Model-Based Enterprise Approach in the Product Lifecycle Management
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Definition

Innovations in product development and process technologies represent a promising strategy to face the increasing competitiveness of modern markets in the global economy. Also, customer requirements become more and more specific and the complexity of products is still increasing. Industries need to adopt effective solutions during the product development process and to support, for sustainable purposes, all the phases of the product lifecycle. Advanced model-based solutions emerge for digitally supporting these industrial needs. In this context, a Model-Based Enterprise (MBE) represents an organization that adopts modeling technologies, such as Model-Based Definition (MBD) solutions, to integrate and manage both technical and business processes related to product design, production, support, and retirement. Past research discusses the model-based approaches focusing on technical product development, mainly referring to the design and the manufacturing phases.

1. Introduction

To be competitive in the modern markets and in the global economy, where the complexity of products is still increasing, the industries need to adopt effective solutions during the product development process and to support, for sustainable purposes, all the phases of product lifecycle [1][2]. The customer requirements are becoming more and more specific and the market demand tends to be very dynamic and also unpredictable in such cases. On the other hand, industrial organizations address new forms of product development, including multidisciplinary, cooperation, and co-design. Traditional approaches limit and challenge the businesses and the execution of their development activities, affecting the management of the product lifecycle phases [3]. Low-cost manufacturing of high-quality products also remains an essential part of the current economy, and technological advances made it possible [4]. Many product development processes are no longer serial step-by-step processes and, moreover, the design and the engineering activities are generally a waterfall process where engineers work independently and in parallel. For all these reasons, it is critical to have a single definitive data source to ensure data accuracy, consistency and to better manage the product lifecycle [5]. Advanced model-based solutions, including both technologies and methodologies, emerge for supporting digitally the development of a product and all its lifecycle phases, and to create a digital representation of real business processes and products. The transition from traditional product development practices (e.g., the use of 2D drawings) to digital drivers based on product models represents a sustainable solution to: (i) optimize the product development process [6]; (ii) better manage the product lifecycle in the beginning-of-life, middle-of-life and end-of-life [7]; (iii) improve the communication between both technical and less-technical teams [8]; (iv) reduce the development time and costs and minimize the risk of non-compliance [9]. In particular, the paper faces the sustainability concept in relation to all the phases of the product lifecycle (e.g., sustainability-by-design, green manufacturing, and sustainable product disposal). The automotive and aerospace sectors are the first industries that have adopted these solutions. For example, Boeing took the lead in adopting MBD technology in the R&D (Research and Development) of Boeing 787 aircraft, achieving collaboration between the design and manufacturing partners [10]. In these contexts, the wide adoption of 3D models is common as the authoritative source of geometrical data. 2D drawings are still used (e.g., in manufacturing plants, technical documentation) but are directly generated from 3D models [11].

A Model-Based Enterprise (MBE) represents an organization that applies modeling and simulation technologies to integrate and manage all of its technical and business processes related to product design, production, support, and retirement [12]. By adopting product and process models for defining,
executing, controlling, and managing all the enterprise processes, and by applying science-based simulation and analysis tools to optimize processes at each step of the product lifecycle, it is possible to reduce the time and the cost of product innovation, development, production, and support \(^{[13]}\). It is expected that the configuration of a model-based enterprise could potentially reduce the costs by 50% and the time to market by 45% if compared with common traditional practices \(^{[9]}\).

