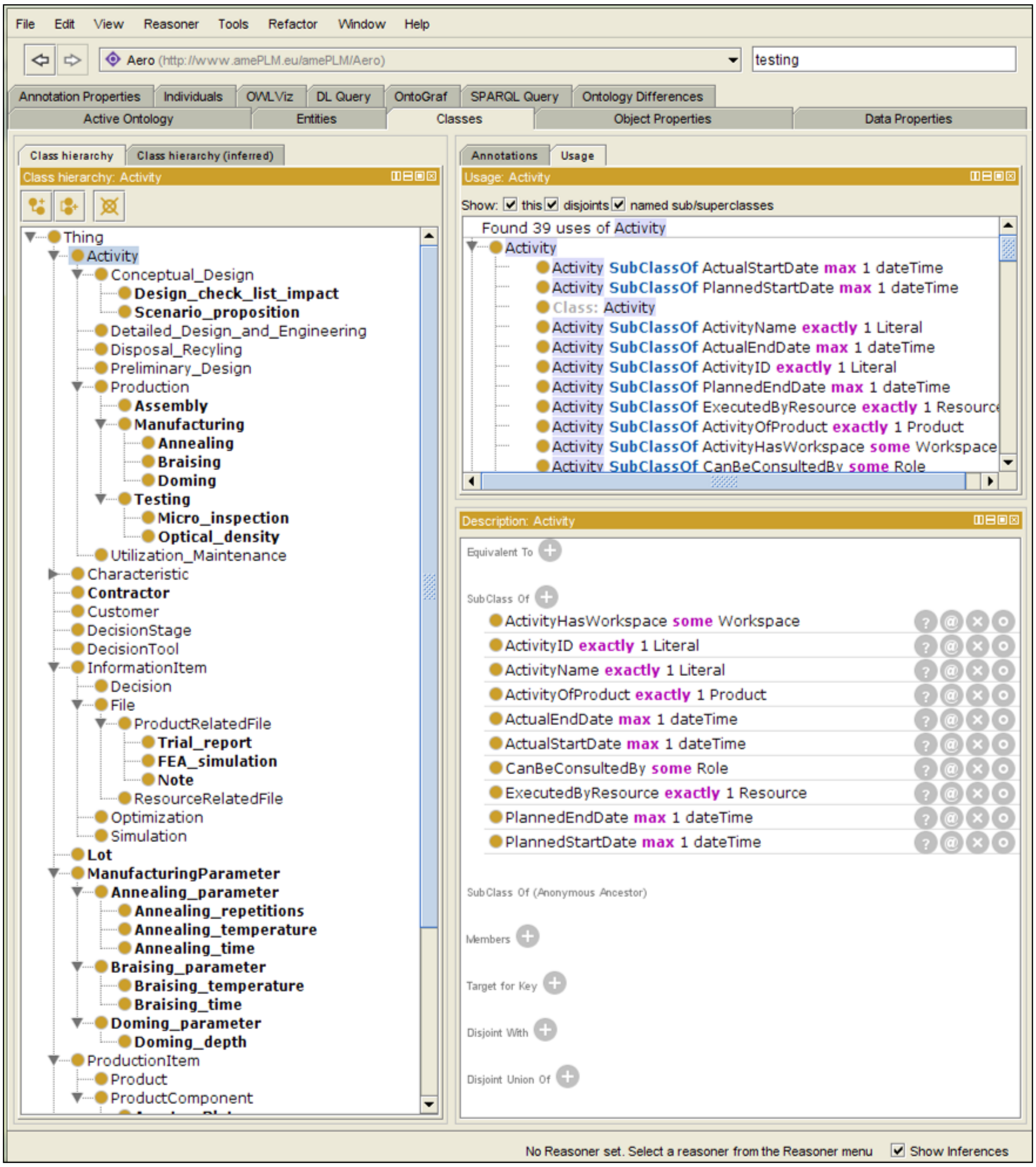

Fig.6. Implementation of the use case PLM ontology in Protégé.

