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Towards Knowledge-based System to support Smart Manufacturing Processes in Aerospace Industry based on Models for Manufacturing (MfM)

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Abstract. The Product design and manufacturing of an Airplane is complex and requires the involvement of multiple experts sharing information and knowledge from multi-perspectives within and across institutional boundaries. From the Fourth Industrial Revolution, new concepts are emerging like smart manufacturing, which is a convergence of modern enabling technologies with artificial intelligence to increase manufacturing efficiency and eliminating pain points, ensuring higher quality levels and customization. Models for Manufacturing (MfM) is a recent methodology that presents an organization to formally defined information and knowledge. However, MfM does not consider information tracking and inconsistencies analysis across the PLM phases. Based on this context, this research explores the proposal of a Product Design and Manufacturing Knowledge-based system (PDMKBs) based on MfM and Semantic Web Technologies. PDMKBs is composed of 4-layers: ontology layer; semantic resolution & alignment layer; Application & Analysis Layer and Data Layer. OWL and Semantic rules are used to formalize the information and knowledge and to share, convert or translate information from multiple perspectives to infer the relation between multiple product design and manufacturing levels. The PDMKBs was tested in the tooling design to manufacturing a sheet metal part of the A400M. The main research contributions are: (i) the well-defined structure to formalize heterogeneous information and knowledge; (ii) the improvement of information and knowledge exchange between heterogeneous domains across different phases of the manufacturing process.

Keywords: Smart Manufacturing, Models for Manufacturing, Knowledge-Based System, Ontology, Semantic Rules.

1 Introduction

The design and manufacturing of an aircraft are complex and no trivial processes. To illustrate the complexity of an aircraft, the Airbus A400M is composed of a set of about 700.000 parts and its parts are designed and manufactured in seven countries all over the world by different structures as shown in Fig. 1 [1]. The design and manufacturing of an aircraft involve engineers from different nationalities located in different countries. During this process, information and knowledge about different components must be shared across different phases of the product development process or manufacturing planning process.

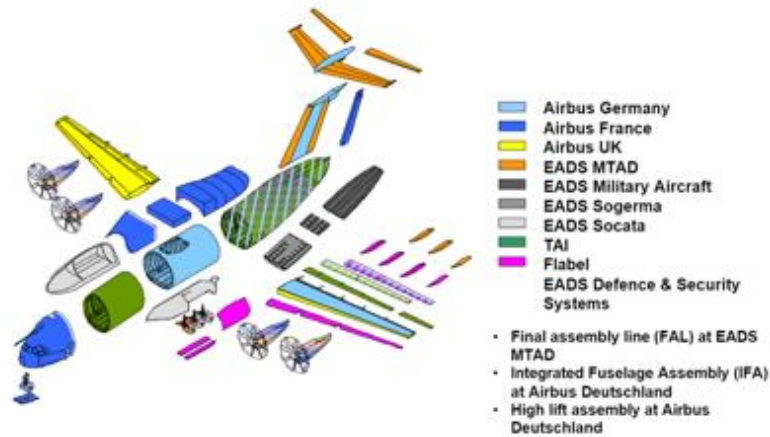


Fig. 1. Industrial Workshare of the A400M. Source: [1]

Product Data Management (PDM) and Product Lifecycle Management (PLM) have been used to achieve a correct product development process, manufacturing planning and process traceability [2]. PLM enables the users to collaboratively design, manufacture, and manage products across different phases of the development lifecycle. The novel technologies from the fourth industrial revolution have to speed up the digitalization process and increasing the amounts of engineering information available for the engineers across the product development lifecycle. For example, the Digital Twin is a new concept that seeks to create a dynamic virtual representation of a physical object or system across its lifecycle [3]. This new technological scenario requires novel ways to manage all this information and knowledge since it does not consider the meaning associated with each captured

information and their relationships across different phases of the product lifecycle [4][5].

Recent researches systematize the information to help the engineers to perform the Industrial Design and Manufacturing of an aerospace product [6]. The Model for Manufacturing (MfM) methodology aims to provide a set of Processes, Methods and associated Tools (MPT) to support the discipline of manufacturing in a model-based context [7]. However, the methodology does not consider the relationship of the information and knowledge as well as manage the information inconsistencies that can be created across the product lifecycle.