A key component of the MBE approach is represented by the Model-Based Definition (MBD) \(^{[14]}\) defined as the practice of using 3D CAD (Computer-Aided Design) models to mathematically describe the product or component specifications, including Product Manufacturing Information (PMI), annotations and other technical attributes \(^{[15]}\). The MBD is a part of a new strategy of product lifecycle management based on CAD models transition from simple gatherers of geometrical data to comprehensive sources of information for the overall product lifecycle \(^{[11]}\). A direct consequence of this shift is represented by the evolution of both businesses and computer-aided tools because of the usage of annotated 3D models that serve as the single source for all technical product information, also eliminating the need for 2D engineering drawings. Until recently, most engineering and manufacturing activities relied on hardcopy and/or digital documents to transfer engineering data and to lead the manufacturing processes \(^{[3]}\). Conversely, by enabling an integrated and collaborative environment based on 3D product definition details that are shared across the enterprise, a rapid, seamless, and affordable deployment of the product is ensured from concept to disposal. While the MBD has been gaining popularity in engineering and manufacturing environments, several questions remain unsolved regarding the full definition of MBD models. Standards such as ASME Y14.41 and ISO 16792 exist to document how a model should be defined with annotations. These standards also help in understanding how to interpret the data within the model. However, they do not document the required amount of information that the model must contain. It is important to understand what information needs to be communicated when considering moving from 2D drawings to 3D CAD models, so that engineers can efficiently perform their tasks \(^{[8]}\).

Furthermore, the management of product information is a key activity that interests both technologies and methodologies and that affects all the lifecycle phases (i.e., plan, design, build, support, dispose) \(^{[16]}\). The adoption of MBE practices is becoming a reality in industry, as highlighted by the increasing number of companies that are moving towards model-based environments \(^{[14]}\).

In this context, this research aims to investigate the relationships of model-based enterprise approaches, including model-based definition practices, with all phases of the product lifecycle. In particular, the focus is on understanding how MBE and MBD support, benefit, and challenge the organizations during the lifecycle phases. Previous research faces these topics mainly for the management of product information during the technical development activities such as the design phase \(^{[17][18][19][20]}\) and the manufacturing phase \(^{[3][20][21]}\). These links appear much aligned with the concept of PDM (Product Data Management) that includes systems for the handling of data throughout the whole design, engineering, and development process, also considering the control of workflows \(^{[22]}\). An interesting wide perspective from the side of the other phases of the product lifecycle seems to lack in the literature and this research wants to confirm or reject this statement. For this reason, the study analyzes the relationships between model-based enterprise approaches and the other phases of Product Lifecycle Management (PLM), crossing the boundaries of PDM.

### 2. Papers Evaluation Phase

Before introducing the results of the study on MBE and MBD solutions, it is important to provide a concise definition of each phase of the product lifecycle to understand the related sub-activities and link the potential of model-based approaches. Considering the study of Grieves \(^{[23]}\), the product lifecycle is composed of five main phases:

- **Plan**: the product model starts from the requirements analysis which is the first step in the development process. The requirements come either directly from the customer or indirectly from marketing, which analyses market needs;
• Design: starting from the requirements, the concept, and, subsequently, the prototype of the product is
developed. Different alternative prototype options can be implemented that meet the same
requirements with different functions and technologies;

• Build: when the product is completely defined, manufacturing determines how to build it. Different
issues are considered depending on whether or not there is a suitable plant or machinery to make the
product in question;

• Support: maintenance, sales, and distribution functions use product information to demonstrate product
features and characteristics to the customers, and to understand whether they can meet their needs;

• Dispose: retirement, disposal, and recycling concepts close the product life cycle and product
information is necessary for these activities to be carried out efficiently.

Considering that the research aims to investigate the relationship between the model-based enterprise
(and therefore model-based definition) approach and product lifecycle management, two macro-areas of
analysis are considered: (1) the role of MBE/MBD in relation to product lifecycle and (2) the benefits and
challenges of using MBD technology in relation to the PLM. These macro-areas are detailed below.

2.1. The Role of MBE/MBD in Relation to the Product Lifecycle

2.1.1. MBE/MBD in the Entire Lifecycle

Some of the 19 selected papers address the issue of data management through MBD models in relation to
the whole product lifecycle.

In particular, the survey conducted by Ruemler et al. on the use of MBD in the industry shows an
interest in the use of this technology, but also a difficulty in its adoption due to the lack of a single source
for managing data and information across workflows.

