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Managing manufacturing data and information in product lifecycle management systems considering changes and revisions

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Abstract: Manufacturing data and information are produced and used during the lifecycle of product development. Product lifecycle management (PLM) systems provide a suitable platform for managing them. For appropriate management of manufacturing data, it needs to be identified, classified, and stored based on the structure of PLM systems. In this paper, the results of an industrial manufacturing data collection study are interpreted, and their relation to the main structures in PLM systems is specified. Subsequently, a new information model for assigning this data and information to the PLM data model is presented. The main contribution of this information model is the definition of property and change objects and integrating them with the structure of PLM systems; changes and revisions of those data are formally defined and hence traceable.

Keywords: manufacturing data and information; product lifecycle management; information model; information structure; bill of material; bill of process, bill of resource; PPR; change; revision

1 Introduction

Manufacturing data and information are produced, updated and used throughout the lifecycle of a manufactured product. It consists of any type of data and information related to manufacturing, such as data and information about the product, processes and manufacturing systems. For managing this data and information, some information systems started to appear in the midst of the third industrial revolution (1980s). Product lifecycle management systems started to be used for managing manufacturing data at the beginning of the 2000s. Engineering activities such as virtual modelling and simulation are part of building a digital factory in the fourth revolution of industry (Industry 4.0). A proper management of manufacturing data and information is needed for these engineering activities. According to the role of manufacturing data in Industry 4.0, product lifecycle management (PLM) became the backbone of virtual development (Eigner and Stelzer, 2009; Jeschke et al., 2017; Kropsu-Vehkapera et al., 2009; Madrid et al., 2016). Hence, the critical role of up-to-date manufacturing data and information in building digital factories and later performing engineering activities in virtual engineering and cloud manufacturing is obvious and PLM systems are used for managing this data and information.

Several information models have been developed for managing manufacturing data and information, of which some of them are used for structuring data and information in PLM systems such as ISO10303 (STEP standard) and ANSI/ISA-95 (Instrument Society of America, 2000; STEP Tools Inc., 2014). Although these standards provide information models for managing manufacturing data, they are designed in a generic way to be flexible and cover many application areas. In many cases, this level of flexibility results in a lack of details on management procedures such as structuring data and information and change management. In contrast, current PLM systems do have revision management capabilities, but only on the level of whole information entities or documents. This paper presents a more explicit and extensive information structure, which can help manage changes and revisions of manufacturing data, whilst supporting the traceability of older revisions of properties and their corresponding entities. In the PLM structures, an entity can be a part of a product in the Bill of Material (BoM), or a machine in the Bill of Resource (BoR) or an operation in the Bill of Process (BoP). BoM is the structure of the product and consists of the different parts and assemblies of a product. BoP shows the different processes and their relationships for manufacturing a product. BoR is a factory's structure and contains the resources needed to produce a product.

There are two main advantages of keeping older revisions of entities and their properties. Firstly, whenever a user needs information about previous revisions of an entity and its properties, they are available such that the full history of the entity is accessible. This information helps to track changes in products, processes and resources and later to analyse the consequences of previous changes and make better decisions in the future. The second advantage of keeping older revisions of entities and their properties is about using property data in engineering activities. In modern Computer-Aided Engineering systems, there are frequently some legacy virtual models connected to these entities (i.e., product, process, and resource) and their data. If an entity, its properties, and its corresponding virtual models are managed with each other, then they can be used and reused in multiple studies and experiments, such as simulation and optimisation.

This study originated with manufacturing data collection and data classification in the manufacturing engineering domain in an automotive component company with a focus on discrete event simulation (DES). The selection of DES-related data was made due to the wide variety of data types that are used in DES, from design, manufacturing, maintenance to services so that they can be representative of manufacturing data. After collecting manufacturing data types, they are classified based on the main structures in the PLM systems, which are BoM, BoP, and BoR, and subsequently, a new information structure is proposed. In this new information structure, a property class for adding manufacturing data has been defined, and the procedure for making the association between properties and their corresponding entity in the PLM structure has been identified. Based on these associations, changes to an entity, through the change in its associated properties, propagate to changes in other associated entities. Finally, by defining an explicit change class, different revisions of properties and entities can be maintained in the PLM system. Through managing revisions and changes, users always have old revisions of an entity with all properties that are associated and belong to that revision. The novelty of our approach lies in the equal treatment of changes to properties and changes to entities. This is achieved by representing properties as objects rather than attributes of entities.

2 Literature review

In this section, PLM systems will be reviewed in the context of their role in managing manufacturing data and information. Subsequently, some definitions related to simulation in general and DES, in particular, are defined. The information model used is the Unified Modelling Language (UML) class diagram, some basics about UML are also explained. Furthermore, a background about data and information is provided, and some available manufacturing data and information models are presented to identify the strength and weaknesses of the available models for managing manufacturing data and information.

2.1 Product lifecycle management

Each product has a lifecycle that can be divided into several different phases: business idea, requirements analysis, development, production, operation, maintenance, and disposal (Crnkovic et al., 2003). A review of the literature reveals that the definition of PLM is not necessarily the same in different research fields. CIMdata (2002) defined PLM as a strategic business approach, but Grieves (2005) and PLM Development Consortium define PLM as an information-driven approach (Stackpole, Beth, 2003). Siemens and AMR have a computer science view in their definitions of PLM, in which they define it as an information management system or group of software applications (Burkett et al., 2003; Siemens, 2016).

Generally speaking, PLM can be defined, from the business viewpoint, as "a business approach for management and use of corporate intellectual capital, such as product, process and production system-related data, and information, including people's experiences and knowledge over the extended enterprise." Nowadays, PLM systems are a kind of information system for managing product and production-related data and information through their tight integration with other CAx technologies and other business and shop floor information systems. This integration constitutes an ideal platform for transferring and managing data between different heterogeneous engineering software systems. Manufacturers use PLM for managing product, process, and resource (PPR) data; therefore, BoM, BoP, and BoR are the core structures of PLM systems for managing PPR data and information (Martin and D'Acunto, 2003; Morshedzadeh et al., 2019; Smirnov et al., 2013; Tae-hyuck et al., 2007). In PPR, the product is the physical part or assembly, and the process is the manufacturing transformation of a product. The resource includes anything that is used in the process to build a manufactured product such as plant, machine and tool.