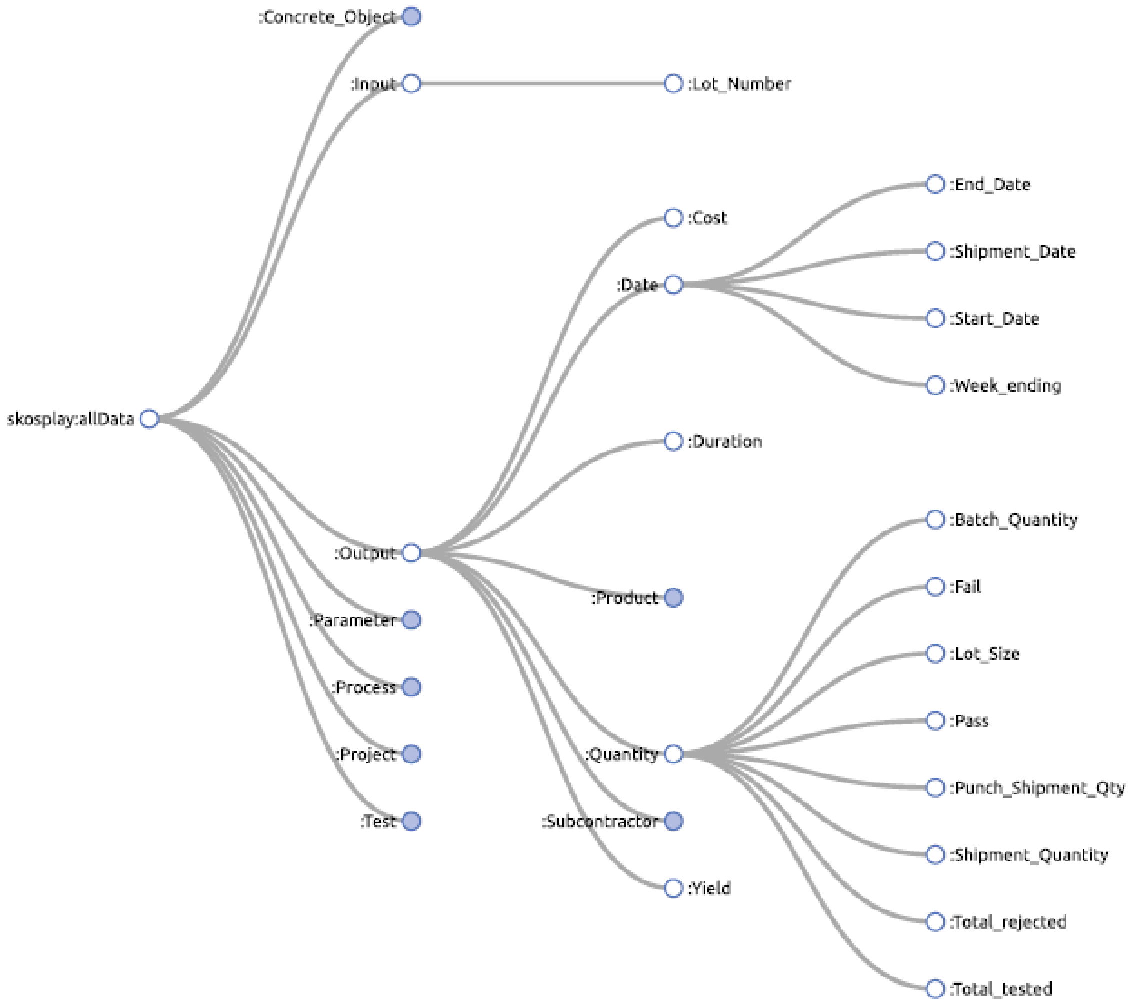

Fig. 7. Excerpt of a taxonomy supporting the transformation of manufacturing and quality data in the pilot case.

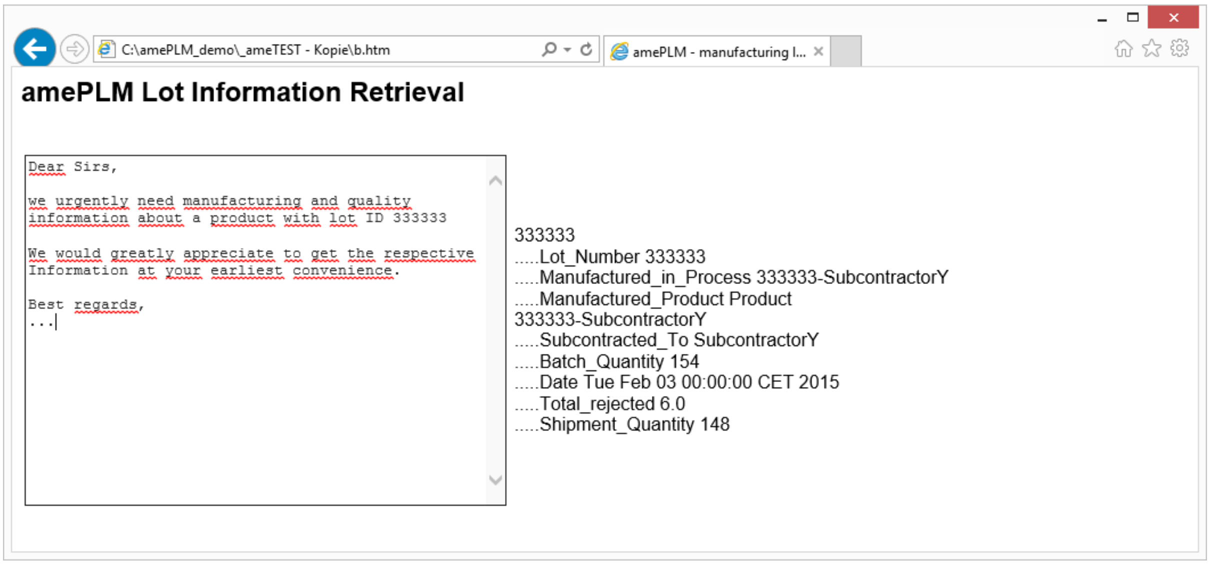

Fig. 8. User interface for the automated information retrieval in the pilot case