Adamenko, Pluhnau and Nagarajah and Pippenger state that manufacturing companies should
evolve from document-centered data and information management to an MBD approach so that all
relevant information for each product lifecycle phase is obtained from a single source, eliminating the
need for many models, protocols, and redundant documentation. This prevents important data and
information from being lost along the different phases of the product life cycle. Using the MBD approach,
the necessary information and data are properly stored in CAD files, in annotated form, according to the
process and product lifecycle phases considered. In this way, the geometry of the product part can be
simplified according to its role, process, and function thus simplifying data management, ensuring the
data exchange across and inside the company, and protecting its know-how.

Hartman, Rosche, and Fischer differentiate the type of CAD files to be used in the following formats:
native CAD formats, derivative data formats, lightweight collaborative files, and neutral files. This
distinction is important because the product representations used across the lifecycle change with
respect to the desired functionality at each stage, and the exclusive use of one class of representation
over another could limit the flexibility of design tools. On the other hand, one of the basic principles for
product lifecycle management and model-based enterprise is that movements and transfers of
information throughout the enterprise to enable effective decision-making can be accomplished by a
high-fidelity digital product representation.

In this regard, the work of Rinos et al. aims to eliminate counterproductive data formats used in
industry (e.g., those based on 2D drawings) to optimize collaboration between different company
departments. For this reason, they propose a method that uses an MBD 3D PDF-based template to create
a document in a lightweight data format that contains the necessary information for all product lifecycle
processes.
In line with this view, Briggs et al. [27] highlight the need for a transition from production based on 2D drawings to one in which all stages depend on model-based definition data. This transition can enable integration between the tools and related MBD outputs of one organization’s engineering and those of other organizations. To this end, it is important to make product definition data and MBD accessible, viewable, and usable by users at all stages of the product lifecycle.

Yang et al. [2] state that the quality of the MBD model plays a key role in achieving model-based enterprise. In particular, they promote the use of flexible tools and standards to avoid misunderstandings between the stakeholders involved in the use of these models at different phases along the product lifecycle. If inconsistencies arise in product data and MBD models, the result could be increased production costs, an extended production cycle, and failure to achieve MBE.

From the research conducted by Wardhani et al. [28] and Trainer et al. [29], it is possible to recognize that there are gaps in standards, as well as in tools, that do not allow the MBD implementation and therefore the industry progress towards MBE. In particular, they focus on the STEP (Standard for Exchange of Product Model Data) AP242 standard and discuss the possibility of fully defining product data in the product lifecycle and enabling collaboration between different CAD systems. However, issues related to the different proprietary data formats are highlighted; the current MBD approach still does not support the storage of the information needed in the different stages of the product lifecycle [28].

Similarly, Hedberg et al. [30] argue that standards-based information integration is not feasible today. In fact, their research, which aims to test the ability of consensus-based data standards to integrate product lifecycle stages through the implementation of a small model-based enterprise, shows that popular data standards used in the industry do not support automatic data alignment without significant human intervention.

On the other hand, Goher, Shehab, and Al-Ashaab [31] believe that issues in MBD development and implementation can be divided into three macro-categories: (1) technical issues (such as knowledge of product definition elements and information flow, and use of standards); (2) management issues (in terms of changing from conventional drawings to MBD models); and (3) certification issues (i.e., design data should have the characteristics for maintaining availability, accessibility, integrity, quality and security throughout the product life cycle).

Furthermore, Alemanni, Destefanis, and Vezzetti [31] claim that companies often lack a comprehensive strategy and appropriate methods to support the development of MBD. Therefore, they propose a unified and objective approach based on the QFD (Quality Function Deployment) model to define the MBD. This is a common methodology to structure data into reusable and unified forms within 3D models at all product lifecycle phases.

Finally, Zhang et al. [10] state that MBD-based integrated data management is a key technology to enable model-driven dynamic synchronization of activities involved in the production of complicated and customized products (C&CP). This technology achieves efficient collaboration between different business activities, because the MBD dataset can fully describe both geometric and non-geometric information related to different parts of the product, preserving data consistency and connectivity during its lifecycle.