2.2 Discrete Event Simulation

Simulation is a study of the characteristics or behaviour of a physical or conceptual system by utilization of models. Through changing one or several input variables in a simulation model, values in the output variables will be changed accordingly so that the input-output relationships represented by the model can be analysed (Maria, 1997; Schumann et al., 2011). A discrete event simulation (DES) model is a kind of simulation in which variations of the state variables have been tracked at a set of discrete points in time, triggered by scheduled and conditional events. DES is used prevalently in industries, especially for performance evaluations of manufacturing and material-handling systems (Banks et al., 2004). The extensive application areas that can be covered by DES, from design, manufacturing, maintenance to services, have created the need for different types of manufacturing data when developing/updating the models. As argued by (Banks et al., 2004), collecting valid, useful and accurate input data is one of the most challenging and essential problems in simulation. Because of this reason, we will focus on how various data types used with different applications of DES can be effectively managed in this study.

2.3 UML Class diagram

A UML class diagram defines the types of information that are of importance in a given domain. It consists of so-called classes (standing for a set of data objects that share the attributes defined in the class), and associations that define possible links between objects. For example, a class like a "Machine" may be associated ("vendor") with another class "Company" (Rumbaugh et al., 2004). The associations have cardinalities that specify how many objects of one class may be associated with the other class. For example, a machine has a single company as a vendor, and a company may have any number of machines being sold.

UML class diagrams are used for structuring information in a certain field and they are the basis for the database design for information systems, such as PLM systems. In virtual engineering, a particular challenge is to represent a product, process, and resource-related data with their changes. In this paper, UML has been used to define the solutions to the information structuring problem for manufacturing data and information, to address these challenges.

2.4 Data, Information and Knowledge

Data, information and knowledge are interrelated to each other. Data can be simply defined as strings of symbols. Strictly speaking, there is not any meaning or context in data. It is information that relates the processed data to give them meaning. Subsequently, knowledge represents information that is understood and recognized by a person. Therefore, data is a building block for information and knowledge is generated from information (Mills and Goossenaerts, 2001; Rowley, 2007; Vosgien et al., 2011; Zins, 2007).

2.5 Manufacturing data and information

Any manufacturing activities depend on data and information as their important resources at all stages of the product lifecycle, from design to planning, operations, and after-sales operations (Cecelja, 2002). Manufacturing data and information includes data and information from product, production and manufacturing systems. It also consists of the generated data and information through different Computer Added technologies (CAx), such as Computer-Aided Design (CAD), Computer-Aided

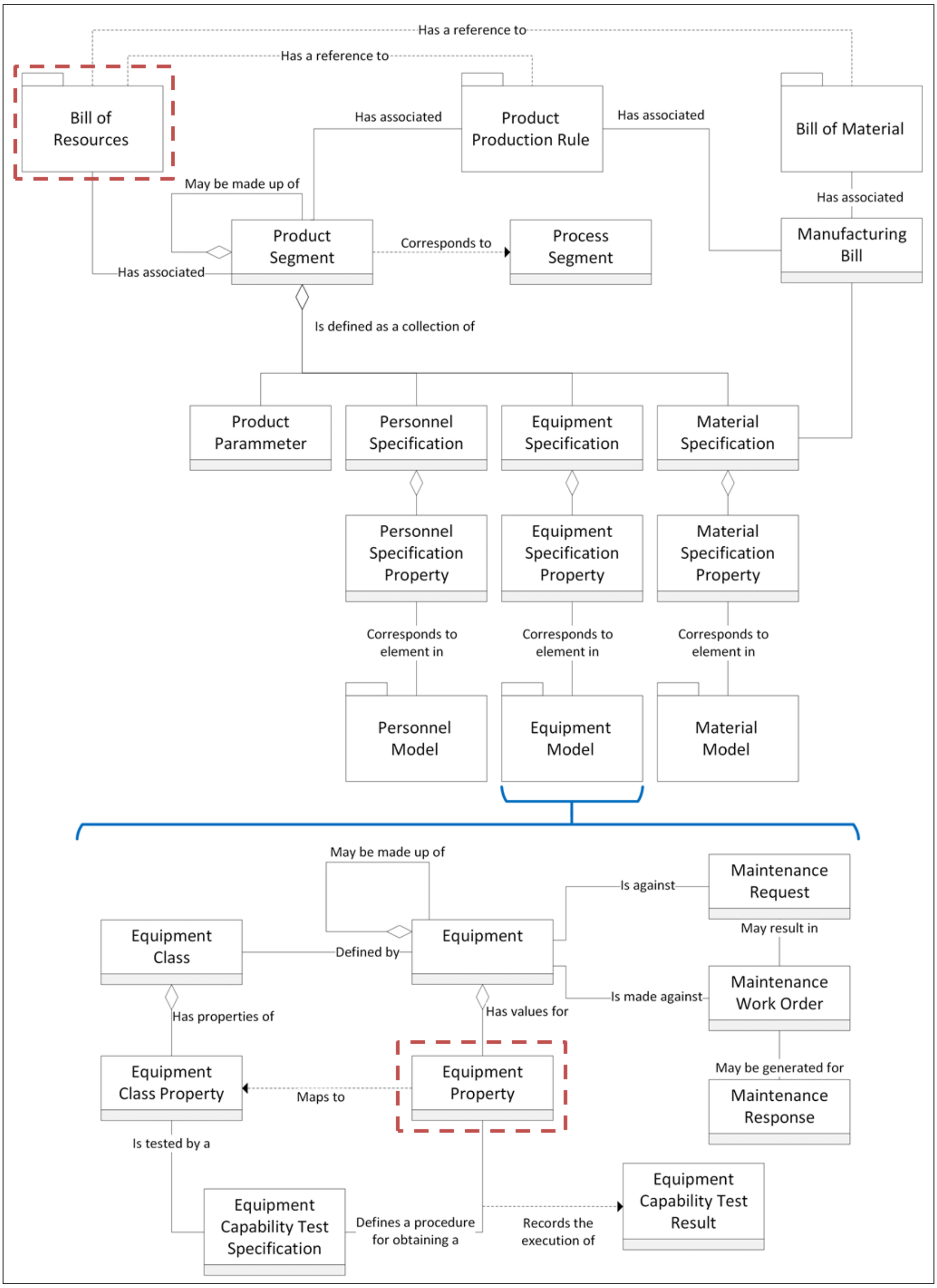
Engineering (CAE), Digital MockUp (DMU) during the product development process (Vosgien et al., 2011). Managing this huge amount of data and information involves deriving information and data structures. In the following, some existing standards and information structures for managing manufacturing and simulation data will be presented. Some of these are used for structuring manufacturing data in PLM systems and some of them are used specifically for managing manufacturing simulation data in different data and information management systems.

