An approach to Model Lifecycle Management for supporting collaborative Ontology-Based Engineering

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Abstract. To reduce costs and increase production capacity, and meet market demand in a sustainable manner, the aerospace industry is placing a growing emphasis on designing the entire product life cycle. This necessitates a novel approach to make a significant advancement and ensure competitiveness in the 21st century. One solution that has emerged is the utilization of Ontology-Based Engineering (OBE) methods, processes, and tools. However, implementing OBE has presented challenges related to modeling, such as effectively managing lifecycles, workflows, and the sharing and reuse of models. To address these challenges, the authors have proposed the Models for Manufacturing (MfM) methodology, which offers a novel way to model manufacturing systems with collaborative, extensible, and reusable characteristics. These characteristics align with the concept of Model Lifecycle Management (MLM). This article highlights the difficulties faced by the aerospace industry when adopting models based on the entire product lifecycle, drawing parallels to the adoption of 3D modeling in the nineties. Furthermore, it explores how the MLM system proposed by the authors can effectively address these issues.

Keywords: Model Lifecycle Management, Ontology-Based Engineering, Models for Manufacturing, Product Lifecycle Management

1 Introduction

Rapid advancement of information and communication systems has facilitated the rapid spread and evolution of globalization. Collaborative business environments, where companies share and work together, have become commonplace. However, this new paradigm of real-time collaboration and communication presents challenges such as information security, the evolution of shared work environments, and coordination between different work environments.

Globalization encompasses not only the manufacturing of products, but also extends to the entire product lifecycle. Engineering systems modeling has relied on various modeling techniques, often based on the expertise of the individuals involved. This creates difficulties in collaborative processes when modeling techniques evolve or differ among teams and companies. To address this issue, two areas of focus have emerged.

The first area involves standardizing modeling techniques, leading to the emergence of model standardization through OBE [1]. A model is an abstraction or representation of a system or reality created to facilitate understanding and analyze its behavior. Modeling is employed in various disciplines, environments, and testing laboratories to analyze existing, past, or future systems.

Working in collaborative environments requires managing the lifecycle of models, enabling analysis and evaluation of various stages, defining revisions and configurations, and monitoring model evolution. This role is fulfilled by an MLM system, like Product Lifecycle Management (PLM) systems fulfill the role for CAD models.

The objective of the paper highlights the difficulties faced by the aerospace industry when adopting models based on the entire product lifecycle and explore how the MLM system proposed by the authors can effectively address these issues. The paper is structured as follows. Section 2 provides a brief review of the literature and overview of previous work. Section 3 examines the status of the European Aerospace Industry, while Section 4 describes the current state of model development. Section 5 presents the research and prototypes implementing a MLM system, and the final Section 6 concludes the paper and outlines future research work.

2 Literature review and previous work

A model is a representation of a system comprising objects with attributes and relationships [2]. In engineering, multiple modeling techniques are employed, including state-diagram based system analysis [3], Object-Process Methodology (OPM) [4], Model Driven Architecture (MDA) [5], and System Engineering Model Driven (SEMD) [6] among others. These methodologies serve the purpose of organizing specifications and generating models for diverse system types. Significant efforts have been undertaken to standardize and integrate these models, with notable examples being Arcadia [7] and SysML [8].

Research efforts have also been dedicated to the development of novel languages and the integration of ontologies and semantics into modeling. Lifecycle Modelling Language (LML) [9] and Graph Object Point Property Role and Relationship (GOPPRRE) [10] are notable examples of such approaches. Ontology development has emerged as a global research topic, and OBE encompasses a range of activities involved in creating ontologies, methodologies, and supporting tools [11]. Ontology, in this context, refers to a shared understanding within a specific domain [12]. The National Institute of Standards and Technology (NIST) and projects within the European Union (EU), such as the Ontocommons project [13], funded by Horizon 2020, have explored the interoperability between different engineering disciplines and the notion of commonality in ontologies. In line with this collaboration, the Industrial Ontologies Foundry (IOF) [14] seeks to establish a comprehensive and open set of core reference ontologies for digital manufacturing. The key objectives include achieving interoperability, establishing information linkage, formalizing requirements, and ensuring quality and traceability.