This is a typical semantic interoperability obstacle that concerns the definition of the concept and semantic support for the communication between information and knowledge models. Interoperability is defined “as the capacity of two or more systems to exchange information and to use the information that has been shared” [8]. Thus, the most common way to support semantic interoperability is to research integrated solutions through the definition of common information models formally well-defined and their relationships.

Based on this context, this paper proposes the towards Knowledge-Based System (KBS) framework based on MfM and semantic interoperability technologies to support collaborative and smart manufacturing processes in the aerospace industry. This research contributes to the analyse of inconsistencies during the information and knowledge sharing between the product design and manufacturing process.

The remainder of the paper is structured as follows: Section 2 presents a technological background to support the problem definition and solution to be proposed. Section 3 is dedicated to present the KBS framework based on MfM and semantic interoperability technologies. Section 4 demonstrates the application of the framework and the preliminary results in a specific experimental case, and finally, Section 5 discusses the results, main advantages and limitation of the research.

2 Technological Background

2.1 Model for Manufacturing (MfM)

Model for Manufacturing (MfM) is a novel model proposed by [7] that is based on Model-Based Systems Engineering (MBSE). MBSE is a

methodology where computer-aided graphical modelling authoring tools are used to specify the functions and behaviours of the systems [9]. MfM was structured in 3-Layers Model (Data Layer, Ontology Layer and Service Layer) as shown in Fig. 2.

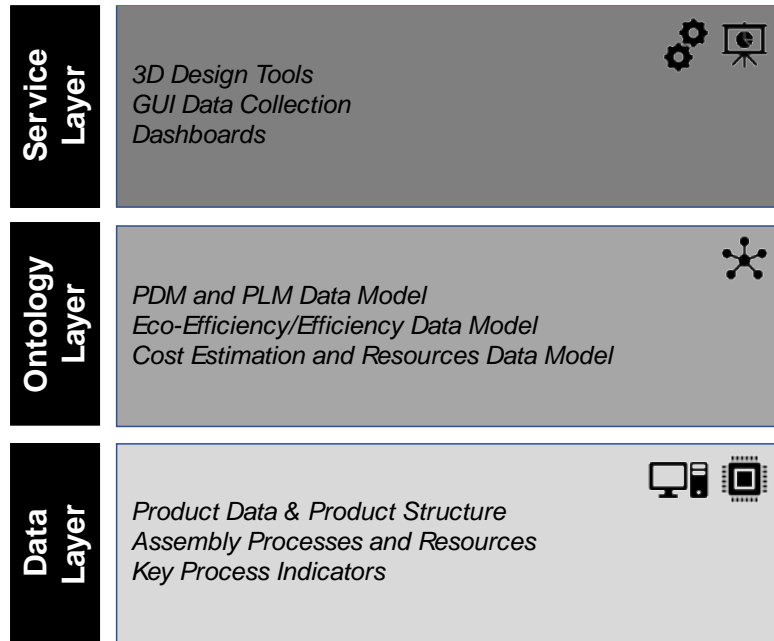


Fig. 2. Three Layer Model (3LM) framework. Source: Adapted from [7].

The Data Layer (Level 0) gathers information from the databases and interfaces related to the product development and manufacturing process. The Ontology layer (Level 1) is the core of the model because it holds all the Business processes and scope, data and semantic models, and behaviour requirements. Finally, the Service Layer (Level 2) includes the software tasks. The behaviours of the different services are defined in the Ontology layer as part of the ontology definition. The service layer holds software as simulation tools, visualizers, data analytics, dashboards and space design exploration tools.

2.2 Knowledge-Based Systems (KBS)

Knowledge-Based Systems (KBS) or Expert Systems is a computer program for specialized applications that require expertise (generally based on Artificial Intelligence (AI) techniques) to reason a knowledge

base to solve complex problems [10]. According to [11], KBS is composed of three major components as follow:

- *Knowledge Base* is normally static and changes little during the operation of the system. It is obtained in the knowledge acquisition or knowledge representation phase during the development of KBS. In many cases, knowledge is abstracted and has the main concepts about the problem or application solution.
- *Working Memory* contains transient knowledge that changes significantly during the use of the system. It is initialized with the specific attribute values relevant to one particular case or one specific application case. It is a specialization of the knowledge base according to the attributes of the real application.
- *Inference Engine* is the operational component that applies the knowledge base to the working memory. It produces results and explanations for the problem of the real application relating the attributes of the specific application with the knowledge modelled in the knowledge base.