ANSI/ISA-95: ANSI/ISA-95 is a standard developed by the Instrument Society of America for managing manufacturing data and information. The standard covers three information areas (Instrument Society of America, 2000):

- Production capability: personnel, equipment and materials.
- Product definition: scheduling, material information, and production rules.
- Production: production information, inventory information and the production scheduling information.

Some of the information provided in this standard can be handled by PLM systems, but there are also other types of information that have to be managed by other information systems, such as enterprise resource planning (ERP) and supply chain management (SCM). As shown in **Figure 1**, in this standard, the distribution of information in different segments of information areas are presented in such a way that information about BoM, BoR, BoP are represented in the production definition area and information about equipment and material properties as some kinds of manufacturing data are in the production area. Even in this standard, some classes such as “Equipment Property” and “Material class Property” exist for managing manufacturing data and information, the direct association of these classes within the three main structures of BoM, BoP and BoR in PLM systems are not well defined. Moreover, the ANSI/ISA-95 standard does not offer any procedure for managing the changes of entity properties.

Figure 1 The relation of the Bill of Resources in the product definition model (top) and the Equipment property class in equipment model (down), adapted from (Instrument Society of America, 2000)

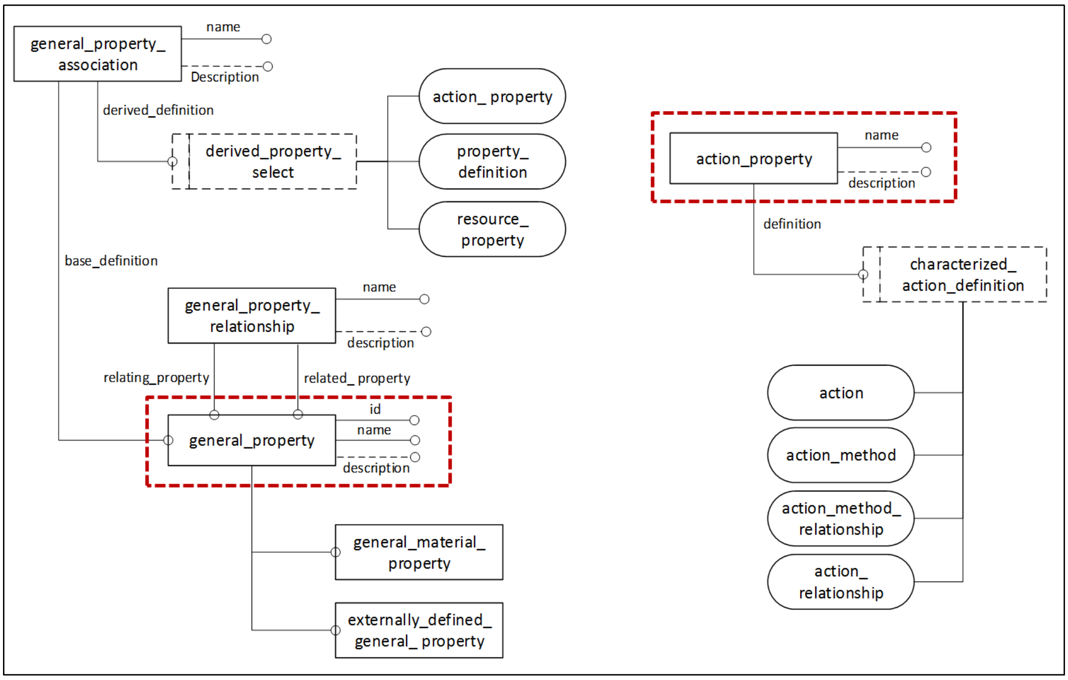


Core Manufacturing Simulation Data: Core Manufacturing Simulation Data (CMSD) is a standard for managing manufacturing data used for simulation. In this standard, manufacturing data and information have been divided into different packages of layout, part information, support, resource information, production operations and production planning (Simulation Interoperability Standards Organization, 2012). This standard employs the Unified Modelling Language (UML) and the XML Schema definition language for structuring and representing manufacturing information. CMSD is used for the automation of input data for DES, but information structures in the CMSD are not compatible with structures in PLM systems (Panagiotis Barlas and Heavey, 2016; P. Barlas and Heavey, 2016).

ISO 10303: ISO 10303, also known as the STandard for Exchange of Product model data (STEP), is a well-known standard for manufacturing data management, in which different information structures have been developed for various application areas. For example, AP214 (ISO 10303-214) is the standard of core data for automotive mechanical design processes and AP212 (ISO 10303-212) is labelled as the standard of "electrotechnical design and installation" (Paviot et al., 2011; Rachuri et al., 2008; The ASD Strategic Standardisation Group (SSG), 2015). Although in some cases, some of these application areas are connected to each other, they cannot be connected and used easily for managing all the necessary manufacturing data and information as in a single system, such as PLM systems, because of the wide variety of application areas (Euler-Chelpin, 2008; Rachuri et al., 2004; Sudarsan et al., 2005).

In the STEP standard, several classes such as "general_property", "property_definition", "resource_property" and "action_property" have been defined to give flexibility to the users for structuring their data and information as they desire (iso.org, 2010; STEP Tools Inc., 2014). Figure 2 shows application interpreted models (AIM) for two types of classes for managing manufacturing data, which are "general_property" (left) and "action_property" (right). It is noticeable in Figure 2, the relation of properties with PPR is not specified in detail and there is not a specified procedure for managing any changes of properties. The information model provided in this study is more detailed in relating properties and PPR and also specifies a way to manage any changes of these properties.

