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Abstract. Nowadays the organizations want to be flexible and responsive to the market changes and to keep up with technologies, optimizing the time and cost of products life cycle. The product development process has become increasingly dynamic and complex, also requiring the collaboration among business partners. For this reason, companies need to create a robust interoperability between disciplines and departments. Traditional engineering practices, processes, tools and mindset should evolve to use a single definitive data source to ensure accuracy and consistency of data throughout the product lifecycle and to enable rapid and cost-effective distribution of product information from upstream to downstream. In this context, the Model Based Enterprise (MBE) represents a fully integrated and collaborative environment that embraces feedback from the various stages of the product lifecycle improving the model representation. The key component of this approach is the concept of Model-Based Definition (MBD). There are several barriers to the implementation and adoption of model-based approaches within the companies, although this does not limit its adoption at different levels.
The concepts of Model Based Enterprise and Model Based Definition are analysed in order to clarify their relationship with the product lifecycle management and to identify existing maturity models. The objective of the paper is to evaluate the maturity of MBE applications. Following a theoretical approach, the Core-MBE framework is developed as an innovative tool for assessing the level of maturity of organizations in a model-based transformation process. Two manufacturing case studies (an aerospace company and a mechanical carpentry SME) were carried out to validate the proposed framework.

Keywords: Model Based Definition, Model Based Enterprise, Maturity Model, Product Lifecycle Management, Manufacturing.

1 Introduction

We live in the era of digitization [1] in which the product development is becoming increasingly complex and dynamic. Furthermore, respect to traditional business environments, it is required new forms of collaboration and synergies. Therefore, traditional engineering practices, processes, tools, and mindsets need to evolve not only to address this complexity but also to capitalize on it.

Nowadays, the product design process is generally carried out by many engineers who work independently and in parallel in a waterfall of design and manufacturing efforts. So, most product development is no longer a serial, step-by-step process [2]. Product development collaboration is time consuming and costly; demanding that engineers employ clever methods to achieve a collaborative design process that gains time.

With these premises, it is fundamental to use a single definitive data source to ensure data accuracy and consistency as product moves through the lifecycle [2]. In this manner, manufacturers can transition to “high value” production and compete on a basis of productivity and excellence as opposed to low-cost labor sources [3]. This main concept gave rise to the paradigm of the Model Based Enterprise (MBE). MBE is seen as a fully integrated and collaborative environment based on 3D product definition details and shared across the enterprise with the intention of enabling rapid, seamless, and affordable deployment of products from concept to disposal. The key component of this approach is the product definition, called "Model-Based Definition" (MBD) [4].

Until recently, most engineering and manufacturing activities relied on hardcopy and/or digital documents, including 2D drawings, to convey engineering data and to lead the manufacturing processes [1]. Nowadays, advanced model-based technologies and methodologies are emerging to support digitalization by creating digital representations of real business processes and products [2]. Model-based enterprise concepts can only provide point solutions without wider coordination. The realization of the model-based enterprise could potentially cut costs by 50% and reduce time to market by 45% if compared with previously used conventional practices [3]. A critical issue resides in the difficulty in formally establishing the exact procedures, the associated implementation costs and the practical steps that can lead companies to these savings. Many barriers exist in the adoption of model based approaches, from technological, resources and capabilities needs, to organizational structure and standardization [5]. Also, organizations still have difficulty in understanding what MBD is and confusing it with the MBE. In addition, to use these innovative technologies, companies need to have from a medium to high level of management, as well as of standardization policy and training sessions for the internal staff. On the other hand, employee training and software licenses imply some costs and the inherent complexity of 3D-based processes are often listed as reasons that small and medium-sized manufacturers (i.e., automotive and aerospace suppliers) do not adopt or implement MBD technologies and processes [4], [6]. Nevertheless, the adoption of MBE practices is becoming a reality in industry, as evidenced by the increasing number of companies that are moving to model-based environments [6].

Starting from this scenario and considering the most important drivers and issues, the concept of Model Based Enterprise, and consequently that of Model Based Definition, will be analysed in order to first support industrial organizations in distinguishing them. After building a knowledge base of reference, it will be possible to clarify the relationship that these topics have with the concept of product lifecycle management. In addition, it will be investigated the presence of existing maturity models to assess the readiness of organizations in the adoption of model-based approaches. Consistently, the paper focuses on evaluating the maturity of MBE application. Finally, an original maturity model will be proposed with the aim to assess in a comprehensive framework the maturity level of MBE within organizations.