The initial proposition of the concept of a MLM was introduced in 2014 at the INCOSE conference [15], where it elucidated various indispensable functionalities essential for the comprehensive management of model lifecycles. MLM bears resemblances to PLM, a well-established approach employed for the management of product lifecycle information. Metamodels play a crucial role in delineating the language used to describe models and enabling their manipulation [16]. The study of MLM has also been undertaken in conjunction with the MfM methodology [17]. MLM represents a relatively nascent challenge that has garnered limited research attention thus far. Nonetheless, it exhibits notable parallels with PLM. Considering their conceptual resemblances, techniques and tools employed in PLM can be effectively leveraged to provide support for MLM. Certain functionalities related to MLM have been subject to more extensive investigation as expounded in the reference [18].

Within the aerospace industry, the comprehensive design of the product lifecycle plays a pivotal role in achieving cost reduction, increasing production capacity, and effectively responding to market demands. The authors have introduced the concept of the industrial Digital Mock-Up (iDMU) [19], which is currently advocated as the prevailing design paradigm in the manufacturing domain. The iDMU paradigm aims to facilitate knowledge integration, enable reuse and traceability, minimize costs, improve quality, expedite time-to-market, and automate the generation of manufacturing documents. Europe is actively engaged in the development of aerospace programs, with support from the European Union (EU) and international consortia, aiming to sustain its leadership in the industry. Prominent initiatives like Clean Sky and Clean Sky 2 are geared toward enhancing the sustainability of air transport by replacing existing aircraft with fuel-efficient models that emit reduced noise and emissions while utilizing clean fuels such as hydrogen. Defense projects such as Eurodrone and New Generation Weapon System (NGWS) further enhance defense capabilities. These programs necessitate the adoption of new technologies and tools, presenting challenges in terms of cost-effectiveness, timely delivery, and certification.

The intricate nature of the aerospace industry demands the establishment of novel working models, collaborative efforts, and the utilization of modeling and simulation techniques to expedite development cycles, validate designs, facilitate certification, achieve cost reductions, and minimize environmental impact. The integration of OBE solutions, PLM systems, simulations, and production/service models is of paramount importance. Digital platforms that foster open environments, allowing for seamless model exchange and access to design data, are indispensable. To ensure, the definition of methodologies and frameworks for model development and integration through ontologies and metamodels is crucial for ensuring effective implementation.

3 Status of model development in aerospace industry

The transition from 2D drawings to 3D representation, facilitated by information systems, has yielded significant advancements in product design quality and efficiency. Nevertheless, this shift has presented challenges stemming from limited expertise and familiarity in effectively managing 3D models. In the initial stages, the engineering department independently generated and oversaw their respective 3D models stored within designated folders. The need to share models across various design areas required the establishment of user access protocols to prevent conflicting modifications. The management of model maturity and versioning emerged as critical considerations, effectively addressed through the implementation of information systems.

Subsequently, software manufacturers responded by offering model management solutions that incorporated features such as versioning and workflows, giving rise to Product Data Management (PDM). PDM mainly focused on product design aspects but lacked seamless integration with other functional areas. Over time, increasing industry requirements led to the development of collaborative PLM systems. These comprehensive PLM systems encompass the entire product lifecycle and encompass a broader scope by integrating industrial processes and resources, including the industrial Digital Mock-Up (iDMU) [19]. In general, the evolution involved transitioning from 2D to 3D, managing models between departments, and progressing from PDM to PLM for comprehensive product management.

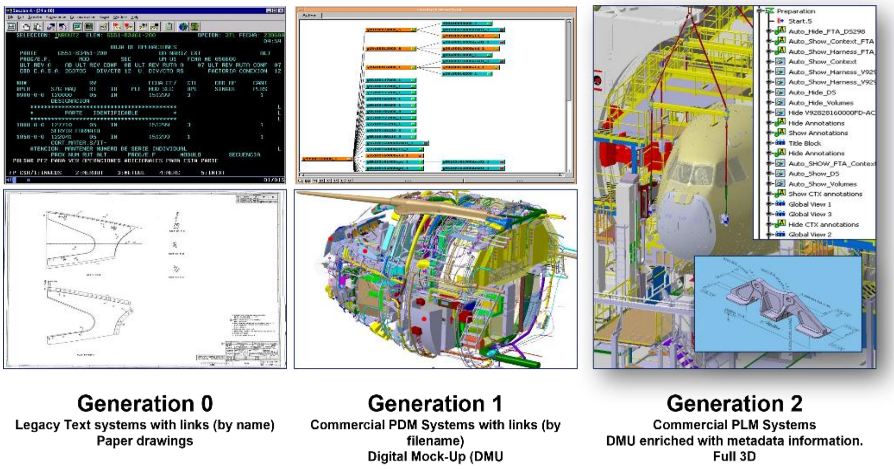

Fig. 1. Generations 0 to 2 showing the status of product information management.