Figure 2 Application interpreted model (AIM) for general_properties (left) and action_properties (right), adopted from (STEP Tools Inc., 2014)



Information models for PLM and manufacturing data: The standards described above cover manufacturing-related information and data, but there are some information structures more specific about PLM core data. Some researchers present information structures for products, processes, resources, and plants (P3R) (Lee et al., 2012) or simply PPR (Colledani et al., 2009, 2008; Euler-Chelpin, 2008; Smirnov et al., 2013). In some information structures, the human is considered as a separate object (not as a resource) and the information structure is based on the PPR+H (Lee et al., 2011; Zhao et al., 2015, 2012). Kong et al., (2020) proposed a method for structuring data in order to provide stable and efficient data support for the applications of digital twin systems. Liu et al. (2020) presented an information model for managing manufacturing data with the digital twin collaboration possibilities and Andres et al. (2021) designed a data model for collaborative manufacturing environments by building a taxonomy of data concepts. In recent years, sustainability-related data has been considered as a manufacturing data type in the presented PLM information structures. Zhao et al. (2012) defined several classes related to product, process, plant and enterprise classes in their PLM information model for collecting sustainable related data as their attributes. For example, the "Noise pollution level" as a manufacturing data type had been defined as an attribute of the "Emissions and pollution" class, related to the "Process" class. Vadoudi et al. (2017) integrated geographical data with product-related data for the possibility of enhancing sustainable products and Mandolini et al. (2019) defined a lifecycle data model that facilitates the interoperability of eco-design software tools.

As the summary of the literature review about manufacturing data and information, the structures described in many of the above-cited articles and standards placed manufacturing data in attributes of the entities and not as a separate class. In particular cases, manufacturing data have their own classes, but those classes have been defined for specific types of data and they are limited, such as only product-related data or process planning-related data. Furthermore, a generic way for the change management of manufacturing data has not been found in any of the presented structures. As such, according to the literature review of information structures and different standards, there is a need for an information structure for managing manufacturing data and information that can be aligned with the core structures in the PLM system. In this paper, as a prerequisite for structuring manufacturing data and information, the results of data and information collected in the area of DES will be presented and classified. Then, an information structure for managing this data and information is presented.

3 Data collection methodology and results

The first step for designing an appropriate information structure is to specify the data types. Since manufacturing data can be found in different documents, then in this section, a data collection methodology adopted for collecting documents from meeting with different disciplines in the industry will be explained. These documents are used as a source for extracting manufacturing data types, and these data types are classified based on their relation to the PPR mapping. Since PPR is the basis for core structures in PLM systems (BoM, BoP and BoR), this classification can help to design an information structure align with PLM structures.

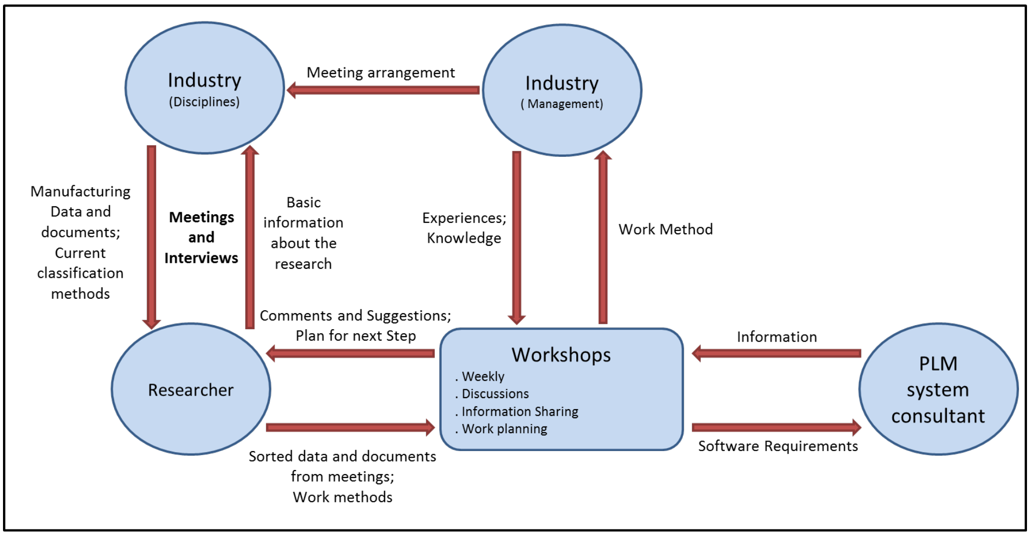
3.1 Data collection methodology

The data collection phase of this research study was made by a close collaboration between the authors and different disciplines of manufacturing in an automotive component factory. Figure 3 shows the data collection methodology in this research. In this methodology, data and documents are collected through nine meetings of two hours with employees of the factory who are responsible for different disciplines, outlined below:

- Advanced engineering
- Manufacturing engineering
- Equipment
- Equipment suppliers
- Packing
- Quality control
- Gauging and tooling
- Productivity engineering
- Maintenance

From the above disciplines, clearly, equipment suppliers are not part of the company's disciplines but their documents contain some manufacturing-related data. Because of that, equipment suppliers and customers are also considered as disciplines in the manufacturing area. Before the meetings, those responsible for different disciplines were informed about the research and asked to provide documents containing the related data for those discipline meetings. Interviews are semi-structured and interviewees had to fill a form to provide some additional information about documents such as type, language, producer, sender, receiver, source and etc. With this additional information about the collected document, their content data can be extracted and analyzed in more detail. Through the data collection procedure, eight weekly workshops have been held between the researchers, management from the company and a consultant who was involved in the PLM implementation in the industry.

Figure 3 Data collection methodology



During these workshops, the data and documents collected were presented and evaluated as well as the relation of this data and the possibility of managing them in the

current PLM systems were identified. Documents collected had been used as sources for specifying different types of manufacturing data.
From the meetings with a total of nine different manufacturing-related disciplines, about 46 types of documents were gathered. After extracting types of manufacturing data from collated documents, these data types are classified according to their relation to the PPR mapping.

3.2 Data collection results

The output of several meetings with representatives from different disciplines in the area of manufacturing was 46 different types of documents. The documents collated do not cover the complete lifecycle of the product; however, they are a part of documents that are used or produced in the manufacturing engineering division of the automotive production industry.
After the collection of the documents, they had been studied and the different types of manufacturing data and information extracted from these documents are specified. In total, about 571 types of data have been collected and saved in a table (Table 1). Since there were lots of duplications and combinations in data collected, they were analysed and purified. Finally, 264 data types were identified for classification.

