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Semantic enrichment approach for low-level CAD models managed in PLM context: Literature Review and Research Prospect

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Abstract:

The proposed approach in the paper is dedicated to enrichment of CAD models storage in PLM (Product Lifecycle Management) systems or archive databases. The paper considers low level CAD models (i.e. frozen geometry and without CAD model tree) based on standards such as STL, IGES and STEP AP203 first edition where the CAD model tree is absent. The paper also highlights the differences in semantic richness between these standards and their degrees of industrial implementation. STEP AP242 standard is considered as a high level representation for CAD files. The paper aims to review the literature that addresses the methods for semantic enrichment of CAD models by using ontologies. The future challenges and one possible research direction are then discussed. A first application called VAQUERO for CAD enrichment using an ontology based on STEP AP242 standard is proposed.

Keywords: Computer-Aided Design, Standardization, Product Lifecycle Management, Knowledge Management, Ontology

1 Introduction

Semantic enrichment is being conducted on components that do not have a sufficiently CAD model support. The low level most often means that only faceted geometry or a "frozen" solid are available [1]. The model is thus only viewable, measurement actions are complex or even impossible, and design intents, often represented by a CAD model tree are absent. This absence prevents any possibility of changing the geometry and creates the need for enrich the CAD representation with expert information called "semantic"[2], [3].The information supported by a CAD model is covered by two types of information: geometric

information (pixel/voxel, facet - triangle, exact surface, exact solid) and expert information (material, assembly – positioning and constraints, CAD model tree composed of sketches, features and parameters, 3D tolerances - Geometric Dimensioning and Tolerancing (GD&T), Product and manufacturing information (PMI), annotations such as text additions for design and manufacturing). Currently 3D model generated with well-known native CAD software that contains both geometry and expert information as above described is considered semantically rich. On the other hand, a CAD model containing only the geometric information may require a semantic enrichment process to recover the expert information.

The needs for semantic enrichment are then concerned in PLM (Product Lifecycle Management) systems because such IT applications are widely acclaimed for supporting product development [4]. PLM systems manage product data including CAD files, engineering drawings, product specifications, CNC programs, engineering modifications, product configurations and much more [5], [6]. Thus, the major issue of PLM is to ensure full interoperability, defined by [7] as “the ability for two systems to understand one another and to use functionality of one another”. Thus, the rich semantic CAD models used in PLM systems [8] are known to provide a cost-effective and consistent solution for dealing with the large-scale interoperability issues that are a real industrial challenge (AFNET [9] and PROSTEP [10]).

However, CAD model editing in primary view (i.e opens in CAD software) encounters many difficulties. Indeed, designers or users who need to edit CAD models could be confronted to the fact of “lack of information” to achieve their engineering tasks. It means that it is possible that just a “frozen” CAD model without any support documents such as drawings are available. This fact is due to these following reasons:

- For long product’s lifecycle where a CAD model with geometric information is only available. Mainly due to the changing of CAD software by companies.
- For technical reasons linked to CAD engineers who have not designed the original CAD model allowing to bring both geometry and expert information.
- For change old CAD models stored in basics standards (STL, IGES)

- For confidential reasons between the Original Equipment Manufacturer and the supplier where a “frozen” CAD model is only available.
- Inconsistency with translation between the CAD model available in standard shape and the CAD software used. That mainly causes the loss of the CAD model tree [11].

Thus, native CAD models that only edit in a frozen manner such as tessellated and solid geometry need to be enriched and CAD models in the followings standards formats STL, IGES, STEP AP203 (i.e edited in frozen representation) have to be necessary enriched.

Nowadays, standards include more than just geometry and dimensioning information in 3D models. They now encompass rich data such as material information, styling, annotations, manufacturing process data and cost data, as well as other features across the design files, including product structure and the formal representation of the semantics associated with the data. Such rich design and manufacturing information contained in the 3D model remains valuable across the entire life cycle of a product. However, this complexity can result in a closed, legacy or native format that is not compliant with other CAD systems, making it difficult to used file formats such as STL, IGES or preliminary versions of STEP AP203 [12]. The low-level CAD model within these formats do not take into account GD&T (Geometric Dimensioning and Tolerancing) and PMI (Product and Manufacturing Information) and then are not usable for the engineering tasks (FEM simulation, CAM simulation etc.)

When such a CAD model needs to be enriched, there are two possibilities: request engineers to make a new native model (assuming that this issue will occur again in the future because of CAD software evolution), or create a systematic methodology that helps designers to semantically enrich CAD models with expert information.

In the paper, the defended research statement is to propose a systematic methodology allowing expert information enrichment for low-level CAD models. Thus, a semantic enrichment based on annotations is defended in the contribution. Solutions based on “feature” or CAD model tree reconstruction are assumed not necessary because requiring a lot of time. Annotations based on STEP AP242 standard are sufficient to have more usable low level CAD models.

The paper provides a literature review related to semantic enrichment of 3D models using ontologies based on standards. The scope is designed to answer questions related to enrich 3D models; to assess the limits of existing standards for supporting semantic representation and to address the role ontologies play in improving the semantic enrichment.

To achieve these objectives, the paper is organized as follows. Section 2 describes the needs in the current use of CAD models for PLM system users. The results of the experts' interviews are then proposed and summarise the expectations of the CAD models usages. A review of the content of CAD models is proposed. The goal is to define the low-level and the high-level content. For this aim, the research review is conducted to study the content of CAD standards such as STL, IGES, 3DPDF and STEP. Native formats are not part of the goal of the review because they are closed and not fully interpretable according to legacy strategy of software vendors. Standard formats are interpretable, opened and often referenced to ISO or other organisations for standardisation. STEP AP242 is considered as a semantic high-level reference. Section 3 provides an in-depth review of the literature on the use of ontologies in PLM for semantic enrichment of CAD models. Section 4 discusses the limitations of existing approaches using ontologies and suggests a research prospect that promotes the development of an open application using an ontology based on the STEP AP242 standard.

2 Usages of CAD models in PLM system

2.1 Open questions on the current use of CAD models

In PLM systems, extracted CAD models in primary view (i.e open in CAD software) are heterogeneous in their formats: legacy or native formats and neutral formats. In order to determine the importance of CAD models usages in PLM systems, it is essential to collect feedback from users of CAD models in a PLM context. Thus, four CAD/PLM experts were contacted in order to collect their expectations:

- An expert engineer of the design department of an automotive manufacturer (PSA group, also known as Stellantis, <https://www.stellantis.com/fr>). An expert engineer of CAD/PLM department of an aeronautical company (Safran Aircraft Engines, <https://www.safran-aircraft-engines.com/>)
- The head of a French digital standardisation association (<https://www.galia.com/>).
- An senior expert specialised in CAD/PLM integration of the Inetum company (<https://gfi.world/fr-fr/>)

The exchanges were formulated through direct interviews by conference call and e-mail exchanges. Questions were formulated to determine what formats they use in primary review, and what are their expectations regarding the usage of CAD models. Their answers indicated that there are mainly five major expectations:

- **Query and retrieval of CAD models:** access to CAD models is essential in order to use it or to perform engineering activities. Accessing to CAD models is made through PLM systems (primary view) or CAD database.
- **Change, revision and annotation of CAD models:** To save time when making changes or extracting information contained on an existing design regardless of the used CAD formats, CAD models must be properly annotated by containing any expert information;
- **Visualization in secondary view of CAD models:** The user should be able to view the CAD model and the CAD model tree related to its design;
- **Technical interoperability (sharing) of the information contained in the CAD models:** Any semantic information in primary view related to the design such as a product's features, constraints, and parametric information must be shareable;
- **Archival CAD models** by using CAD catalogues or CAD archives by indexing rules. CAD models have to be easily retrieved from basic queries. The retrieved CAD model must be opened in primary view and contains both geometry and expert information.

Semantically rich CAD models are required to meet the expectations mentioned above. It means that CAD model has to contain geometry information (exact 3D geometry) and expert information (i.e semantic).

The expectation confirms that solutions have to be brought to enrich basic CAD models in frozen shapes. The statement defended here is that enrichment solutions based on annotations are enough to improve the technical interoperability [13] of low-level CAD models. The annotations have to be supported by a reference (i.e a rich standard). It could be an advanced CAD formats or standards. The next section addresses a list of existing standards and determines which the best reference is.

2.2 Standard CAD formats, the information contained

Given the interest that the contribution has shown in focusing on the geometry information and expert information, it is then a question of looking at the contents of these formats to see what characterises them in terms of semantic information.

2.2.1 STL

STereo lithography (STL) file format can be saved in two variants, binary and ASCII (readable by human). STL file is a tessellated model derived from an approximation of a CAD model [14]. It is made of a surface mesh that contains many sets of triangular facets. The file does not contain any topological data, and has no missing facets or gaps, degenerate facets (where all its edges are collinear), overlapping facets, or manifold topology conditions.