In 2015, Mas et al. [20] conducted a comprehensive review of PLM within the aerospace industry, focusing on its impact. Their study highlighted key PLM advancements over the past 50 years, with a particular emphasis on topics related to product information management. The authors delineated three distinct generations of PLM, spanning the period from 1960 to 2015, representing an evolutionary progression from

Generation 0 to Generation 2. Generation 0 entailed the utilization of legacy PDM systems coupled with attached drawings. This was followed by Generation 1, characterized by the adoption of commercial PDM systems that incorporated attached 3D Computer-Aided Design (CAD) models, leading to the establishment of a Digital Mock-Up (DMU). Finally, Generation 2 marked the integration of commercial PLM systems capable of encompassing all metadata related to the product. The evolution of product information management across these generations is succinctly summarized and presented in Figure 1.

In 2021, an updated review was published, focusing on major players in the aerospace industry, namely Airbus and Boeing, and their projects related to Generation 3. These strategic initiatives are focused on the utilization of modeling and simulation techniques. Generation 3 is distinguished by the adoption of OBE as the foundation for product information management, accompanied by the implementation of Continuous Engineering and Digital Twin methodologies and processes [21]. Figure 2 provides a visual representation of the current Generation 3, where the central focus revolves around the model as the primary object. This perspective underscores the integration of various components, such as the 3D model, metadata, and characteristics, all of which are considered integral parts of the model itself.

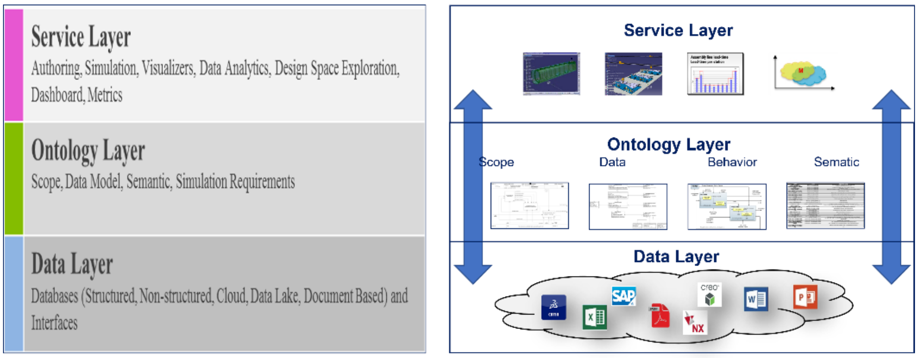

Fig. 2. Generation 3 shows the status of product information management.

In recent years, the benefits of Modeling and Simulation (M&S) have expanded beyond product design to industrial and operational systems. This has sparked interest and efforts in OBE methodologies and brought attention to the need for a more connected approach. However, the industry has struggled to learn from past mistakes in the 3D geometric realm, resulting in similar problems arising with M&S technologies in the product lifecycle. The challenges in OBE include the following challenges:

- Challenges considering models development include the lack of methodologies for the entire lifecycle, the need for comprehensive metamodels, and the absence of common development tools.
- Challenges considering framework perspective include a lack of model sharing and reusability, narrow solution focus limiting their applicability, localized optimiza-

tion missing out on company-wide benefits, inadequate control over model maturity, and a lack of defined workflow for design, verification, validation, and acceptance, causing collaboration challenges.

Overall, there is a demand for a strategic vision and connected models that provide holistic solutions throughout the company, optimize local environments, and enable effective requirements management, verification, and validation.

4 Model Lifecycle Management for supporting collaborative Ontology-Based Engineering

The authors proposed in [22] how the MfM methodology, an OBE methodology, can be managed based on the MLM concept and how PLM tools offer the necessary functionalities to support OBE. As described above, the evolution of models follows a path like the one followed by 3D geometric models that were eventually managed from PLM [23]. Applying MfM methodology and MLM to the problems described in the previous section, practically most of them can be supported by the functionalities of an MLM. Solutions can be group following the main MLM functionalities:

- Vaulting: The need for visibility of existing models, their scope, and the solutions they provide. This would avoid the existence of redundant models and would help in the decision process of launching new projects knowing what has already been developed. It is also useful to detect which models are necessary and have not yet been developed (requirement models). The rationalization of existing models and the decisions of new ones to be developed will be supported by the visualization and queries necessary to filter them by different attributes such as scope or solutions they provide with respect to the existing ones.
- Configuration: Establish a procedure to manage model configuration. A procedure to manage the relationships between different models and to be able to detect which other models are affected by a change and evaluate the impact.
- Workflow: Model statuses and lifecycle management under workflows. Implement a procedure for managing model status (in-work, verified, validated, released, etc.).
- Visualization: Visualization of models and their properties (metadata). Definition of projects and access or operations for the different roles involved in the life cycle of a model, people, and organization.
- Interface: Models import and export capabilities to external modelers.