Table 1 Excerpt of the data types collected in the study

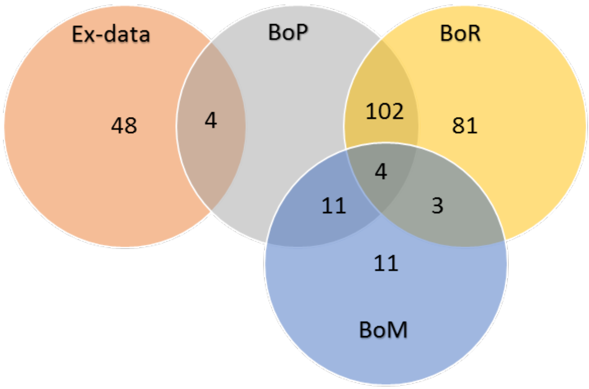
93	Part denomination	BoM	
94	Family denomination	BoM	
95	Feature1 denomination	BoM	
96	Feature2 denomination	BoM	
97	Feature3 denomination	BoM	
98	Sequence or percentage distribution	BoP + BoM	
99	Part number	BoM	
100	Batch size	BoP + BoM	
101	Assembled with main variant	BoP + BoM	
102	Icon	BoM	
103	Colour	BoM	
104	Raw material cost	BoM	
105	Target cycle time	BoP + BoM	

Most of the data types in table 1 are properties of engineering entities, e.g., the target cycle time of a process. Indeed, the very purpose simulation and optimization in virtual engineering is to understand how to find the best values for these properties.
In this study, data types have been classified into four categories. Since data has to be structured in a PLM system, data types are classified according to their relation to which product, process or resource, the relationship has been justified based on the changes in the corresponding product, process or resource. The four categories are:

- Product-related data: Data types related to products, such as dimensions
- Process-related data: Data types related to processes, such as cycle time
- Resource-related data: Data types related to resources, such as energy consumption
- External data: data that does not belong to the previous three categories, such as working hours

Some of the data types belong to just one group and they do not change with changes in other groups. For example, standby energy consumption or investment costs of a machine is a resource-related data type and they are independent of changes in the product or processes. Other examples are part dimensions and raw material costs, which are related to the product so that they are independent of changes in processes or resources. However, some data types are shared properties and depending on two or more classes. For example, the availability of a resource belongs to both resource and process, so that changes in process or resource will affect the availability of that machine. There are also some groups of data types that do not belong to these structures, such as working hours. These data types can be transferred from other information systems in the enterprise (such as ERP or SCM) to the PLM system, which can then been used in different engineering activities such as DES. Figure 4 shows how data types are distributed in different groups. External data (presented as Ex-data) is a type of data that does not belong to BoM, BoR or BoP. Based on this classification, different data types have to be structured within one or several of these PPR structures (BoM, BoP, and BoR).

Figure 4 Classification of manufacturing data



As an outcome of this classification, no data type exists that is related to processes only but not related to product and/or resource. This is simply because the existence of the process is dependent on the product and resource.
Based on the data type collection, their classification results, and also available information models for managing manufacturing data and PLM following arguments can be achieved.

- Some manufacturing data are shared between two or more entities in PLM structures, and then there is a need for a separate class (property class) for manufacturing data
- The three core structures of PLM (BoM, BoP and BoR) and their relation to property class has to be specified
- A change class must be defined in the desired information model to make changes of properties and entities manageable and traceable.

We conclude that the properties of engineering entities are of paramount interest to engineers. The classical approach in IT systems is to regard properties as attributes of objects (Rumbaugh et al., 2004). The state of an object is defined by the combination of its attribute values. Changing an attribute value does not change the object identity. This approach makes it difficult to trace changes to attribute values. In classical PLM systems, object revisions are used to maintain different versions of an engineering entity. The problem with this approach is that it does not support that different engineering entities share the same property, such as the cycle time of a process. We thus argue that properties should be *reified*, i.e. they become objects themselves that are linked to the engineering entities. Further, changes are reified as well to maintain the dependency network between updated entities and their properties.

With concerning the above arguments, in the next section, the synthesizing of an information model for PLM core structures and managing manufacturing data and changes with property and change classes will be explained.