The recent advancement of KBS has been to adopt the technologies called description logic, for the development of systems that use the internet approaches [12]. The internet often has to deal with complex, unstructured data that cannot be relied on to fit a specific data model. The standard for these types of knowledge-based Internet systems is Semantic Web Technologies.

2.3 Semantic Web Technologies

Semantic Web Technologies presents information and knowledge in a structured form, building contextual understandings in one or multiple domains. Additionally, it allows automatic processing, exchange and reuse of data by software agents system or semantic reasoner systems. To enable the encoding of semantics with the data, technologies such as Resource Description Framework (RDF) [13] and Web Ontology Language (OWL) [14] are used. These technologies are used to formally represent metadata, based on the ontology concept.

Ontologies provide a mechanism for several capabilities for both machines (e.g., information systems, cyber-physical systems) and humans. They represent knowledge of a domain, interoperability, inter-

agent communication, make possible more flexible automation, and reduce the risk [15]. In this way, the ontology concept has become a significant concept for Intelligent Information Integration, Internet Information Retrieval, Knowledge Management and the Semantic Web. The reason for this expansion is due to the promise of providing a shared and common understanding across specific domains [16]. Ontology has been developed to provide machine-processable semantics of information sources that can be communicated between machine to machine (M2M) [17]. It is also used by intelligent systems for the interoperation between heterogeneous systems.

Aligned to the ontologies, a Semantic Reasoner or Rules Engine is a piece of software able to infer logical consequences from a set of asserted facts or axioms. Semantic Reasoner enables the identification of information inconsistencies across the product or manufacturing process. Currently, some related works [4, 18–20] have recognized ontology mapping and semantic reasoner as key technology to deal with the semantic interoperation problem. Mapping is a critical operation in traditional applications such as (i) information integration, (ii) query answering, and (iii) data transformation. The mapping process contributes to the solution of the heterogeneity problem between ontologies because it tries to find correspondences between semantically associated entities that belong to different ontologies. It takes as input two ontologies, each one consisting of a set of components (classes, instances, properties, rules, axioms, etc.), and determines as output the similarity matching [21].

3 Product Design and Manufacturing Knowledge-Based System approach applied in Aerospace Industry

Smart Manufacturing is a convergence of modern enabling technologies and artificial intelligence to increase manufacturing efficiency and eliminating pain points, ensuring higher quality levels and customization [22]. This new paradigm contributes to the product design and manufacturing of complex products since these phases are extremely critical and they represent 85% of the whole cost of the product development [23][24]. So that, all information must be effectively exchanged across all perspectives.

The MfM presents a novel methodology to structure the heterogeneous information and knowledge shared during the manufacturing process. It

systematizes the data collection about Product Data and Product Structure and Assembly Processes and Resources in a Data Layer [6, 7]. However, the MfM methodology proposed does not explore the information traceability and inconsistencies identification during information and knowledge sharing across the Product Design and Manufacturing Planning.

Semantic Web Technologies presents solutions to formalize information and knowledge in a well-defined manner through the use of Web Ontology Language (OWL) [18]. Additionally, the use of Semantic Web Rule Languages (SWRL) allows the formalization of information relationship across different domains and phases of the development lifecycle [25, 26]. Based on these concepts, it was proposed towards Product Design and Manufacturing Knowledge-Based System (PDMKBs), which integrates the approaches proposed by MfM and Semantic Web Technologies.