2.2.2 IGES

The Initial Graphics Exchange Specification (IGES) format is a very popular neutral format for digitizing the exchange of CAD information. The IGES format is designed to store both 2D and 3D data [15]. Although the IGES has been very successful in some applications, it was designed mainly to communicate design data, but many other types of data are

required to support manufacturing, marketing, technical areas, cost analysis, and configuration management.

2.2.3 3D PDF

3D PDF is the name of the PDF file format, which also provides native support for 3D data [16]. Published as the international standard ISO 24517-1 (PDF/E), it uses U3D [17] and PRC (<http://3dpdfconsortium.org/>) to store CAD geometry representations. However, this file format is not yet implemented in all CAD systems. In December 2017, the STEP and PDF ISO working groups formed a joint ad-hoc committee that proposed modifying the PDF standard to add STEP AP242 as a 3D stream.

2.2.4 STEP

Standards such as ISO 10303, known as the Standard for Exchange of Product model data (STEP), deal with product structure, geometry and parts-related information [18]. In STEP's modular approach, information models form modules and integrated resources, from which specific content standards (application protocols or APs) such as AP203 (Configuration controlled 3D design of mechanical parts and assemblies) and AP214 (Core data for automotive mechanical design processes) are developed. They are still evolving to meet the needs of modern CAD with AP242 ed2, CAE with AP209 ed2, CAM with AP238 and PDM with AP239 ed3. These pairings represent the implementable data specification of STEP. An extension of STEP, called STEP AP242: "Managed Model-based 3D Engineering", is motivated by the necessity for the long term archiving of 3D data. (<http://www.ap242.org/>) This extension is the result of an initiative to favour common effort, as an alternative to previous work on AP203 and AP214, by extending them to new topics (such as 3D printing) and other information supported by CAD models, including GD&T [19] and PMI [20], resulting in a convergent application protocol. STEP AP242 contains both presentation and representation of GD&T information as referenced in [20]. The presentation of tolerances is standardized by ASME Y14.41-2012 [21] and ISO 16792:2021 [22] and can for example be visualized by polylines or tessellated geometries. The main technical

requirements for STEP AP242, apart from information exchange and archiving, are to provide a consistent data model for XML exchange [23] and PDM systems [24], and to provide geometry representation from wired representation to parametric representation (table 1).

2.3 High-level CAD Standard

Table 1 shows the detailed information contained within the standards and was inspired by the work developed by GALIA association (<http://www.galia.com/en/dyn/AboutUs.as>).

Information contained	Exhaustive information contained	STL	IGES	3D PDF	STEP AP203	STEP AP214	STEP AP242
Geometric information	Tessellated representation	●		●			●
	Wired representation		●	●	●	●	●
	Surface representation		●	●	●	●	●
	Exact solid representation			●			●
	Parametric 3D representation with construction history (CAD model tree)			●			●
Expert information	Drawings		●	●	●	●	●
	Semantic presentation and representation of 3D annotations and tolerances					●	●
	Form Features for design and manufacturing				●	●	●
	Composites						●
	Kinematics			●		●	●
	Parts assemblies			●	●	●	●
	Component definition (metadata, maturity, etc.)			●		●	●
	Product line specifications (diversity library)				●	●	●
	BOM description					●	●
	Activities and projects					●	●
Classifications					●	●	

Document management				●	●	●
Overview of the changes				●	●	●
Characteristic properties			●	●	●	●
Functional and organic cuttings					●	●
Systems and area cut-outs						●
Requirements						●
Manufacturing process				●	●	●

Table 1: Information contained by standard CAD standard; table inspired of GALIA

Not all the above-mentioned formats are semantically rich, except for STEP AP242. It has been promoted to sustain manufacturing industry with important and standardized information for making smart the manufacturing systems [25].

2.4 Research statement, STEP AP242, the high-level semantic for CAD models

STEP is currently considered the safest format for many activities such as for long-term archiving in manufacturing and visualisation of product data. The LOTAR International project (<http://long-term-archiving-and-retrieval.org/>), recommends the archiving and retrieval of digital and technical product information, including CAD and PDM data, in a neutral standard form such as STEP AP242. Thus, STEP AP242 is considered here as the high-level semantic for CAD models.

In theory, it seems that from 2009 - 2012, when STEP AP242 and LOTAR were created, the usages and practises based on AP242 are too recent to claim that CAD enrichment needs have completely disappeared. For example, aeronautical, automotive and nautical products have a longer product life than 15 years. The standard/neutral CAD models created before 2010s are considered low-level and are potentially candidate to be enriched. This means that many low-level CAD models need to be enriched.

Then, enrichment solutions based on annotations and referred to STEP AP242 will allow to recover high semantic representation of low levels CAD models. For that, an

ontology-based approach could be used. The next section proposes a review of existing solutions.

3 Literature Review of Semantic Enrichment of CAD models by usages of Ontology-based approaches

3.1 Literature review methodology

To obtain a clear understanding of the usage of **ontologies**, a literature review was conducted according to the following steps:

- A list of keywords was prepared according to the context of this study, i.e., considering the data storage context into a PLM or PDM system. This study investigates the semantic contained into 3D CAD models by using ontologies. So, the selected keywords are **PLM/PDM**, as well as **CAD/CAM**, **3D file format**, **interoperability** related to 3D models, and **ontology**.
- The keywords were used to query into some well-known electronic databases, including Elsevier (Scopus and ScienceDirect), Inderscience, IEEEExplore, Springer (SpringerLink) and Taylor & Francis.
- The papers whose terms are related to one of the keywords and ontology were reviewed and selected

3.2 Paper analysis and classification

A preliminary effort on evaluating papers on low-level CAD models enrichment was made by:

- Grouping all the articles found in Elsevier, Inderscience, IEEEExplore, Springer and Taylor & Francis, and then applying an impurities removal filter for the duplicates found in more than one database, as well as in surveys, reviews, or non-scientific

papers such as magazine articles. The number of papers considered relevant for these reviews was further reduced in this phase; and then

- Screening the remaining papers considering the title, the abstract and finally the full text.

After the application of these filters, the most relevant papers were classified in descending order of published year, according to the users' expectations as listed in table 2, as well as with the reasons and motivations for their selection.

ref	Year	Authors	Users' expectations				Archival	Reasons and motivation for selecting the paper
			Query and retrieval	Change, revision and annotation	Visualisation in secondary view	Technical interoperability (sharing) in primary review		
[26]	2021	Huet et al.	●	●		●		Proposition of context aware cognitive design assistant to simplify rules prescribed by design manuals and improve design
[27]	2021	Favi et al.	●			●		Formalisation of tacit design into explicit design knowledge for metal casting components with 3D modelling and design
[28]	2021	Mohammed et al.	●					Linking assembly constraints and PMI from STEP AP242 to motion constraints on a robot during its assembly operation
[29]	2020	Pham et al.	●					A visual query and retrieval system called VAQUERO (VisuAlization and QUERy based Ontology) to access medical imagery data in PLM through an ontology
[30]	2020	Kwon et al.	●			●	●	They explore and prove the concept of merging as-designed and as-inspected models to take advantage of the benefits of digital wire and smart manufacturing..
[31]	2020	Pane et al.			●	●		A methodology for automatically selecting complex robot skills and its parameters for executing an assembly task
[32]	2020	Plumed et al.		●		●		A voice based system to manage extended annotations in CAD and facilitates the capture of design knowledge
[33]	2020	Ferruccio et al.		●		●		An ontological model built from a classification of different CAD features to represent the knowledge coming from CAD components

[34]	2019	Mohd et al.			●	●		Development of a consensus ontology for supporting additive Manufacturing data (data file, material, CAD model, etc.)
[35]	2019	Hallman et al.		●	●			Transposition of GD&T from STEP to STL CAD model
[36]	2019	Hao et al.	●	●				An automatic annotation based on probability-based method of key functional semantics for assembly
[37]	2018	Gandon F		●		●		Literature review of goals and contributions of ontologies over the first twenty years of its existence
[38]	2018	Sanfilippo EM				●		Integration of notions such as product, material, and process for a feature-based product ontology
[39]	2018	Urick B				●		Presentation a Coordination of geometrical and topological ontology efforts in CAD, CAM, (ISO TC184 SC4 WG3, ISO TC184 SC4 WG12 T1, Web3D consortium)
[40]	2017	Danjou et al.				●		A Closed-Loop Manufacturing approach based on STEP-NC (ISO 14649) for managing knowledge
[41]	2017	Zhang et al.	●	●	●			Query and retrieve semantic information of faces and machining features from an ontology-based conceptual model
[42]	2017	Sikos	●					A semantic query system using the industrial standard X3D standard X3D (ISO/IEC 19775-19777) transformed into ontology
[43]	2017	Qin Y et al.		●		●		Answers to question regarding integration of CAD model into Ontology Web Language
[44]	2016	Tchofa et al.				●		Integration of a Dynamic Manufacturing Network and a federative interoperability framework for PLM by Airbus Groups Innovations.
[45]	2016	Qin F et al.	●	●	●	●		Use of a semantic descriptor based on ontology theory a semantic web for accessing 3D CAD models
[46]	2016	Mazzola et al.	●	●		●		The CREMA Data Model ontology allows query manufacturing data and add annotation based on a data stream schema
[47]	2016	Han et al.	●		●	●		Building of a semantic matching model based on a Weighted Bipartite Graph (WBG) for