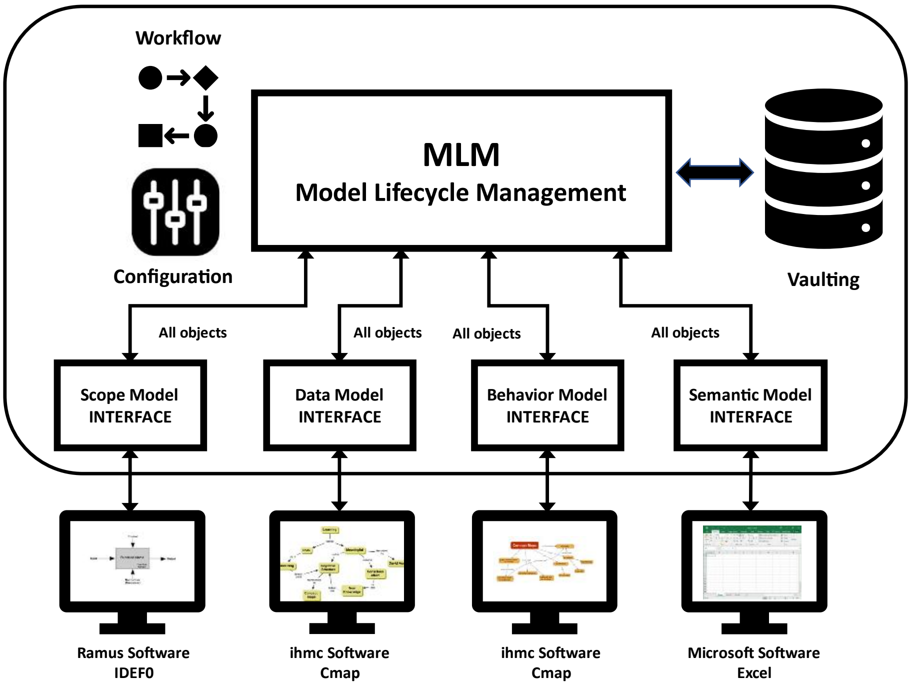

Fig. 3. First approach for MLM solution.

The proposed model is illustrated in Figure 3. The Scope model, which establishes the boundaries within which the model operates, is represented using IDEF0 diagrams and created using Ramus software. The subsequent stage involves creating the ontology through the Data model, which defines the information managed within the selected scope. Currently, concept maps are utilized for modeling the Data model, employing software tools such as CmapTools by IHMC or GraphViz. The Behavior model is being developed using a customized diagram type in the GraphViz software. This model specifies the simulation requirements for the company processes, as previously defined in the Scope model. Lastly, the Semantic model is being constructed in the form of spreadsheets using software such as Excel. The purpose of the Semantic Model is to prevent ambiguities in database usage, ensure consistency in connections with the models, and maintain continuity in the ontologies throughout their lifecycle.

The interfaces depicted in Figure 3 were specifically developed to interface with the modeler applications employed by the authors in their work on various industrial use cases [24-27]. The MLM system accommodates the objects originating from these modelers but encounters two significant challenges: (1) all the object information is required to pass through the interface; and (2) decoration information such as positions, colors, shapes, etc., is lost in the process. Among these challenges, the first issue is identified as the primary concern, as the passed object information often includes elements specific to the modeler application that are not part of the MfM model. Consequently, this limitation restricts the utilization of any modeler within the MLM environment. Efforts are thus focused on addressing this issue to ensure seamless integration and effective model management within the MLM framework.

To address this challenge, a comprehensive set of metamodels was developed to establish the specifications that any authoring tool within the MfM methodology must adhere to. These metamodels encompass all types of objects, properties, and relationships associated with the MfM model types (Scope, Data, Behaviour, and Semantic). Metamodels were implemented both in the interfaces us let translate just the required objects as in the MLM to adapt its capabilities to them. Consequently, MLM becomes capable of managing models created by various modelers operating under different methodologies. The revised scenario is illustrated in Figure 4, showcasing the interoperability and flexibility achieved through the integration of the metamodels into the MLM solution.