4 Synthesizing the UML class diagram

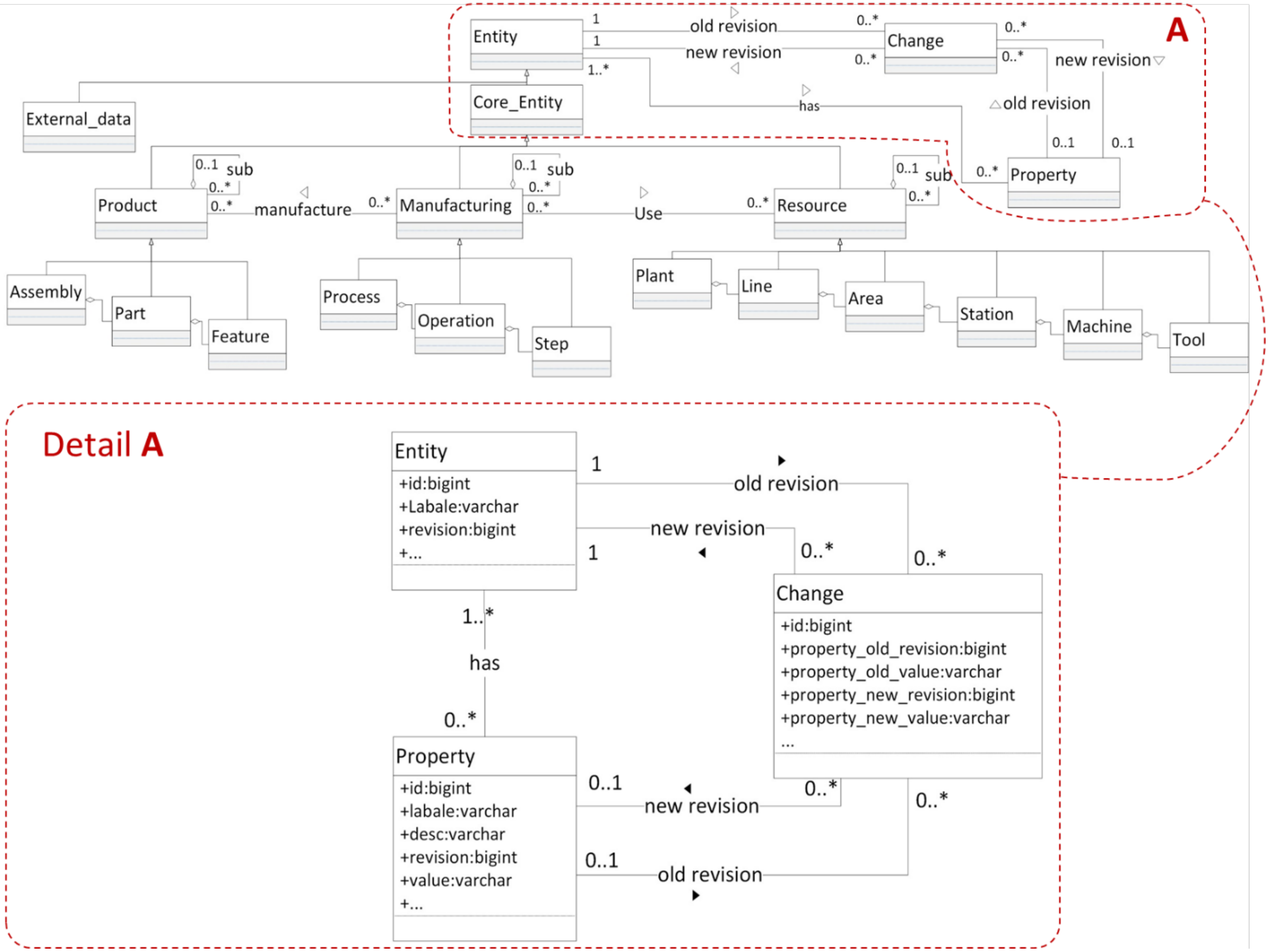
In this section, a ULM diagram for managing manufacturing data and information will be outlined based on the bottom-up classification of manufacturing data elements. Figure 5 shows a PLM information structure with property and change classes that are associated with the core of PLM. Since this class diagram is based on the core of PLM, three structures for BoM, BoP and BoR have to be defined respectively in the information structure. In this diagram, the entity class has been divided into two subclasses of external data and core entity. The core entity class consists of three classes of product, resource and manufacturing process to cover BoM, BoR and BoP. These three parts of the information model have been explained in the following.

BoM: BoM is a hierarchical structure of different parts of a product. In this model assembly, part and feature are three subclasses of product. Each assembly consists of several parts and each part consists of several features. If a user wants to have assemblies in two levels of hierarchy (as assembly and sub-assembly), then there is a possibility of having several instances of one class with the aggregation relationship. For example, an assembly instance can have another assembly instance as its parents.

BoR: Plant, area, line, station, machine and tool are sequential classes for building a hierarchical structure of BoR. In the BoR structure also, a class can be a subclass of itself. For instance, an area can have several sub-areas with the aggregation relationship.

BoP: Classes of process, operation and steps are used to define BoP. For BoP, similar to BoM and BoR, instances of the same classes can be used in different levels of structures. For example, a process instance can consist of another process instance as its sub-process.

Figure 5 The UML Class diagram for managing manufacturing data and information with details of the part with changes and revisions (A)



The core entities and their relations have been defined based on available definitions and structures in standards and literature, combined with the analysis of processes and structures in the industry. For example, BoR has been adopted from ISO and NIIST standards. In the ISO standards, manufacturing systems have been divided into the enterprise, site, area, work centers, work units, and equipment levels (ISJ1EC 62264-1, 2003, p. 1). NIST divided manufacturing systems into facility, shop, cell, workstation and equipment level (Jones and McLean, 1986). According to these deviations and the collected data in the industry, BoR has been divided into the plant, area, line, station, machine, and tool in this research. Since literature mainly focused on one part of core entities with different level of detail, in this research entities are gathered, integrated and finally presented in a unique and homogeneous structure. Even though the presented structure is explicit, keeps the flexibility for structuring PPR entities.

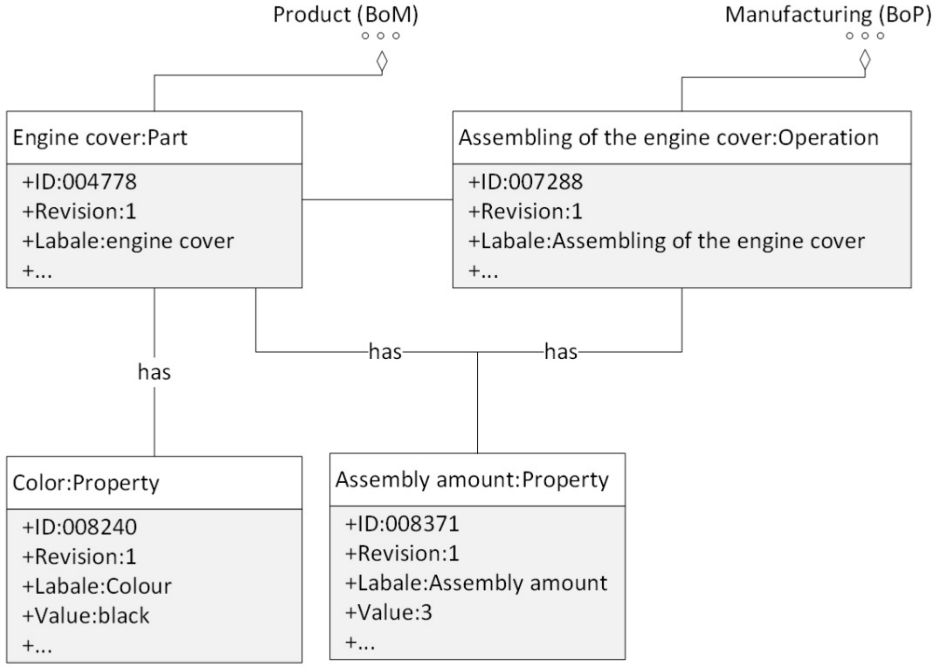
The main and innovative part of this research is managing manufacturing data and their changes through the “property” and “change” classes of the designed information model. As mentioned in the literature review section, in the studied standards and literature, manufacturing data are placed as attributes of PLM core entities, or they are associated with entity classes as specific named classes without considering their changes. Having a separate class for manufacturing data (Property class) gives the ability to add, remove and manage manufacturing data with more freedom when compared to defining these data types as attributes of entity classes.