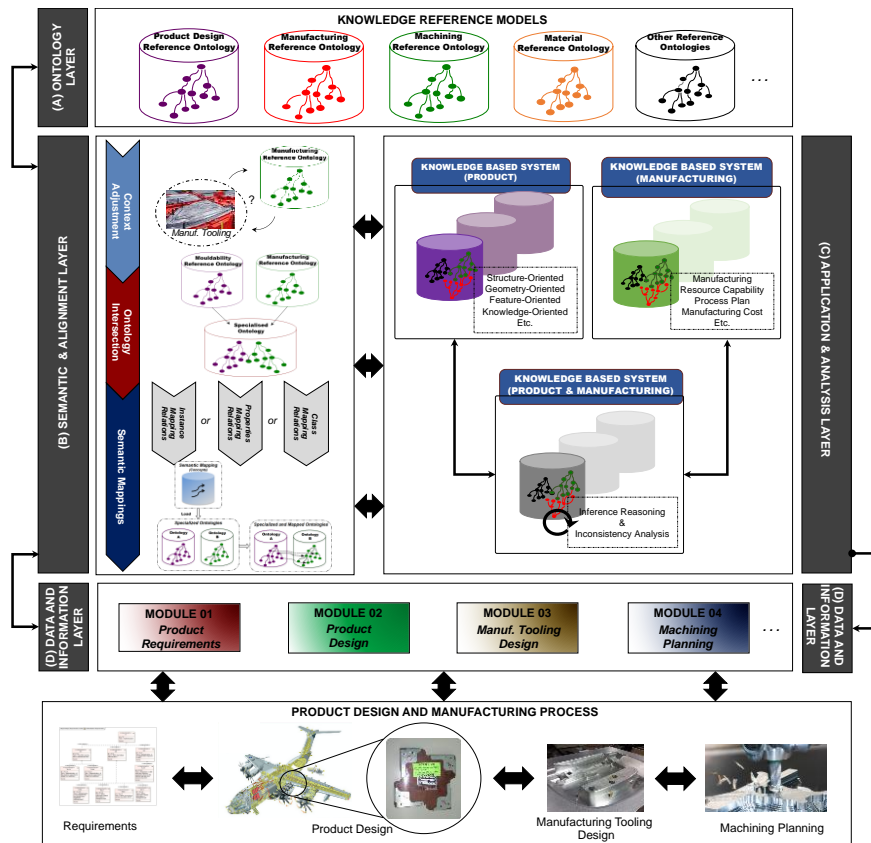


Fig. 3. Product Design and Manufacturing Knowledge-Based system (PDMKBs).

According to Fig. 3, PDMKBs is composed of 4-layers:

- *Ontology Layer (Detail "A" of Fig. 3)* - It defines and gathers the knowledge reference models about Product Requirements, Product Design, Manufacturing Planning, Machining, Materials, and so on. The knowledge about specific domains is modelled in an elementary form and in a formal way. The knowledge is modelled in a common logic-based formalism using Web Ontology Language (OWL), through the Protégé tool.
- *Semantic Resolution & Alignment Layer (Detail "B" of Fig. 3)* - This layer semantically aligns and relate the data and information from the Data Layer with Ontology Layer to trace and identify inconsistencies across different phases of the development in real-time and collaborative action. It occurs through three processes: (i) semantic alignment; (ii) ontology intersection; and (iii) semantic mapping. Semantic Alignment identifies the corresponding reference ontology to support the module of the data layer. Ontology Intersection proceeds with a fusion of multiple reference ontologies in one specialized ontology. Finally, Semantic Mapping creates semantic rules to establish the relationship between data and information extracted from the Data Layer as well as to instantiate them in the reference ontologies. The mapping information and knowledge are directed to the Application and Analysis Layer.
- *Application & Analysis Layer (Detail "C" of Fig. 3)* - This layer is responsible to gathers the specialized ontologies with specific information extracted from the real world through the data layer. The information can be segmented in Product Model and/or Manufacturing Model according to the specific application needs. Additionally, the specialized ontologies are analyzed through the inference engine (Pallet2 reasoner) to identify inconsistencies during the product design, manufacturing planning and process, assisting the stakeholders in real-time. This research does not consider autonomous actions, but this analysis will allow to the system correct automatically some of the problems identified.
- *Data & Information Layer (Detail "D" of Fig. 3)* – All data and information can be extracted from the real world through different approaches such as (i) Product Requirements is extracted from the CSV files, (ii) Product Design is extracted

from CAD systems through XML files, (iii) Manufacturing Planning is extracted from CAD and CAM systems through XML files, (iv) Manufacturing Processes are extracted from multiple platforms Programmable Automation Controllers, Industrial Computers, Smart Sensors, Internet of Things (IoT) devices, and so on, through UPC UA protocol. The data and information will be instances in the specialized ontologies, which is analyzed in the Semantic Resolution & Alignment Layer.

Section 4 presents a short application of PDMKBs during the manufacturing planning of a specific component of A400M aircraft and their results.