							retrieving CAD assembly models.
[48]	2015	Sriti et al.		•		•	Information exchange between PLM systems and other enterprise information systems through translation of data models of the sources into ontologies.
[49]	2015	Cuong et al.	•		•	•	The interface uses graphs for query and allows to visualise and integrate meta data (data of bio-medical imaging using PLM systems)
[50]	2015	Shin et al.		•		•	Transformation of product usage data into information that can support design modification by finding and fixing defective design parameters.
[51]	2015	Imran et al.	•			•	Proposal and evaluation of a knowledge-sharing framework in the form of an formal assembly reference ontology
[52]	2015	Bruno et al.				•	Proposal of reference ontology that manages all the PLM domain information
[53]	2015	Gruhier et al.	•			•	Development of a three dimensions spatiotemporal ontology in Assembly-Oriented Design based on JANUS platform
[54]	2015	Kadiri et al.				•	Literature review for defining the role, challenges and needs of ontologies in the context of PLM and CAD
[55]	2015	Baysal et al.		•		•	Adding Core Product Model concepts for developing an information model for the representation of function, behaviour and form of CAD
[56]	2014	Ulliana et al.	•		•		A framework for retrieving and accessing semantic information based on ontology related to 3D model.
[57]	2014	Assouroko et al.	•		•	•	Semantic web and visualisation graph techniques to ensure semantic interoperability by means of semi-structured data (CAD, meta data, files, etc.)
[58]	2014	Samer et al.		•		•	A reasoning approach to CAD feature mapping between Catia V5 and Solidworks.
[59]	2014	Lu et al.	•				Querying engineering drawings by transforming classification trees from CAD model into a shipbuilding domain ontology.
[60]	2014	Danjou et al.				•	OntoSTEP-NC to trade between PDM (CAD-CAM data) and ERP (CNC data) platforms

[61]	2014	Allanic et al.,	●					Accessing BIM information by using an ontological model
[62]	2014	Borsato M		●		●		Development of an ontology for products and processes with an emphasis on sustainability during product's lifecycle
[63]	2014	Ramos et al.		●		●		Integration of Machine of Process ontology reuse with ontology validation and learning in the manufacturing domain
[64]	2014	Dreus et al.				●		Design and implementation of a domain language for Handling Modular Ontologies, based on an Model Driven Architecture
[65]	2014	Camba et al.		●	●	●		An extended textual annotation for CAD models. The annotation manager is a Solidwork plug in
[66]	2013	Usman et al.				●		Integration of manufacturing knowledge using model driven architecture into different CAD/PLM systems
[67]	2013	Fortineau et al	●	●		●		Module or layered solutions of the inference ontologies applied in PLM allow to query data and to use them by annotating them
[68]	2013	Bermeo et al.		●	●		●	Translation of IGES standard into an ontological model for capturing knowledge coming from CAD models
[69]	2012	Panetto et al.			●	●		A product ontology (Onto-PDM) based on ISO and IEC, interoperable with PLM applications
[70]	2012	Liao et al.		●		●		A semantic annotation approach focused on the interoperability problem, all along the product lifecycle
[71]	2012	Abdul et al.				●		A neutral format ontology that integrates CAD features from CAD tools
[72]	2012	Barbau et al.		●	●	●		Translation of STEP standard definitions into an ontological model called OntoSTEP allowing CAD model manipulation
[73]	2012	Lahoud et al.	●			●		Presentation of semantic and knowledge platform (SemKnow) which covers process of knowledge management
[74]	2011	Lim et al.		●		●		The use of design and manufacturing repository for annotating multi-faceted product family ontology (MFPFO)
[75]	2011	Eck et Schaefer	●			●		Transformation of storage location

								containing CAD/CAE/PLM information into semantic model that can contain the same info
[76]	2010	Mckenzie et al.		•			•	An XML file allows annotation and communication between different software packages and translation of a 3D model from CAD software to an ontology
[77]	2010	Matsokis et al.		•			•	Demonstration of the benefits of the ontology model by translating the Semantic Object Model and the product data into an ontology
[78]	2010	Wang et al.					•	Integration of design decisions and quality knowledge by building an ontology
[79]	2010	Rachuri et al.		•			•	Interrelations between logical formalism languages and product information for developing product CAD models.
[80]	2010	Zhan et al.		•				Ontology-based adaptive design evaluation to share knowledge related to product data in CAD/CAE
[81]	2009	Catalano et al.	•	•			•	A product design ontology (PDO) to formalize knowledge from CAD and design process and share these knowledge
[82]	2009	Khilwani et al.					•	Literature review on semantic web applications and ontology in the manufacturing domain
[83]	2008	Kwak et al.					•	Integration of data on car parts into a single ontology model for PLM object
[84]	2008	Hanayneg et al.					•	Resource Description Framework (RDF) documents with the standard XML syntax allow information to be exchange
[85]	2007	Andersen et Vasilakis		•			•	Introduction to ontological modelling of 3D models, and ontological presentation of STEP part 42.
[86]	2007	Dartigues et al.					•	Integration of CAD and CAPP into an ontology for enable interoperability
[87]	2007	Zhanjun et Ramani	•			•		Framework of an ontology based query processing for accessing design information in documents
[88]	2007	Lin et Harding	•	•				Cross-company and cross-workplace issues related to the requirements of ontology-based semantic information
[89]	2006	Posada et al.					•	Presentation of ontology based compression

							system using STEP AP227 and CIS/2 for interoperability
[90]	2006	Peachavanish et al.	●			●	An ontology framework for enabling interoperability between CAD and Geospatial Information Systems (GIS)
[91]	2006	Kim et al.			●	●	An assembly design ontology to capture semantic information related assembly Cad models
[92]	2005	Tae-Sul Seo	●			●	Proposition of a STEP AP224 ontology based method to exchange information between commercial CAD software
[93]	2005	Sudarsan et al.	●			●	A framework for accessing and reusing product information embedded in PLM systems
[94]	2005	Aziz et al.				●	Modelling ontology for enabling knowledge sharing for SME (small to medium enterprise)
[95]	2004	Jardim et al.				●	Improving interoperability between PLM systems by adopting a common taxonomy
[96]	2004	Marenco et al.	●			●	A query integrator system for enabling the communication of multi database network system
[97]	2004	Zhang et al.			●	●	Presentation of technologies for sharing and visualise internet-based product information
[98]	2004	Yoshioka et al.	●		●	●	Framework for knowledge Intensive Engineering
[99]	2004	Kitamura et al.	●			●	Ontological schema for capturing functional knowledge in a production company
[100]	2003	Siang et al.	●	●		●	Proposition of ontology generic design activities based on literature
[101]	2003	Daisy et al.	●			●	Presentation of MDO environment using multiple technologies for project manager
[102]	2003	Zhao et al.				●	Different roles of ontology in automated process safety
[103]	2002	Hameed et al.	●				Acquisition of knowledge and detection of mismatches between expert's ontologies
[104]	2002	Wang et al.		●		●	Needs and requirements for conceptual engineering design
[105]	2001	Macchi et garetti.				●	Approach for integrating business level into modeling method in MSE and SE area

Table 2. Published papers selected that cover certain user expectations

3.3 Analysis of selected papers in relation to the users' expectations

Ontology has been developed in CAD and PLM and finds its application in different sectors. It has been used to meet users' expectations such as revealed in the table 2. Thus, for query and retrieval, most of the selected papers apply some rules in order to organise and classify the parts (and their related documents). [26] apply design rules in a context aware cognitive design in order to have a good result when searching for 3D part. The searching system uses a keyword for retrieving a component. Several Authors, such as [41], [45], [53] use a semantic descriptor for querying and retrieving a part inside a system. The descriptor could be a component name or something related to the component. It can be noticed that the descriptor is based on the ontology. So, the taxonomy of the component is accepted before the use of descriptor for retrieving the component.