### 2.1.2. MBE/MBD in the Design Phase

Other analyzed papers focus on the importance of introducing MBD practices for enhancing the design phase of the product lifecycle.

In particular, to improve the design efficiency, Huang et al. [17] propose a 3D process design method based on MBD technology that aims to provide a theoretical basis for the realization of the 3D process design of complex systems. This method overcomes the difficulties related to: (i) the heterogeneity of data sources in the design phase; (ii) the non-uniformity of information between different company
departments; (iii) the redundancy of data throughout the design and production process.

MBD technology renders technical information in a three-dimensional environment, creating an MBD dataset that can fully describe the product [18]. For this reason, Yang et al. [18] propose the MBD attributes method, in which MBD attribute models are created by combining the various MBD attributes associated with different product types. In this way, the designer can directly select the attribute values, thus reducing his workload and improving the integrity and accuracy of the MBD dataset and consequently also the design process.

Duan, Shen, and Liu [19] also believe that introducing MBD in the design phase could bring valuable benefits to the company. In particular, the authors focus on the design part inherent in component assembly and investigate a solution to facilitate the MBD integration in relative position accuracy (RPA) measurement in order to make the products’ parts or components compliant with the design specifications.

Finally, Zhu et al. [20] focus on the implementation of MBD technology in advanced design. Specifically, they state that the MBD design model should be characterized by three main entities, such as: the definition of the design model for each part of the product; the use of 3D annotations; and the explication of product attributes.

### 2.1.3. MBE/MBD in the Build Phase

Some of the analyzed papers address the adoption of the MBD model for supporting the manufacturing (or building) phase of the product lifecycle.

In particular, Liu, Duan, and Liu [32] state that MBD model-based inspection plays an important role in manufacturing processes because the information can be integrated into the 3D model providing a unified product definition. Therefore, they propose a concept of integrated model-based inspection to promote the integration of design and manufacturing and to improve manufacturing efficiency and quality control capability.

Likewise, Hedberg et al. [3] state that to realize the vision of MBE, a single “digital thread” must be created. The digital thread would enable real-time design and analysis, collaborative process flow development, automated artifact creation, and full process traceability in a seamless real-time collaborative development between stakeholders. To achieve this goal, the authors emphasize the importance of filling the lack of standards for defining PMI (Product Manufacturing Information) so that data can be interpreted and presented consistently by different engineering and manufacturing operations.

On the other hand, Adamenko, Pluhnau, and Nagarajah [21] state that many manufacturing processes are still centered around documents or drawings. Moreover, organizations often use the same drawings for as many departments as possible in order to avoid redundant models in PLM systems. The negative effects of this trend are several: (i) drawings are overloaded with information; (ii) manufacturing models contain information that is not needed for that process; and (iii) manufacturing engineers must spend additional time finding the information they need.

Finally, the study conducted by Zhu et al. [20] focuses on the MBD technology implementation in complex manufacturing systems as a new form of collaboration. The authors state that it is necessary to create an MBD process model and not rely only on the MBD model of the design phase. In fact, the MBD design model does not consider intermediate manufacturing states of parts, but only provides process information. Therefore, an integration of both the design and manufacturing systems is required to efficiently use MBD technology.

### 2.2. Benefits and Challenges of Using MBD Technology in Relation to PLM
This section aims to gather the benefits and challenges that emerged from the literature study, regarding the use of MBD technology in relation to PLM.

According to [17][19], the use of MBD technology in design and manufacturing processes has improved data integration and made the workload associated with design, manufacturing, and assembly personnel efficient, thus contributing to improved process performance.