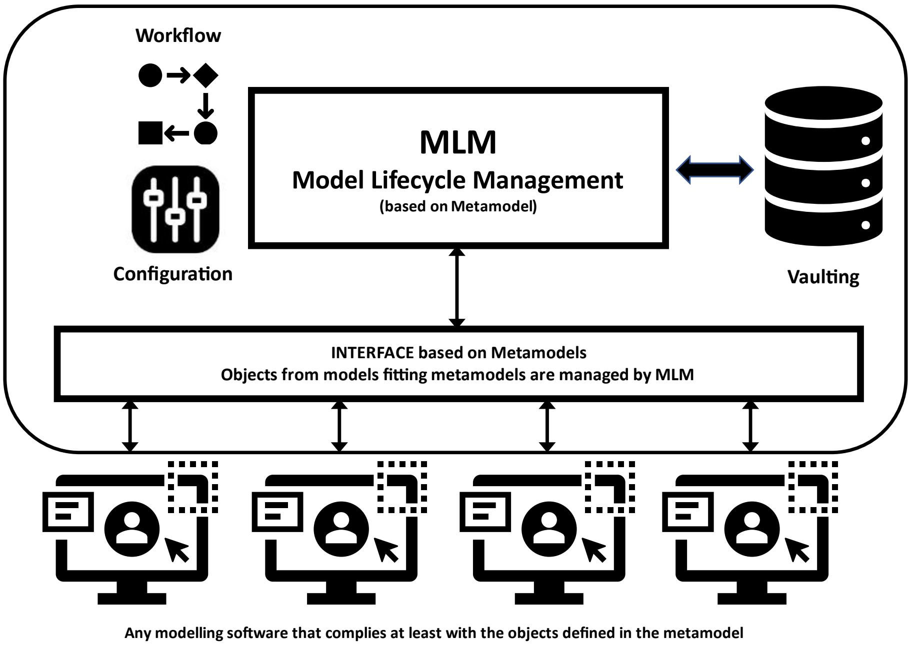

Fig. 4. New approach for MLM solution.

Furthermore, the proposed MLM solution incorporates several notable enhancements:

- Tool agnosticism: The MLM solution is designed to be tool-agnostic, without favoring any specific software. The authors advocate for the use of Free Open Source Software (FOSS) tools, which enable seamless reading, writing, understanding, sharing, and discussion of models among proficient engineers. This comprehensive toolset covers all aspects of modeling, from definition to simulation and trade-off processes, thereby facilitating the optimization of solutions.

- Enhanced Decision-making Environment: By providing a shared and common environment within the company, the MLM solution contributes to more informed decision-making processes. It helps align projects with the overarching company strategy, allowing for strategic decisions rather than relying solely relying on tactical considerations.
- Improved Reusability and Sharing: The MLM solution simplifies the process of reusing and sharing models within the organization by establishing clear and standardized definitions of various concepts or entities, along with their corresponding relationships. This promotes effective management of these entities and facilitates seamless collaboration among stakeholders.

The authors have introduced a prototype system architecture design and interfaces, which have been implemented using open-source software. This system serves as a collaborative PLM solution, specifically addressing the creation, management, enrichment, and reutilization of manufacturing models [20]. The efficacy of this approach has been validated through a preliminary study focused on Incremental Sheet Forming technology, specifically for the production of 3-axis Numerical Control (NC) machining metallic parts [27].

5 Conclusions and future research work

This paper elucidates the imperative for the aerospace industry to embrace a disruptive leap in order to effectively confront future challenges and achieve success with a positive outlook. The current disruptive approach, centered on the application of Modeling and Simulation and specifically Ontology-Based Engineering, has led to the identification of various challenges that must be addressed to ensure the successful implementation of this approach and its resilience in the future.

One crucial aspect in the successful adoption of OBE methodologies is the establishment of a robust model management system, which can be effectively addressed through MLM which encompasses key characteristics that offer potential solutions to many of the challenges faced by the aerospace industry in managing their models. The definition of metamodels, vital for accurate design and management of models, contributes to improved coordination and integration among stakeholders.

Furthermore, the ultimate validation of the concepts, along with the inclusion of open interfaces to facilitate interoperability with diverse modeling environments across different domains, remains contingent on real-world implementation within the aerospace industry. This implementation is anticipated to support the transformative leap, enabling earlier and more sustainable impacts in product design, industrial systems, and cost reduction throughout the product lifecycle.

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