Concerning the annotation, [65] bring extended annotations to CAD model. The annotation is free on CAD model, so it is difficult to view annotations and it is defined by the user. If it could be defined by a standard, it would allow to easily reuse the CAD model. [32] proposed a voice based system to manage extended annotations in CAD and facilitate design knowledge capture. An annotation tab in the CAD system interface allows voice annotation to be attached to geometry. Although the speech recognition module is responsible for recording the user's voice, automatically transcribing the signal and creating a text annotation from the audio signal, we may wonder about its effectiveness on the existence of the multitude of languages. [35] combine STEP and STL information to automate the mapping of GD&T (Geometric Dimensioning and Tolerancing) information assigned on the CAD model from STEP files on discrete geometries (STL). The method allows CAD model of STL to carry on visual annotations. Those visual annotation could allow to satisfy secondary visualisation of users' expectations. Annotations of [32], [35] are not contained in an ontology. The use of ontology could allow to have a good taxonomy. That is why [33], [34],

[46], [72] used part or component classification based on ontology in order to annotate the components. The annotations are carried out by the ontology. So, it is not the 3D model that carries out the annotations like other works but it is the ontology.

The technical interoperability expectation is mainly covered by the literature. Most of the works proposed to map features of different CAD systems in order to allow an interoperability between CAD systems. For examples [45], [58] and [71] have created an ontological file format for enabling interoperability and information sharing. Approaches dedicated to study and develop semantic data models with their concepts, relations and their respective properties in order to support system integration were introduced in [83]. Ontologies have also been developed for closed-loop PLM and for specific phases such as manufacturing [40], [50]. A product design ontology that formalizes the functionality of shape processing methods in the design workflow was introduced in [81]. Ontologies can help to enrich the 3D model with different types of expert information. The OntoSTEP proposed by [72] resulting from translation of the STEP schemas definitions into an ontological model cannot be used to instantiate and exchange those expert information whose schemas are not included in STEP AP203. In order to represent the expert information whose schemas are not provided in AP203, OntoSTEP ontology was combined with the CPM/OAM ontology [54] to achieve a big common CAD model data ontology. The authors intended to use OntoSTEP to share both geometric and non-geometric data among different CAD systems. The claims of introducing ontologies into CAD and PLM models to enrich CAD models and enable long-term interoperability and archiving have been supported by [43] [54] [80]. The reason for this is that languages such as the express language for STEP have difficulties in explicitly interpreting, representing and exchanging the semantics assigned to data in CAD models. Some researchers, such as [19], [72] pointed out that such exchange was difficult to be truly implemented only by STEP neutral file-based exchange method because it requires an explicit interpretation, representation, and exchange of the semantics assigned to those data, and unfortunately, the EXPRESS language for STEP model is not based on formal semantics and therefore cannot satisfy this requirement [33]. So, [30] have used the

ontological model of STEP AP242 (<http://www.ap242.org/>) that goal is to define all the functional information for a CAD model, to merged the Quality Information Framework (QIF) standard in order to leverage good inspection and design decision making. The decision making is based on the ontological model of the semantically rich STEP AP242 format. Thus, the CAD model using this semantic model will evolve and can be used for future projects.

3.4 Conclusion of the literature review

The literature review shows that works using ontologies do not take into account the different expectations of CAD/PLM users. The technical interoperability in primary view expectation is widely covered by the literature. A large majority (90%) of papers considers ontologies to solve technical interoperability issues between CAD systems. Nevertheless, only 10% of papers considers the visualisation in secondary view expectation. It is possibly a lack of consideration of the literature as ontologies can support services related to the semantic web and can facilitate rich visualisation of CAD models in a PLM and therefore in web environment. It should also be noted that few papers (less than 1%) deal specifically with the solving problem of long-term archiving by the ontologies. This, also, is missing in the literature as the problem of long-term archiving could be reduced by the semantic web-technology offered by the ontologies. This could allow to store CAD models in a lightweight format limiting the importance of storage (hard disk), while integrating CAD models with rich semantics (expert information). For query and retrieval expectation and for change, revision and annotation expectation, 40% of papers considers ontologies as a good solution. The usages of ontologies, according to the web semantic technologies, help to structure queries and facilitate the CAD models retrieval. The use of ontologies allows to classify the annotations made by the user according to the syntax of the ontology. As a result, the annotations are classified, which makes it possible to find them later. The strong assumption is that the “institutional memory” is ensured by the CAD and PLM users because their annotations are framed by the ontological syntax.

The main negative point we can draw from this literature analysis is the non-availability of the different ontological models.

For us, ontology is promising for targeting user expectations and specifically for enriching CAD with annotations. The main condition is that ontologies and associated implementation applications should be provided as open source in order to be tested and reused.

Thus, we assume that the usage of an ontology (for example based on STEP AP242) brings a strong classification and taxonomy. Then, the annotations made by user will be attached to the classes of the taxonomy from the STEP AP242 ontology. This allows to ensure a certain uniformity of the annotations and then their usability by the other users.

Therefore we propose to develop OntoSTEPAP242 (the ontology of STEP AP242) which will be used to semantically enrich low level CAD models and a system named “VAQUERO For Semantic CAD Enrichment”, for a semantic enrichment implementation approach

4 Research prospect: an annotation solution using ontologies based on the STEP AP242 standard

4.1 Semantic enrichment using Ontologies

Companies have always used different CAD standards for exchanging and archiving CAD models. All standards must deal with issues such as data conversion, the loss of semantics contained, and the impossibility to annotate or visualize in primary view the CAD model, etc. These issues can be illustrated with the so-called low-level formats, such as STL, IGES and STEP AP203 (i.e without a CAD model tree), which do not show the CAD model tree or the constraints and parametric modelling [107]. Therefore, CAD models are generally considered as central representations to support semantic information sharing all along the lifecycle, but which clearly require dedicated mechanisms.

The use of ontologies, which appear to be a reliable solution to the issues for the representation of information contained in the CAD models, could be a way to move towards a deeper collaboration between users, based on an effective interoperability of systems. Ontologies allow the semantic representation of different features integrated in 3D models. Therefore, they provide suitable keys to access the content of the CAD models. The user also has the possibility to add expert information enabling a significant enrichment of the modelled CAD model. For instance, the improvement of an existing ontology such as OntoSTEP by adding information related to GD&T [19] , PMI [108] , and the manufacturing specifications [40] is an relevant research prospect. The project H2020 CSA OntoCommons also considered the research prospect. The project addresses the standardisation of data documentation across all domains related to materials and manufacturing (<https://ontocommons.eu/>). Therefore, prior this requires creation of a standardised ontology which should be considered within the framework of the Industrial Ontologies Foundry (IOF - <https://www.industrialontologies.org/>) and thus contribute to the co-creation of open reference ontologies that meet the needs of manufacturing and engineering and advance data interoperability, based on a standard such as STEP AP242 (OntoSTEPAP242). The next section shows a first demonstrator of CAD annotations using OntoSTEPAP242 proposal.

4.2 VAQUERO for Semantic CAD enrichment, using of OntoSTEPAP242, textual annotations of low-level CAD models

VAQUERO (Visual Ontology bAsed QUERy) for CAD enrichment system was proposed as a first edition as a demonstrator to proof the usage of OntoSTEPAP242 for CAD semantic annotations. The system would allow the semantic enrichment of low-level 3D models from semantically rich STEP AP242 standard. (https://gitlab.utc.fr/snzetcho/semantic_enrichment.git) This system should enable the evolution of these 3D models as valuable approach to improve data communication and

information exchange. As it can be seen on figure 3, it should be proposed an open access application that allows interoperability between different systems in order to favour the enrichment of 3D models.

The use of ontology in VAQUERO for CAD enrichment system allows to ensure a certain taxonomic uniformity of the added semantic information because it is modelled based on STEP AP242 which covers the whole product life cycle.

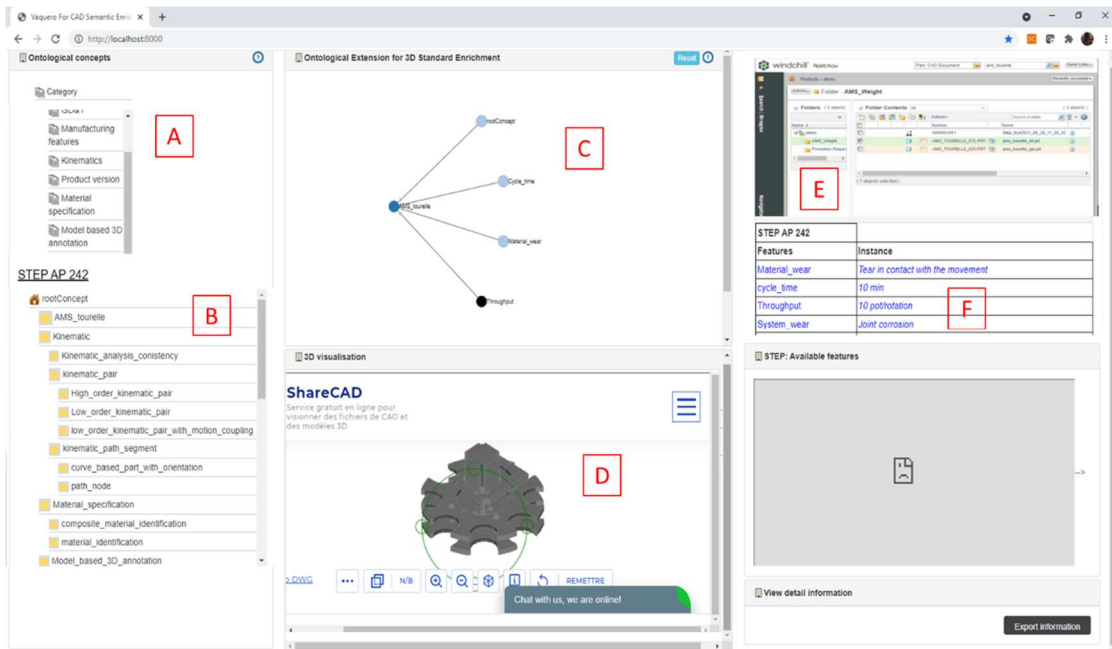


Figure 3, VAQUERO for CAD enrichment; a first demonstrator of CAD textual annotations based on OntoSTEPAP242

annotation form – OntoSTEP AP242

Motor A

Select the feature: Face_shape_element C

Attribut of that selected feature:

Plastic D

Specify category:

Material specification B

Add another feature and attribut Close

Figure 4, annotation form of VAQUERO for CAD enrichment

Vaquero for CAD enrichment includes applications such as :

- A PDM system such as Windchill PDMLink for allowing the retrieval of 3D models that will be used for the primary view (figure 3.E).
- The 3D model visualization in primary view must be through a 3D viewer such “ShareCAD” embedded into VAQUERO. That 3D viewer could open all the low-level CAD models (figure 3.D).
- An ontology based on STEP AP242 standard (OntoSTEPAP242) is proposed and available at: https://gitlab.utc.fr/snzetcho/semantic_enrichment.git. User navigates in the ontology from tree-structures and graph from the dedicated panels. Quick selections called “Category” are proposed to navigate easily in the ontology (ontological Category panel, figure 3.A). A graph representation of the ontology is proposed to clearly identified relations between concepts (panel in the middle, figure 3.C). A full tree-structure of the ontology is proposed to select a detailed ontology concept (STEP AP242 panel, figure 3.B). CAD and PLM users can use the independently panels. There are dynamically linked.

- A panel for allowing annotation of the low-level CAD models. Users select the CAD model and click on the button to open the annotation form (figure 4). The user will use an annotation form to fill in all the associated ontological STEP AP242 concept in order to add textual annotations related to the 3D model.
- The Annotations associated to the CAD model is available in the dedicated panel (figure 3.F).

The annotation form (figure 4) is associated to the frozen CAD model (figure 4.A) and is linked to the “Category” or “ontological concept” selected by the CAD/PLM user (figure 4.B). For STEP 203 frozen CAD model, faces or features could be selected in order to attach the annotations (figure 4.C). Then the annotation is in textual shape (figure 4.D). The case study shown in figures 3 and 4 is the part of a weight system control of cosmetic containers. The annotation is here attached to the frozen STEP AP203 of the electric motor (figure 3.D and figure 4.A).

In the cases IGES CAD model, the annotations are attached on the global CAD models or a face of the frozen CAD model. In the case of STL format, the annotations are attached to the global CAD model only because VAQUERO does not integrate segmentation or shape recognition algorithms.

The original low-level CAD model is conserved but now linked to an XML file containing STEP AP242 textual annotations enrichment. The exported XML file is integrated in the PLM solution closed to the original frozen CAD model location (figure 3.E).

5 Conclusion

This paper proposes a literature review allowing to highlight the need to develop Ontologies for low-level CAD model enrichment (i.e CAD model available in frozen geometry). STEP AP242 is considered as a high-reference standard. It means containing both geometry and expert information for rich CAD models. The research statement defended in the contribution is to use an ontology based STEP AP242 called

OntoSTEPAP242. The usage of this kind of ontology will allow to standardize textual annotations enrichment of low-level CAD model. Indeed, the technical interoperability of these CAD models could be improved. A first demonstrator called VAQUERO for CAD enrichment has been developed and available at https://gitlab.utc.fr/snzetcho/semantic_enrichment.git.

The contribution has been fully dedicated to CAD models opening in primary view. A future work will be to consider CAD models used in secondary view (such as PDM viewer). In fact, JT, which is now standardized and used for industrial practises, could also be considered as a rich viewer CAD format. It was initially developed by Siemens PLM Software and standardized as ISO14306 [10], [109], [110]. But it should be mentioned that technical solutions has to be found for enrichment of low level CAD viewer.

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References

- [1] F. Buonamici, M. Carfagni, R. Furferi, L. Governi, A. Lapini, and Y. Volpe, "Reverse engineering of mechanical parts: A template-based approach," *Journal of Computational Design and Engineering*, vol. 5, no. 2, pp. 145–159, 2018, doi: 10.1016/j.jcde.2017.11.009.
- [2] M. I. Ouamer-Ali, F. Laroche, A. Bernard, and S. Remy, "Toward a methodological knowledge based approach for partial automation of reverse engineering," *Procedia CIRP*, vol. 21, pp. 270–275, 2014, doi: 10.1016/j.procir.2014.03.190.
- [3] T. Varady, M. A. Facello, and Z. Terék, "Automatic extraction of surface structures in digital shape reconstruction," *Computer Aided Design*, vol. 39, pp. 379–388, 2007, doi: 10.1016/j.cad.2007.02.011.

- [4] S. Terzi, A. Bouras, D. Dutta, M. Garetti, and D. Kiritsis, "Product lifecycle management - From its history to its new role," *International Journal of Product Lifecycle Management*, vol. 4, no. 4, pp. 360–389, 2010, doi: 10.1504/IJPLM.2010.036489.
- [5] B. Eynard, T. Gallet, P. Nowak, and L. Roucoules, "UML based specifications of PDM product structure and workflow," *Computers in Industry*, vol. 55, no. 3, pp. 301–316, 2004, doi: 10.1016/j.compind.2004.08.006.
- [6] S. C. Feng, W. Z. Bernstein, T. Hedberg, and A. Barnard Feeney, "Toward Knowledge Management for Smart Manufacturing," *Journal of Computing and Information Science in Engineering*, vol. 17, no. 3, 2017, doi: 10.1115/1.4037178.
- [7] D. Chen, B. Vallespir, and N. Daclin, "An Approach for Enterprise Interoperability Measurement," *Int. Work. Model Driven Inf. Syst. Eng. Enterp. User Syst. Model.*, no. june, pp. 1–12, Montpellier, France, 2008.
- [8] S. Rachuri, E. Subrahmanian, A. Bouras, S. J. Fenves, S. Foufou, and R. D. Sriram, "Information sharing and exchange in the context of product lifecycle management: Role of standards," *Computer Aided Design*, vol. 40, no. 7, pp. 789–800, 2008, doi: 10.1016/j.cad.2007.06.012.
- [9] J.-M. Crepel, "Overview of STEP AP209 for multi disciplinary analysis interoperability and associated CAE Implementer Forum," *AFNET Stand. Days*, vol. 2018, no. May 17&18, pp. 1–27, 2018.
- [10] R. Beckers, S. Giese, A. Pfouga, and J. Stjepandić, "Interoperability and visualization of complex products based on JT standard," *advances in transdisciplinary engineering*, vol. 4, pp. 828–837, 2016, doi: 10.3233/978-1-61499-703-0-828.
- [11] A. Ball, L. Ding, and M. Patel, "An approach to accessing product data across system and software revisions," *Advanced Engineering Informatics*, vol. 22, no. 2, pp. 222–

- 235, 2008, doi: 10.1016/j.aei.2007.10.003.
- [12] M. J. Pratt, "Introduction to ISO 10303 - the STEP Standard for Product Data Exchange," *Journal of Computing and Information Science in Engineering*, vol. 1, no. March 2001, pp. 1–4, 2001, doi: 10.1115/1.1354995.
- [13] O. Corcho, M. Eriksson, K. Kurowski, M. Ojsteršek, and F. Coppens, "EOSC Interoperability Framework (v1.0)," *EOSC FAIR Exec. Board Working Gr.*, no. May, pp. 1–36, 2020, doi: 10.1038/sdata.2016.18.
- [14] I. Stroud and P. C. Xirouchakis, "STL and extensions," *Advances in Engineering Software*, vol. 31, no. 2, pp. 83–95, 2000, doi: 10.1016/S0965-9978(99)00046-0.
- [15] C. González-Lluch, P. Company, M. Contero, J. D. Camba, and R. Plumed, "A survey on 3D CAD model quality assurance and testing tools," *Computer Aided Design*, vol. 83, pp. 64–79, 2017, doi: 10.1016/j.cad.2016.10.003.
- [16] K. T. Felix Kahl, Stefan Rulhoff, Josip Stjepandic, "Advances in Assembly Planning for Multi- Variant Production Based on 3D PDF," *Int. Conf. Transdiscipl. Eng.*, pp. 871–880, 2017, doi: 10.3233/978-1-61499-779-5-871.
- [17] Z. Nan, L. Qingyuan, J. Huiling, Z. Minghui, and J. Liu, "U3D file format analyzing and 3DPDF generating method," *Commun. Comput. Inf. Sci.*, vol. 757:, pp. 136–146, 2018, doi: 10.1007/978-981-10-7389-2_14.
- [18] M. J. Pratt, "ISO 10303 , the STEP standard for product data exchange , and its PLM capabilities," *International Journal of Product Lifecycle Management*, vol. 1, no. 1, pp. 86–94, 2005, doi: 10.1504/IJPLM.2005.007347.
- [19] M. I. Sarigecili, U. Roy, and S. Rachuri, "Interpreting the semantics of GD&T specifications of a product for tolerance analysis," *Computer Aided Design*, vol. 47, pp. 72–84, 2014, doi: 10.1016/j.cad.2013.09.002.
- [20] R. Lipman and J. Lubell, "Conformance checking of PMI representation in CAD model