Moreover, Zhang et al. [10] and Yang et al. [18] state that product lifecycle management can be improved in terms of data consistency and connectivity through the implementation of MBD-based 3D design. MBD-based 3D design technology uses the MBD as a single data source by defining 3D design information, 3D manufacturing information, and product management information in the 3D digital model of the product. Therefore, the MBD can be adopted across the entire product demand model (design, process, manufacturing, and service model) to support the coordination of the product tooling, manufacturing, assembly, and maintenance process by setting the product design parameter and breaking down the barriers between design, manufacturing and operation and maintenance information.

On the other hand, Ruemler et al. [8] and Alemanni, Destefanis, and Vezzetti [11] argue that model-based definition is a strategy to move from two-dimensional (2D) paper drawings to three-dimensional (3D) computer-aided design (CAD) models, where the model contains all the information so that drawings may no longer be needed. This results in shorter time-to-market, more efficient processes, and better product quality. Product models are also crucial to achieve interoperability between applications, people, and companies, as well as data exchange. However, the same authors claim that MBD development today mainly concerns data structures that need to be in reusable forms and unified within native three-dimensional CAD models. For this reason, it will be necessary to propose a global strategy and appropriate methods to support MBD development and define new standards and common practices to create a common language for modeling and data management.

The study conducted by Hedberg et al. [3] on the comparison of model-based versus design-based processes found that model-based processes result in a cycle time reduction of 74.8% compared to design-based processes; however, both present challenges related to the fulfillment of the design and manufacturing phases of the product life cycle.

According to Pippenger [24], moving to a full MBD environment raises a number of challenges regarding data accessibility and visualization, data content, data presentation, data management, data security, and data retention.

Furthermore, to integrate the concept of model-based enterprise into the industrial world, the MBE strategy has to ensure interoperability of model-based data from the design and manufacturing stages through to the support stage in the supply chain [29]. However, several barriers to the interoperability of model-based data have been identified [29]. In particular, the two-dimensional (2D) drawing is considered the legal record of master data compared to the three-dimensional (3D) model; moreover, in the context of automation, many application programming interfaces do not adequately support the reading and writing of standards-based Product Manufacturing Information. Finally, easy data exchange through standards-based implementations threatens to disrupt the business model of major product lifecycle management tools.

In general, a robust MBE inherently depends on the easiness of data transformation, which is significantly enhanced by the collaborative capabilities of the modeling tools used to create data and the standards used to exchange that data. In fact, the application of appropriated standards ensures that data flows seamlessly throughout the product lifecycle and allows for the reuse of data in the most appropriate formats for collaboration and visualization [25].

Table 1 summarizes the most significant benefits and challenges that emerged from the literature study regarding the use of MBD technology in relation to PLM. These benefits and challenges are listed in no
particular order of priority and are aggregated for the different research papers analyzed.

**Table 1.** Benefits and challenges of MBD technology related to PLM.

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Challenges</th>
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<tbody>
<tr>
<td>- Cycle time reduction of 74.8% compared to design-based processes [3]</td>
<td>- Need for a comprehensive strategy and appropriate methods to support the development of MBD [8][11]</td>
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<tr>
<td>- Improved data consistency and connectivity [10][18]</td>
<td>- Definition of new standards and common practices to create a common language for modeling and data management [8][11][25]</td>
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<tr>
<td>- Supporting the coordination of product tooling, manufacturing, assembly, and maintenance processes [10][18]</td>
<td>- Data accessibility and visualization, data content, data presentation, data management, data security, and data retention [24]</td>
</tr>
<tr>
<td>- Improved process performance [8][11][17][19]</td>
<td>- Interoperability of model-based data from the design and manufacturing stages through to the support stage in the supply chain [29]</td>
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<tr>
<td>- Shorter time-to-market [8][11]</td>
<td>- Interoperability between applications, people, and companies [8][11]</td>
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<td>- Better product quality [8][11]</td>
<td>- Efficiency in the workload associated with design, manufacturing, and assembly personnel [17][19]</td>
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**References**

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Keywords
model-based enterprise; model-based definition; product lifecycle management; manufacturing; systematic literature review

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