4 Application of the approach in an Aerospace Industry experimental case

The A400M design and manufacturing have involved more than 700.000 parts, as presented at the beginning of this article. The product design and manufacturing require the involvement of multiple experts sharing heterogeneous information and knowledge from multiple systems in a collaborative manner across the PLM phases [1]. Fig. 4 presents an overview of an experimental case in which to manufacture a sheet metal part of the A400M airplane, data and information must be shared between product requirement, product design and manufacturing planning.

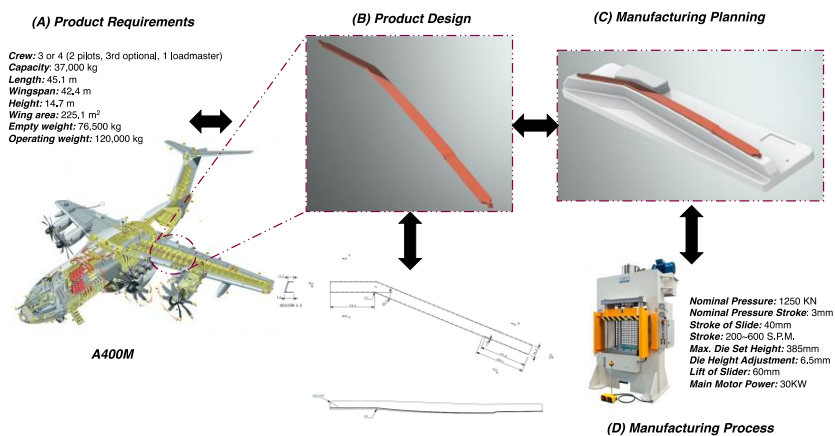


Fig. 4. Overview of an experimental case applied in this research.

This article explores the information and knowledge relationship between Product Design and Manufacturing focused on the Tooling Design to produce a sheet metal component of A400M Airplane, as the detail “A” and “B” of Fig. 4. The first step of PMKBs is to represent the reference ontologies to compose the Ontology Layer (Detail “A” of Fig. 3). This article is only considering the modelling of prismatic sheet metal parts. The research of [27, 28] presents in a formal way information data structure to represent prismatic parts. The Data Structure was translated into an ontology in OWL language as presented in Fig. 5.



Fig. 5. Prismatic Product Design Reference Ontology.

Additionally, it is necessary to understand the characteristics of the product materials, because it directly impacts the product resistance and quality as well as in the manufacturing process. For example, the tooling design must withstand the product shaping during the forming manufacturing. In this way, the research proposed by [29] presents a materials ontology in a comprehensive manner that has information about materials substance, process, environment, and property. Fig. 6 presents the material reference ontology.

Finally, the last reference ontology is the manufacturing ontology reference, which was modelled according to the research [27, 28]. The reference ontology in Fig. 7, represents a part of the manufacturing ontology since it only considers the cavity mould insert of the impression system. This ontology represents the translation process between the 3D product model and the impression system, which will be responsible to manufacture the product.

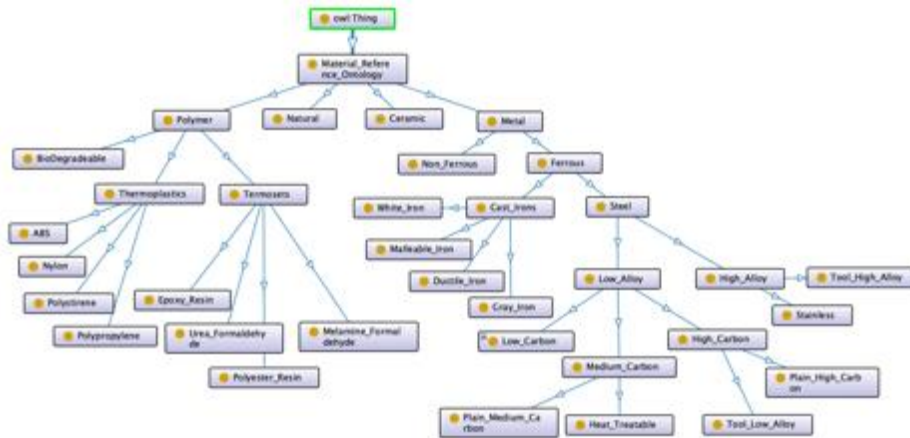


Fig. 6. Material Reference Ontology.