- STEP data exchange files,” *Computer Aided Design*, vol. 66, pp. 14–23, 2015, doi: 10.1016/j.cad.2015.04.002.
- [21] A. Y14.41, “Digital product definition data practices,” 2012.
- [22] ISO 10303 ISO/TC 10, “Technical product documentation-Digital product definition data practices,” 2015.
- [23] J. Boy, P. Rosché, F. Darré, G. Hirel, and J. Haenisch, “Recommended Practices for STEP AP242 IS Business Object Model XML Product & Assembly Structure,” *PDM / CAx / JT Implementor Forum*, 2017.
- [24] J. Boy, P. Rosché, G. Hirel, and J. Haenisch, “Recommended Practices for AP242 Business Object Model XML Assembly Structure,” *CAx-IF Recomm. Pract.*, no. october 30, pp. 1–184, 2018.
- [25] A. B. Feeney, S. P. Frechette, and V. Srinivasan, “A Portrait of an ISO STEP Tolerancing Standard as an Enabler of Smart Manufacturing Systems,” *Journal of Computing and Information Science in Engineering*, vol. 15, no. 2, 2015, doi: 10.1115/1.4029050.
- [26] A. Huet *et al.*, “CACDA : A knowledge graph for a context-aware cognitive design assistant,” *Computers in Industry*, vol. 125, p. 103377, 2021, doi: 10.1016/j.compind.2020.103377.
- [27] C. Favi, P. Stief, J. Dantan, A. Etienne, and A. Siadat, “A CAD-based design for manufacturing method for casted components,” *Procedia CIRP*, vol. 100, pp. 235–240, 2021, doi: 10.1016/j.procir.2021.05.061.
- [28] S. K. Mohammed, M. H. Arbo, and L. Tingelstad, “Leveraging model based definition and STEP AP242 in task specification for robotic assembly,” *Procedia CIRP*, vol. 97, pp. 92–97, 2020, doi: 10.1016/j.procir.2020.05.209.
- [29] C. C. Pham, A. Durupt, N. Matta, and B. Eynard, “Visual ontology-based query

- approach for data access in heterogeneous expertise environment: Application in plm biomedical imaging,” *Comput. Aided. Des. Appl.*, vol. 17, no. 2, pp. 226–248, 2020, doi: 10.14733/cadaps.2020.226-248.
- [30] S. Kwon, L. V. Monnier, R. Barbau, and W. Z. Bernstein, “Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs,” *Advanced Engineering Informatics*, vol. 46, no. March, p. 101102, 2020, doi: 10.1016/j.aei.2020.101102.
- [31] Y. Pane, S. Member, M. H. Arbo, and E. Aertbeliën, “A System Architecture for CAD-Based Robotic Assembly With Sensor-Based Skills,” *IEEE Trans. Autom. Sci. Eng.*, vol. 17, no. 3, pp. 1237–1249, 2020, doi: 10.1109/TASE.2020.2980628.
- [32] R. Plumed, C. Gonz, P. David, M. Contero, J. D. Camba, and D. Val, “A voice-based annotation system for collaborative computer-aided design,” *Journal of Computational Design and Engineering*, vol. 0, no. 0, pp. 1–11, 2020, doi: 10.1093/jcde/qwaa092.
- [33] F. Mandorli, S. Borgo, and P. Wiejak, “From form features to semantic features in existing MCAD: An ontological approach,” *Advanced Engineering Informatics*, vol. 44, no. January, p. 101088, 2020, doi: 10.1016/j.aei.2020.101088.
- [34] M. Mohd Ali, R. Rai, J. N. Otte, and B. Smith, “A product life cycle ontology for additive manufacturing,” *Computers in Industry*, vol. 105, pp. 191–203, 2019, doi: 10.1016/j.compind.2018.12.007.
- [35] M. Hallmann, S. Goetz, and B. Schleich, “Mapping of GD&T information and PMI between 3D product models in the STEP and STL format,” *Computer Aided Design*, vol. 115, pp. 293–306, 2019, doi: 10.1016/j.cad.2019.06.006.
- [36] L. Hao, R. Mo, Z. Han, and B. Wei, “Functional semantics annotation of assembly model using the fusion of bag of relationships model and spectral technology,” *J. Adv. Mech. Des. Syst. Manuf.*, vol. 13, no. 4, pp. 1–14, 2019, doi:

10.1299/JAMDSM.2019JAMDSM0082.

- [37] F. Gandon, "A survey of the first 20 years of research on semantic web and linked data," *Revue des Sciences et Technologies de l'Information - S?rie ISI : Ing?nierie des Syst?mes d'Information*, vol. 23, no. 3–4, pp. 11–56, 2018, doi: 10.3166/ISI.23.3-4.11-56.
- [38] E. M. Sanfilippo, "Ontological foundations for feature-based modeling," *Procedia CIRP*, vol. 70, pp. 174–179, 2018, doi: 10.1016/j.procir.2018.03.002.
- [39] B. Urick, "Coordination of Geometry and Topology Ontology Efforts," *Web3D consortium Discussion*, 2018.
- [40] C. Danjou, J. Le Duigou, and B. Eynard, "Manufacturing knowledge management based on STEP-NC standard: a Closed-Loop Manufacturing approach," *International Journal of Computer Integrated Manufacturing*, vol. 30, no. 9, pp. 995–1009, 2017, doi: 10.1080/0951192X.2016.1268718.
- [41] Y. Zhang, X. Luo, B. Zhang, and S. Zhang, "Semantic approach to the automatic recognition of machining features," *International Journal of Advanced Manufacturing Technology*, vol. 89, no. 1–4, pp. 417–437, 2017, doi: 10.1007/s00170-016-9056-8.
- [42] L. F. Sikos, "A novel ontology for 3D semantics: Ontology-based 3D model indexing and content-based video retrieval applied to the medical domain," *Int. J. Metadata, Semant. Ontol.*, vol. 12, no. 1, pp. 59–69, 2017, doi: 10.1504/IJMSEO.2017.087702.
- [43] Y. Qin *et al.*, "Status, Comparison, and Issues of Computer-Aided Design Model Data Exchange Methods Based on Standardized Neutral Files and Web Ontology Language File," *Journal of Computing and Information Science in Engineering*, vol. 17, no. 1, 2017, doi: 10.1115/1.4034325.
- [44] D. Tchoffa *et al.*, "Digital factory system for dynamic manufacturing network supporting networked collaborative product development," *Data and Knowledge Engineering*, vol.

- 105, pp. 130–154, 2016, doi: 10.1016/j.datak.2016.02.004.
- [45] F. Qin, S. Gao, X. Yang, M. Li, and J. Bai, “An ontology-based semantic retrieval approach for heterogeneous 3D CAD models,” *Advanced Engineering Informatics*, vol. 30, no. 4, pp. 751–768, 2016, doi: 10.1016/j.aei.2016.10.001.
- [46] L. Mazzola, P. Kapahnke, M. Vujic, and M. Klusch, “CDM-Core: A manufacturing domain ontology in owl2 for production and maintenance,” *IC3K 2016 - Proc. 8th Int. Jt. Conf. Knowl. Discov. Knowl. Eng. Knowl. Manag.*, vol. 2, no. November, pp. 136–143, 2016, doi: 10.5220/0006056301360143.
- [47] Z. Han, R. Mo, H. Yang, and L. Hao, “CAD assembly model retrieval based on multi-source semantics information and weighted bipartite graph,” *Computers in Industry*, vol. 96, pp. 54–65, 2018, doi: 10.1016/j.compind.2018.01.003.
- [48] M. F. Sriti, I. Assouoko, G. Ducellier, P. Boutinaud, and B. Eynard, “Ontology-based approach for product information exchange,” *International Journal of Product Lifecycle Management*, vol. 8, no. 1, pp. 1–23, 2015, doi: 10.1504/IJPLM.2015.068011.
- [49] C. Cuong, Nada MATTA, Alexandre DURUPT, Benoit EYNARD, and Guillaume DUCCELLIER, “Knowledge sharing in heterogeneous data context: Application in PLM,” *Proc. 20th Int. Conf. Eng. Des.*, vol. 10, no. July, pp. 1–10, 2015, doi: 10.1007/978-3-319-33111-9_22.
- [50] J. H. Shin, D. Kiritsis, and P. Xirouchakis, “Design modification supporting method based on product usage data in closed-loop PLM,” *International Journal of Computer Integrated Manufacturing*, vol. 28, no. 6, pp. 551–568, 2015, doi: 10.1080/0951192X.2014.900866.
- [51] M. Imran and B. Young, “The application of common logic based formal ontologies to assembly knowledge sharing,” *J. Intell. Manuf.*, vol. 26, no. 1, pp. 139–158, 2015, doi: 10.1007/s10845-013-0768-4.