The following sections provide an overview about the state of the art on the topic of MBE and related existing maturity models. Then, the Core-MBE maturity model will be presented and applied in some industrial contexts. Finally, practical considerations, including limitations and further potential research actions will be discussed.

2 Theoretical Background

2.1 MBE Definition

Technical drawings have played a fundamental role in man’s progress from the time of the ancient pyramids and the classical Parthenon to the geodesic domes and Skylabs of today [7]. Engineering drawing is considered a graphic universal language that can be traced back to prehistoric times. Although it is believed that formal and systematic engineering graphics began with an academic book by French mathematician Gaspard Monge in 1795 [8]. Historically, drawings were used in industry to clearly communicate information about the product definition because of the tools used in the design and manufacturing environments. Therefore, they represented the most effective way of explaining to someone what to do and how to do it, on the basis of the design tools available at the time [4], [7]. The fundamental purpose of an engineering drawing was to design, control and maintain a product’s definition in a precise and clear way with no risk of misinterpretation or assumption. And also, to communicate complexity in a comprehensible and effective manner. Later, drawings gave way to 2D Computer Aided Design (CAD) systems, even if the preliminary outputs were still paper-based artifacts. Even though CAD tools facilitated the design process and enabled engineering drawings to be generated faster and more accurately, 2D CAD was still nothing more than an electronic drafting board. But over time, drawings became more sophisticated in their information content and their representation of the object in analysis, requiring to readers a contextual understanding to make sense of that information. This level of needed contextual understanding is typically dependent upon the reader of drawing tasks in his workflow. So, the 2D drawings started to become more difficult to read than a 3D model [9].

A turning point was represented by the introduction, at the beginning of the 1970s, of the first commercial 3D CAD packages. By the early 80's these were widely available in the market but still expensive, restricting their use to large industries such as aerospace and automotive [9]. Indeed, since the 1980s, occurred the advent of solid modelling and specialized drafting software packages, which have contributed significantly to streamlining the production of engineering drawings.

As solid modelling has evolved, several analysis systems have been created to analyze more precisely how a designer would design and manufacture products. This because more complex shape definitions for increasingly complex products is able to be captured. The 3D definition of geometry has become reality and engineers can easily construct the solids through mathematical models with computer software and display them on the screen. However, the 3D model lacks some needed requirements such as the annotations. While being able to capture complex shape, 3D models typically did not effectively capture information for manufacturing as well, that is did not incorporate the behavioral and contextual information. The variety of information historically found on a drawing is often missing from 3D CAD models due to the software's inability to completely capture behavioral and contextual information.

Due to the absence of relative 3D definition standards, the 3D model played an assistant role to the 2D drawing until the emergence of MBD (Model Based Definition) technology. MBD changed not only the product definition but also the whole design process. This is because MBD technology can contain much more information than a drawing and many companies choose to make annotated 3D models a key component for communication within their company [4], [7], [8]. The model-based definition should be rich in information, providing input to the various consumers who need it [4], including new functionalities to manage, incorporate and show the necessary information of products directly in the 3D model [10] and avoiding the risks of data errors and ambiguities during the transition from drawings to 3D models [11].

In addition, now there is much discussion about which information elements have to be included in these models in order to support the extended enterprise not only in the engineering field. In this context, the concept of Model-Based Enterprise (MBE) was born. Another main motivation for achieving MBE is the increasing competition in the global market [12]. In fact, in a highly competitive globalized market, the transition towards a MBE model represents a significant opportunity for increasing efficiency in product development.

A model-based enterprise can be conceptualized in an environment where the model serves as a dynamic artifact used by the various authors and consumers of information for their respective tasks. The MBE embraces feedback from the various lifecycle stages to improve the model representation for the creation of subsequent products and product iterations [4]. Just as people in the past used drawings in their job functions throughout the product lifecycle, today people are beginning to use a model-based definition in their job functions inside engineering, manufacturing, supplier management and other areas of the organization.

However, there is much debate about what information elements to include to support the extended enterprise outside of the engineering function. Considering that not all the stakeholders need the same information to perform their work, the model often needs to be translated into a different form that show different amounts of information. This issue did not typically exist when drawings were used because that could seamlessly pass from one person to another. Therefore, the evolution of MBD towards the replacement of two-dimensional drawings has created a need to understand the minimum amount of information required in specific workflows so as not to inadvertently expose intellectual property or to unintentionally increase model complexity. Since the necessity to ensure that the information required for specific workflows could promotes effective communication, the use of models poses some challenges with model-based software compatibility and information complexity.