Hence, for managing manufacturing data in this class diagram, the “property” class has been defined. Each piece of manufacturing data can be associated with entities, as the “property” class instance. According to the data classification presented, manufacturing data can be related to BoM, BoP, BoR or external data. If the data is merely related to one of these groups, then there will be just one associate link between the corresponding “property” instance and the “entity” in that structure. For example, if the colour of the cover of the automotive engine is black, then there is the instance of the part class with the name of “engine cover” which is linked to the instance of the property class with the name of “colour” and the value of “black”, as shown in

Figure **6**. If the manufacturing data is related to two or more instances in different structures, then the corresponding property is associated with those two or more entities. Another property example is the “assembly amount,” which means the amount of the incoming material types that are assembled with the main variant. As shown in

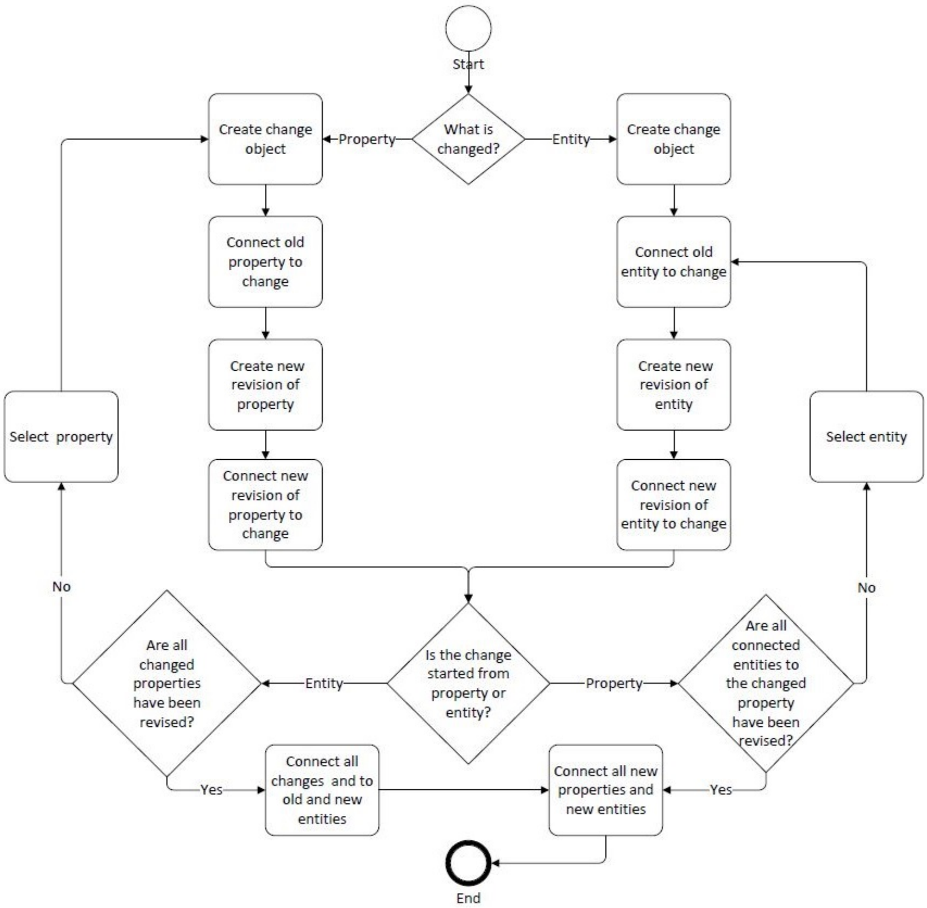
Figure 6, the “assembly amount” property is associated with both the “Assembling of the engine cover” operation and the “Engine cover” part.

Figure 6 The role of entities and properties with two examples of manufacturing data (color and assembly amount)



Having manufacturing data as instances of the “property” class, allows users to apply revisions to properties and make them traceable, and furthermore, through the associations of properties with entities, the relationship of manufacturing data and PLM structures will be specified. These relationship specifications help to identify affected entities (product, process and resource) if one manufacturing data has been changed. As illustrated in Figure 5, Part A of the main UML class diagram, which is about properties and changes, has been expanded to show more detail. Since the manufacturing of a product is a dynamic process, there are always changes in product, resources and process, and these changes in turn cause changes in the manufacturing data related to product, processes and resources. It is essential to have updated manufacturing data for different engineering tasks such as simulation and optimization, and management of these changes is needed. In addition to this, tracking of changes in manufacturing data provides the extra advantage of having information and knowledge about changes and their consequences in the manufacturing of a product. Whenever a change happens to a product, process or resource, there is a probability of changes in one or more of the related data. After updating the manufacturing data that is an instance of the “property” class, then information about this change of property has been saved in an instance of the “change” class. This information is about the changed value of the property and the revision of that property. After the creation of a new revision for property instance with the new value, this new property instance has to be connected to new revisions of entities that had been connected to the old revision of property before (entities such as product, process and/or resource). The information about the old revision and the new revision of property are stated in the related change instance so that the old and new revisions are connected to that change instance. Figure 7 shows a workflow diagram of how changes in entities and properties can be managed. In the presented workflow, according to the start of change, several steps need to be done. If the change starts with an entity, all changed properties related to that entity will be updated, and if the change starts from changing of a property, all related entities to that property will be updated and revised.