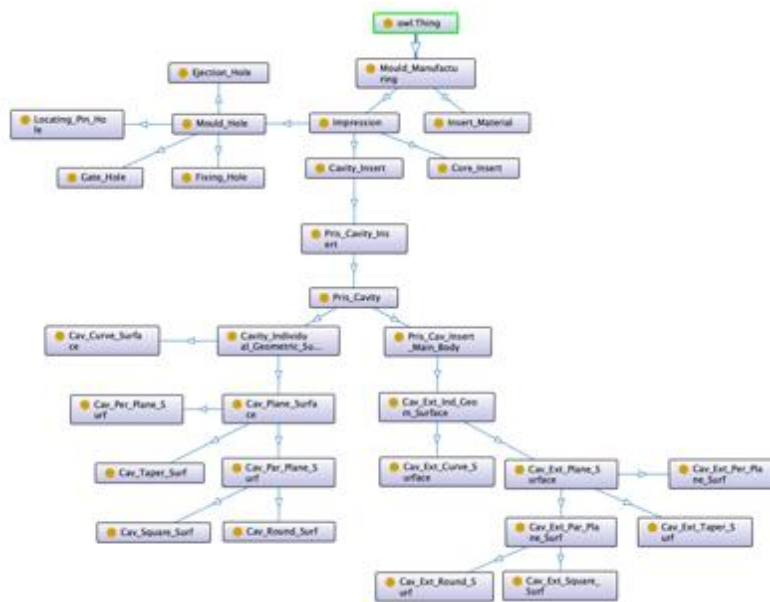


Fig. 7. Manufacturing Planning Reference Ontology.

The data and information about the product design to be manufacturing was directly extracted from the SolidWorks Software with point cloud data and exported in an XML file. Fig. 8 shows the extraction information process, through a Design Assistant, which is responsible to convert the point cloud data into an XML readable for the system.

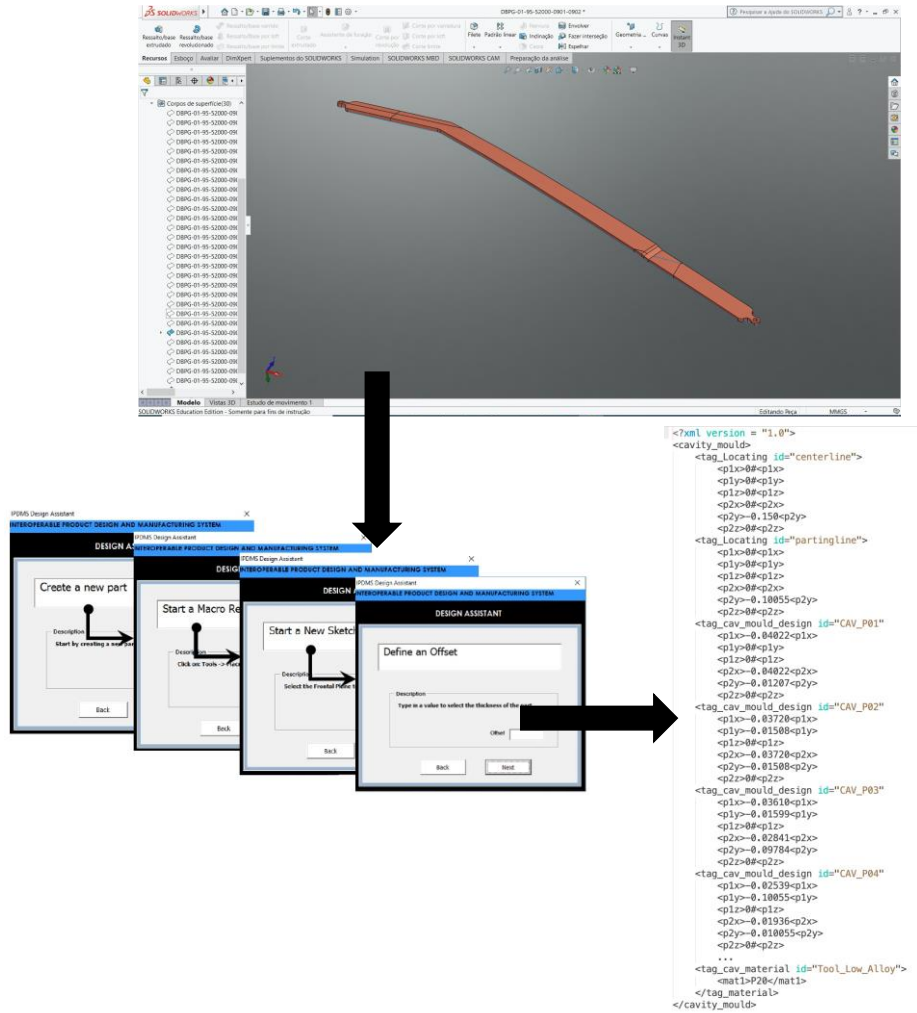


Fig. 8. Product Design Data and Information Extraction.