- [52] G. Bruno, D. Antonelli, and A. Villa, "A reference ontology to support product lifecycle management," *Procedia CIRP*, vol. 33, pp. 41–46, 2015, doi: 10.1016/j.procir.2015.06.009.
- [53] E. Gruhier, F. Demoly, O. Dutartre, S. Abboudi, and S. Gomes, "A formal ontology-based spatiotemporal mereotopology for integrated product design and assembly sequence planning," *Advanced Engineering Informatics*, vol. 29, no. 3, pp. 495–512, 2015, doi: 10.1016/j.aei.2015.04.004.
- [54] S. El Kadiri and D. Kiritsis, "Ontologies in the context of product lifecycle management: State of the art literature review," *International Journal of Production Research*, vol. 53, no. 18, pp. 5657–5668, 2015, doi: 10.1080/00207543.2015.1052155.
- [55] M. M. Baysal and U. Roy, "Representation of functional, behavior, structure and interoperability at different abstract levels of product information," *International Mechanical Engineering Congress and Exposition*, no. november 13-19, pp. 1–9, Houston, Texas, 2015, doi: 10.1115/IMECE2015-53584.
- [56] F. Ulliana, J. Léon, O. Palombi, and M. Rousset, "Combining 3D Models and Functions through Ontologies to Describe Man-made Products and Virtual Humans : Toward a Common Framework," *Computer Aided Design & Applications*, vol. 12, no. 2, pp. 166–180, 2015, doi: 10.1080/16864360.2014.962429.
- [57] I. Assouroko, G. Ducellier, B. Eynard, and P. Boutinaud, "Knowledge management and reuse in collaborative product development – A semantic relationship management based approach," *International Journal of Product Lifecycle Management*, vol. 7, no. 1, 2014, doi: 10.1504/IJPLM.2014.065460.
- [58] S. Abdul-Ghafour, P. Ghodous, B. Shariat, E. Perna, and F. Khosrowshahi, "Semantic interoperability of knowledge in feature-based CAD models," *Computer Aided Design*, vol. 56, pp. 45–57, 2014, doi: 10.1016/j.cad.2014.06.001.

- [59] T. Lu, F. Guan, N. Gu, and F. Wang, "Semantic classification and query of engineering drawings in the shipbuilding industry," *International Journal of Production Research*, vol. 46, no. 9, pp. 2471–2483, 2008, doi: 10.1080/00207540701737922.
- [60] C. Danjou, J. Duigou, and B. Eynard, "OntoSTEP-NC for Information Feedbacks from CNC to CAD / CAM Systems," *International Conference on Advances in Production Management Systems*, pp. 256–263, 2014, doi: 10.1007/978-3-662-44733-8_32.
- [61] M. Allanic, A. Durupt, M. Joliot, B. Eynard, and P. Boutinaud, "Towards a Data Model for PLM Application in Bio-Medical Imaging," *Proc. TMCE 2014, May 19–23, 2014, Budapest, Hungary, Ed. by I. Horv´ath Z. Rus´ak - Organ. Comm. TMCE 2014*, no. September 2015, 2014.
- [62] M. Borsato, "Bridging the gap between product lifecycle management and sustainability in manufacturing through ontology building," *Computers in Industry*, vol. 65, no. 2, pp. 258–269, 2014, doi: 10.1016/j.compind.2013.11.003.
- [63] L. Ramos, R. Gil, D. Anastasiou, and M. J. Martin-Bautista, "Towards a machine of a process (MOP) ontology to facilitate e-commerce of industrial machinery," *Computers in Industry*, vol. 65, no. 1, pp. 108–115, 2014, doi: 10.1016/j.compind.2013.07.012.
- [64] C. H. C. Jojoa and O. M. Drews, "Domain specific language for handling modular ontologies," *2014 9th Comput. Colomb. Conf. 9CCC 2014*, pp. 48–53, 2014, doi: 10.1109/ColumbianCC.2014.6955332.
- [65] J. Camba, M. Contero, M. Johnson, and P. Company, "Extended 3D annotations as a new mechanism to explicitly communicate geometric design intent and increase CAD model reusability," *Computer Aided Design*, vol. 57, pp. 61–73, 2014, doi: 10.1016/j.cad.2014.07.001.
- [66] Z. Usman, N. Anjum, C. Palmer, and J. Harding, "A Model Driven Ontology - based Approach for Manufacturing Knowledge Sharing in PLM," *Enterp. Interoperability*, no.

November 2018, 2013, doi: 10.1002/9781118561942.ch29.

- [67] V. Fortineau, T. Paviot, and S. Lamouri, "Improving the interoperability of industrial information systems with description logic-based models-The state of the art," *Computers in Industry*, vol. 64, no. 4, pp. 363–375, 2013, doi: 10.1016/j.compind.2013.01.001.
- [68] N. V. Bermeo, M. G. Mendoza, and A. G. Castro, "Semantic Representation of CAD Models Based on the IGES Standard," *Mexican International Conference on Artificial Intelligence*, pp. 157–168, 2013, doi: 10.1007/978-3-642-45114-0_13.
- [69] H. Panetto, M. Dassisti, and A. Tursi, "ONTO-PDM: Product-driven ONTOlogy for Product Data Management interoperability within manufacturing process environment," *Advanced Engineering Informatics*, vol. 26, no. 2, pp. 334–348, 2012, doi: 10.1016/j.aei.2011.12.002.
- [70] Y. Liao, M. Lezoche, E. Loures, U. De Lorraine, and B. A. B. P., "Formalization of Semantic Annotation for Systems Interoperability in a PLM Environment," *OnTheMove Federated Conferences & Workshops*, pp. 207–218, 2012, doi: 10.1007/978-3-642-33618-8_29.
- [71] S. Abdul-Ghafour, P. Ghodous, and B. Shariat, "Integration of product models by ontology development," *Proc. 2012 IEEE 13th Int. Conf. Inf. Reuse Integr. IRI 2012*, pp. 548–555, 2012, doi: 10.1109/IRI.2012.6303057.
- [72] R. Barbau *et al.*, "OntoSTEP: Enriching product model data using ontologies," *Computer Aided Design*, vol. 44, no. 6, pp. 575–590, 2012, doi: 10.1016/j.cad.2012.01.008.
- [73] C. Lahoud and D. Monticolo, "SemKnow : A Multi-Agent Platform to Manage Distributed Knowledge by using Ontologies," *Proc. Int. MultiConference Eng. Comput. Sci.*, vol. 1, no. March, pp. 1–6, 2012, doi: 10.1142/9789814439084.

- [74] S. C. J. Lim, Y. Liu, and W. B. Lee, "A methodology for building a semantically annotated multi-faceted ontology for product family modelling," *Advanced Engineering Informatics*, vol. 25, no. 2, pp. 147–161, 2011, doi: 10.1016/j.aei.2010.07.005.
- [75] O. Eck and D. Schaefer, "A semantic file system for integrated product data management," *Advanced Engineering Informatics*, vol. 25, no. 2, pp. 177–184, 2011, doi: 10.1016/j.aei.2010.08.005.
- [76] D. McKenzie-Veal, N. W. Hartman, and J. Springer, "Implementing Ontology-based Information Sharing in Product Lifecycle Management," *Eng. Des. Graph. Div. ASEE*, pp. 1–8, 2010.
- [77] A. Matsokis and D. Kiritsis, "An ontology-based approach for Product Lifecycle Management," *Computers in Industry*, vol. 61, no. 8, pp. 787–797, 2010, doi: 10.1016/j.compind.2010.05.007.
- [78] K. Wang, S. Tong, N. Matta, L. Roucoules, and B. E. Ontology, "Ontology Building of Manufacturing Quality Knowledge for Design Decision Support," *IDMME - Virtual Concept*, no. october, 2010.
- [79] S. Rachuri, H. Suh, and R. D. Sriram, "An Analysis of Description Logic Augmented with Domain Rules for the Development of Product Models," *Journal of Computing and Information Science in Engineering*, vol. 10, no. June, pp. 1–31, 2010, doi: 10.1115/1.3385794.
- [80] P. Zhan, U. Jayaram, O. J. Kim, and L. Zhu, "Knowledge representation and ontology mapping methods for product data in engineering applications," *Journal of Computing and Information Science in Engineering*, vol. 10, no. 2, pp. 1–11, 2010, doi: 10.1115/1.3330432.
- [81] C. E. Catalano, E. Camossi, R. Ferrandes, V. Cheutet, and N. Sevilimis, "A product design ontology for enhancing shape processing in design workflows," *J. Intell.*