Figure 7 Workflow for managing changes and revisions



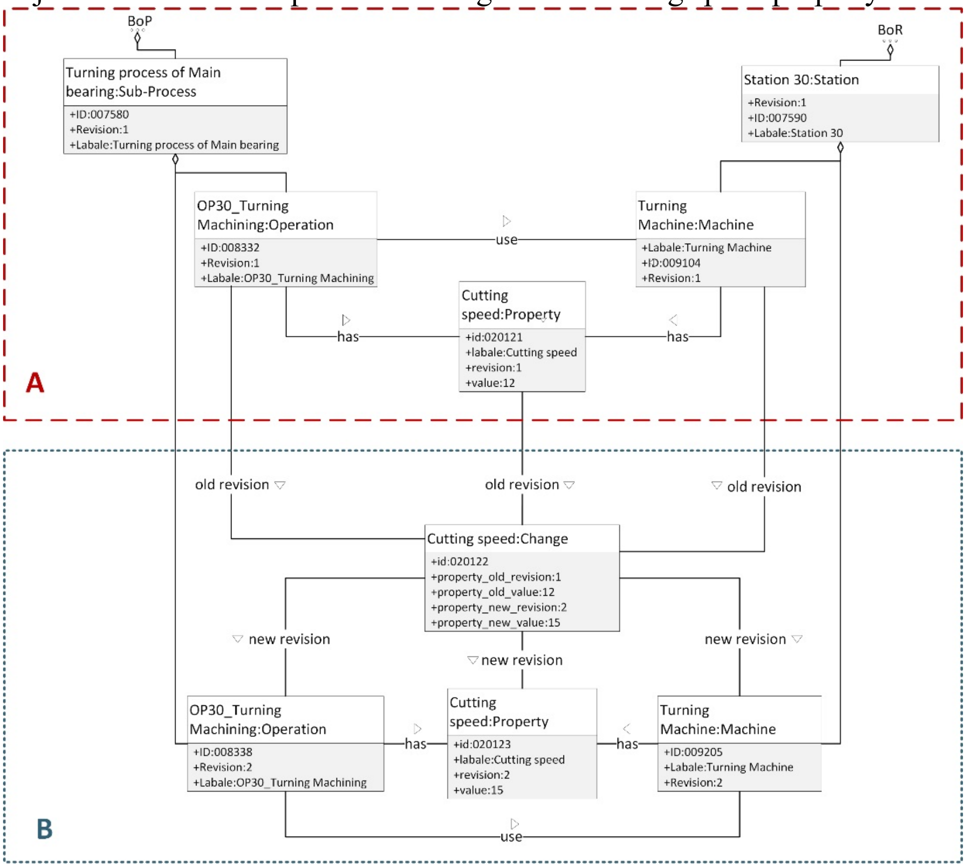
The advantage of using property and change classes is whenever an entity such as a part is changed, those properties of that entity that must be revised are identified. If any of them is a shared property with other entities, such as a process, then a user knows that those entities also need to be updated and revised.

In the next section, object diagrams from the information structure derived will be presented to clarify how changing properties can be structured through the information structure.

5 Explanation of the change process with an object diagram

In this research, the information model derived is used for managing data and information about automotive engine production. Figure 8 (A) shows a part of an object model for engine production in which some parts of BoP and BoR are shown. In this object diagram, cutting speed is a kind of manufacturing data that is related to both process and resource. This property is attached to both turning machining operation and turning machine as a resource. Figure 8 (B) shows the additional objects to the previous object model when there is a change in the turning process. In this scenario, cutting speed is increased from 12 millimeters per second to 15 millimeters per second. Because of that, a user has to revise cutting speed properties with the new value through creating a change instance. Afterward, a new revision of the turning machine has been created and connected to both change and a new revision of the cutting speed property. Since the cutting speed is a property of the Op30-Turning machining operation, this operation also has to be revised and associated with the change and new cutting speed instances.

Figure 8 (A) Part of an object diagram for car engine production, (B) Added objects and relationships after a change to the cutting speed property



If the new revision of the process affecting any other properties, then they have to be identified and revised.

6 Conclusions

Manufacturing data are created, used, and modified during the lifecycle of a product. This data can be used in different engineering activities, such as designing and improving production processes. Current product lifecycle management (PLM) systems provide the platforms for defining different classes and attributes for managing data and information based on different information models and standards, but there is a need for a more detailed and explicit information structure to better support the importance of properties and changes. This new information structure has been developed based on three main information structures in PLM systems: BoM, BoP, and BoR. It also has to be capable of preserving and managing changes in manufacturing data.

In this paper, after explaining some of the backgrounds about PLM, different data and information structures for managing manufacturing data have been explored and a need for an information structure, which has to be aligned with structures in PLM systems, had been specified. Later in this study, several documents that consist of manufacturing data and information had been identified and based on those documents, data collection had been undertaken in a limited scope. From 46 document types, 264 types of manufacturing data have been extracted and these data types had been classified based on their relation to product, process and resource. In the information structure derived, and according to this data classification, a separate class for manufacturing data had been defined, with the name of "property". The association of property instances with entity (product, process and resource) instances specifies the relationship of that data to the entities in BoM, BoR and/or BoP. In order to capture changes in entities and their related manufacturing data, a change class has been included in the information structure. As the final result of this research study, an information structure for managing manufacturing data and information has been derived that associates them to the PPR structure in PLM systems. With this information model, changes in manufacturing data that are caused by changes in products, processes and/or resources can be preserved and retrieved. Through tracing back the revisions historically and further exploration, the effects of previously-made decisions can be analyzed and the gained knowledge can be used for future decisions. By utilizing the suggested information model, manufacturing data and information are always updated, and those data and information can be used to build and maintain digital factories as part of Industry 4.0 and cloud manufacturing. The presented information model helps to capture the entity situation and its status from one change to another, and if there is a virtual model for that entity (digital twin), it can also be updated along with changes of the entity and be connected to the latest revision of entity. The previous status of the entity with its previous properties and virtual models can be saved and retrievable for future analysis and usage.

The main novelty of our approach is the reification of properties. This allows detaching the property value from the entity that is described by the property. Even without change objects, this reification fundamentally improves the data management in PLM systems. In particular, several engineering entities (such as a simulation model for a milling process and the NC program to control the milling) can share the very same property object, such as the cutting angle. Engineers rationalize their decisions on the basis of such properties. By regarding them as objects, they can carry attributes for comments and other metadata to provide engineers with a better understanding of the reasoning for their value.

Alongside property objects, change objects (change classes in the data model) have been integrated with entity and property objects. A workflow is devised for their systematic change management. It should be noted that our proposal is a straightforward extension to existing PLM systems. Such systems support a multitude of object types. We add two generic such object types for properties and changes.

For future work, this information structure can be expanded to manage virtual models, engineering activities, and manufacturing knowledge. This is another reason for saving all revisions of entities and properties with their connections to have entities and their corresponding virtual models in different stages of the lifecycle of the entities. There is also a possibility of automating the presented workflow and different connections by extending current PLM systems.

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