Finally, the two last steps of PDMKBs, which are working together, are Semantic Resolution & Alignment Layer (Detail “B” of Fig. 3) and Application & Analysis Layer (Detail “C” of Fig. 3). The data and information from the real application are aligned with the reference ontologies, specializing them and the semantic mapping are established according to the semantic rules. In the Application & Analysis Layer, the reasoning system (Pellet 2) is carried out and it is possible to identify conflicts or inconsistencies between the Product Design and Manufacturing Planning. Fig. 9 presents the results of the PDMKBs application in the case.

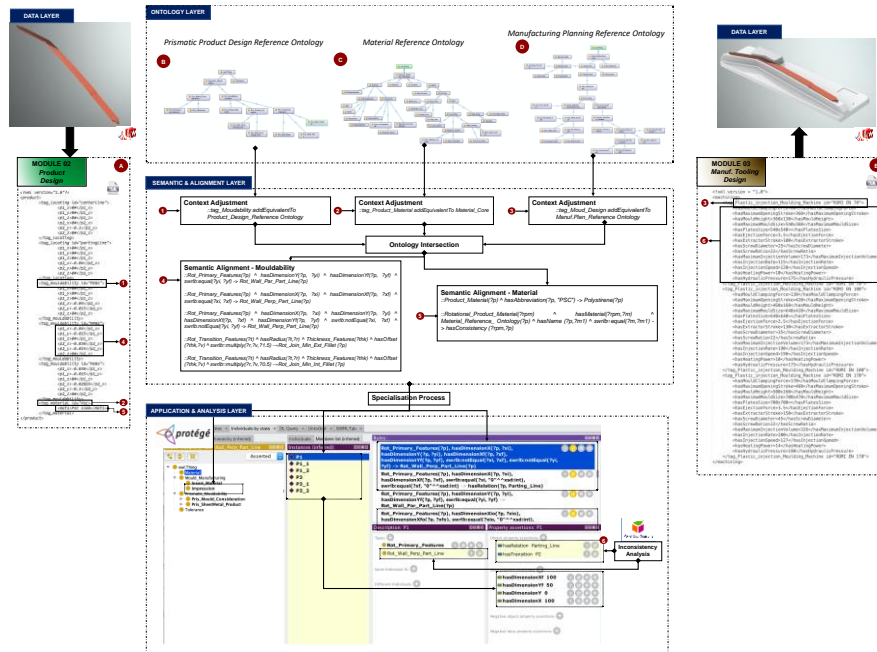


Fig. 9. PDMKBs applied in an A400 sheet metal component.

5 Conclusion

The design and manufacturing of a complex product, like an Airplane, requires effective information and knowledge sharing through multiple phases. In this context, this article has explored Towards Knowledge-based System to support Product Design and Manufacturing in Smart Manufacturing Processes based on a Model for Manufacturing. MfM is a novel methodology based on 3-Layers, that was the foundations of Product Design and Manufacturing Knowledge-Based system (PDMKBs).

PDMKBs is composed of 4 layers: Ontology Layer, Semantic Resolution & Alignment Layer, Application & Analysis Layer, Data Layer. Each layer is responsible to manipulate data, information and knowledge. The data layer gathers and systematizes data and information from the real world. The ontology layer formalizes the reference knowledge which it will specialize in according to the real case. Semantic Resolution & Alignment Layer and Application & Analysis Layer are responsible to ensure the correct relationship and mitigate any problem with the design or manufacturing phases.

The system was experimental tested in a sheet metal part of an A400M airplane. The PDMKBs has demonstrated relevant results to ensure semantic information interoperability during the sequential evolution of the Product Design and Manufacturing since the information is formally structured, traceable and the semantic rules are cyclically analysed. However, the PDMKBs must be evaluated in more cases to measure the gains achieved with the proposed solution.

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