- Manuf.*, vol. 20, no. 5, pp. 553–567, 2009, doi: 10.1007/s10845-008-0151-z.
- [82] N. Khilwani, J. A. Harding, and A. K. Choudhary, “Semantic web in manufacturing,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 223, no. 7, pp. 905–924, 2009, doi: 10.1243/09544054JEM1399.
- [83] J. Kwak and H. Yong, “An Approach to Ontology-based Semantic Integration for PLM Object,” *International Workshop on Semantic Computing and Applications*, vol. 13, no. 3, pp. 19–26, 2008, doi: 10.1109/IWSCA.2008.35.
- [84] Leen Hanayneh, Y. Wang, Y. Wang, and J. C. Wileden, “feature mapping automation for CAD data exchange,” *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, no. August 3-6, pp. 2–11, 2008, doi: 10.1115/DETC2008-49671.
- [85] E. Quak, O. A. Andersen, and G. Vasilakis, “Building an ontology of CAD model information,” *Geom. Model. Numer. Simulation, Optim. Appl. Math. SINTEF*, pp. 11–40, 2007, doi: 10.1007/978-3-540-68783-2_2.
- [86] C. Dartigues-Pallez, P. Ghodous, M. Grüninger, D. Pallez, and R. Sriram, “CAD / CAPP integration using feature ontology,” *Concurr. Eng.*, no. June, p. 34, 2007, doi: 10.1177/1063293X07079312.
- [87] Z. Li and K. Ramani, “Ontology-based design information extraction and retrieval,” *Artif. Intell. Eng. Des. Anal. Manuf. AIEDAM*, vol. 21, no. 2, pp. 137–154, 2007, doi: 10.1017/S0890060407070199.
- [88] H. K. Lin and J. A. Harding, “A manufacturing system engineering ontology model on the semantic web for inter-enterprise collaboration,” *Computers in Industry*, vol. 58, no. 5, pp. 428–437, 2007, doi: 10.1016/j.compind.2006.09.015.
- [89] J. Posada, C. Toro, S. Wundrak, and A. Stork, “Using Ontologies and STEP Standards for the Semantic Simplification of CAD Models in Different Engineering

- Domains,” *In: Journal of Applied Ontology*, vol. 1, no. 3–4, pp. 263–279, 2006.
- [90] R. Peachavanish, H. A. Karimi, B. Akinci, and F. Boukamp, “An ontological engineering approach for integrating CAD and GIS in support of infrastructure management,” *Advanced Engineering Informatics*, vol. 20, no. 1, pp. 71–88, 2006, doi: 10.1016/j.aei.2005.06.001.
- [91] K. Kim, D. G. Manley, and H. Yang, “Ontology-based assembly design and information sharing for collaborative product development,” *Computer Aided Design*, vol. 38, pp. 1233–1250, 2006, doi: 10.1016/j.cad.2006.08.004.
- [92] T.-S. Seo, Y. Lee, S.-U. Cheon, L. Patil, and D. Dutta, “Sharing CAD models based on feature ontology of commands history,” *computer science*, pp. 39–47.
- [93] R. Sudarsan, S. J. Fenves, R. D. Sriram, and F. Wang, “A product information modeling framework for product lifecycle management,” *Computer Aided Design*, vol. 37, no. 13, pp. 1399–1411, 2005, doi: 10.1016/j.cad.2005.02.010.
- [94] H. Aziz, J. Gao, P. Maropoulos, and W. M. Cheung, “Open standard, open source and peer-to-peer tools and methods for collaborative product development,” *Computers in Industry*, vol. 56, no. 3, pp. 260–271, 2005, doi: 10.1016/j.compind.2004.12.002.
- [95] R. Jardim-Goncalves, R. Olavo, J. Sarraipa, and A. Steiger-Garcao, “Ontology-Based Framework for Enhanced Interoperability in Networked Industrial Environments,” *IFAC Proc. Vol.*, vol. 37, no. 4, pp. 623–628, 2004, doi: 10.1016/s1474-6670(17)36184-0.
- [96] P. E. L. M. Iller and P. R. N. Adkarni, “QIS : A Framework for Biomedical Database Federation,” *J. Am. Med. Informatics Assoc.*, vol. 11, no. 6, pp. 523–534, 2004, doi: 10.1197/jamia.M1506.HBP.
- [97] S. Zhang, W. Shen, and H. Ghenniwa, “A review of Internet-based product information sharing and visualization,” *Computers in Industry*, vol. 54, no. 1, pp. 1–15, 2004, doi: 10.1016/j.compind.2003.09.002.

- [98] M. Yoshioka, Y. Umeda, H. Takeda, Y. Shimomura, Y. Nomaguchi, and T. Tomiyama, "Physical concept ontology for the knowledge intensive engineering framework," *Advanced Engineering Informatics*, vol. 18, no. 2, pp. 95–113, 2004, doi: 10.1016/j.aei.2004.09.004.
- [99] Y. Kitamura, M. Kashiwase, M. Fuse, and R. Mizoguchi, "Deployment of an ontological framework of functional design knowledge," *Advanced Engineering Informatics*, vol. 18, no. 2, pp. 115–127, 2004, doi: 10.1016/j.aei.2004.09.002.
- [100] S. K. Sim and A. H. B. Duffy, "Towards an ontology of generic engineering design activities," *Res. Eng. Des.*, vol. 14, no. 4, pp. 200–223, 2003, doi: 10.1007/s00163-003-0037-1.
- [101] Y. D. Wang, W. Shen, and H. Ghenniwa, "WebBlow: A Web/agent-based multidisciplinary design optimization environment," *Computers in Industry*, vol. 52, no. 1, pp. 17–28, 2003, doi: 10.1016/S0166-3615(03)00066-6.
- [102] C. Zhao, M. Bhushan, and V. Venkatasubramanian, "Roles of ontology in automated process safety analysis," *Comput. Aided Chem. Eng.*, vol. 14, no. C, pp. 341–346, 2003, doi: 10.1016/S1570-7946(03)80138-4.
- [103] A. Hameed, D. Sleeman, and A. Preece, "Detecting mismatches among experts' ontologies acquired through knowledge elicitation," *Knowledge-Based Systems*, vol. 15, no. 5–6, pp. 265–273, 2002, doi: 10.1016/S0950-7051(01)00162-9.
- [104] L. Wang, W. Shen, H. Xie, J. Neelamkavil, and A. Pardasani, "Collaborative conceptual design—state of the art and future trends," *Computer Aided Design*, vol. 34, pp. 981–996, 2002, doi: 10.1016/S0010-4485(01)00157-9.
- [105] M. Macchi and M. Garetti, "Enterprise Interoperability: A Critical Survey of Modelling Methods with Special Concern to Manufacturing Systems Engineering," *IFAC Proc. Vol.*, vol. 34, no. 17, pp. 45–50, 2001, doi: 10.1016/s1474-6670(17)33254-8.

- [106] S. Dimassi *et al.*, “An ontology-based framework to formalize and represent 4D printing knowledge in design,” *Computers in Industry*, vol. 126, 2021, doi: 10.1016/j.compind.2020.103374.
- [107] M. J. Pratt, “Exchanging history-based parametric CAD models using ISO 10303,” *International Journal of Product Lifecycle Management*, vol. 4, no. 4, pp. 312–316, 2010, doi: 10.1504/IJPLM.2010.036483.
- [108] P. Haghghi, Satchit Ramnath, Aniket Chitale, Joseph K Davidson, and Jami J Shah, “Automated Tolerance Analysis of Mechanical Assemblies from a CAD Model with PMI,” *Computer Aided Design and Applications*, vol. 17, no. 2, pp. 249–273, 2020, doi: 10.14733/cadaps.2020.249-273.
- [109] A. Katzenbach, S. Handschuh, and S. Vettermann, “JT format (ISO 14306) and AP 242 (ISO 10303): The step to the next generation collaborative product creation,” in *IFIP Advances in Information and Communication Technology*, 2013, vol. 411, no. Iso 14306, pp. 41–52. doi: 10.1007/978-3-642-41329-2_6.
- [110] S. Handschuh, R. Dotzauer, and A. Fröhlich, “Standardized formats for visualization – application and development of JT,” *B. Concurr. Eng. Approaches Sustain. Prod. Dev. a Multi-Disciplinary Environ.*, pp. 741–752, 2013, doi: 10.1007/978-1-4471-4426-7.