2.2 MBE Maturity Model

Organizations are constantly called to obtain and retain competitive advantage, invent, and reinvent new products and services, reduce costs, and time to market, and enhance quality at the same time [13]. Maturity models have been developed to help decision-makers to balance these sometimes-divergent objectives in a more or less comprehensive way, and thereby assist organizations in this endeavor [14]. Indeed, maturity models are also designed to assess the maturity (i.e., competence, capability, sophistication level) of a selected area based on a specific topic and on a more or less complete set of criteria. They are used as an evaluative and/or comparative tool to increase the maturity level of a specific area within an organization and to determine whether effectively this key area has been implemented [14], [15].

The term maturity can be defined as the state of being complete, perfect, or ready, fullness of development [16]. If the term is applied to a person it might refer to the state of being physically, emotionally, and mentally mature. Indeed, personal maturity can be defined in terms of a person's experience, wisdom, independence, willingness, and ability to take responsibility, to work towards achieving the goals, to be serious and emotionally stable. In the same way, organizational maturity can be seen underlying the state of perfection of an organization. When an organization is maturing it means that its performance is improving, and consequently it is becoming more productive and effective, more competitive, and profitable [16]. So, maturity implies an evolutionary progress in the demonstration of a specific ability or in the achieving a target from an initial to a desired or normally occurring end stage [13].

Hence, a maturity model is a structured set of elements that describes and determines an evolutionary path of improvement from immature processes to mature, effective and qualitatively better processes. Thus, maturity models are adopted to assess the status of a company, or its specific area, according to one of the specified conditions to obtain useful information regarding the starting point for process improvement in existing organizations [17].

In addition, concerning maturity assessment models in the literature, the term "maturity" is in most cases perceived in a one-dimensional way, focusing on [13]:

1. process maturity: how much a specific process is explicitly defined, managed, measured, controlled, and effective.
2. object maturity: how much a particular object like a software product, a machine or similar reaches a predefined level of sophistication.
3. people capability: to which extent the workforce can enable knowledge creation and enhance proficiency.

The contexts where all these three elements under examination register an improvement of their maturity level can therefore be seen as ideal cases [13]. In other cases, specific actions can be implemented to assess and then improve the maturity of some specific dimensions.

According to [18], maturity models have the following properties: i) the development of a single entity is simplified and described with a limited number of maturity levels; ii) levels are characterized by certain requirements, which the entity has to achieve on that level; iii) levels are ordered sequentially, from an initial level up to an ending level; iv) during development, the entity progresses forward from one level to the next.

A maturity model is used to define a set of levels or stages, which describe the development of the examined item in a simplified mode using the properties just described.

Furthermore, regarding the practical application and the methodological purpose, maturity models can be categorized according to the objective for which they are designed [19]:

- Descriptive: the maturity model is applied for the as-is assessment.
- Prescriptive: the model indicates how to identify desirable maturity levels and provides a guide on how to implement improvement measures.
- Comparative: the model allows companies to compare themselves with other companies and also to learn from their experiences.

Once having defined what a maturity model is and what it is used for, the next step is to search whether maturity models exist in the literature relating the field of MBE.

The origins of maturity models lie in the software industry for improving its process maturity and, over time, they spread to many other areas [17]. One of the most important framework used in the assessment of process maturity is the so-called Capability Maturity Model Integration (CMMI) developed by the Software Engineering Institute (SEI) [20]. It inspired the conceptualization of other important framework: the EAMM (Enterprise Architecture Maturity Model) provided by the National Association of State Chief Information Officers (NASCIO) for assessing enterprise architectures and information technology infrastructure [21]; the RACE (Readiness Assessment for Concurrent Engineering) method proposed by the Concurrent Engineering Research Center (CERC) to assess the performance of product development process form the concurrent engineering viewpoint [22]; the BPM (Business Process Maturity) model [23] for enabling the identification and assessment of the maturity of business process policies and practices within organizations; the PMMM (Project Management Maturity Model) created for improving the management of business projects [24].

Concerning the assessment of the maturity level of the model-based enterprise, a relevant contribution is provided by the National Institute of Standards and Technology (NIST) [25] that, in collaboration with the US Department of Defense, developed the "MBE Capability Index Assessment Tool" [26]. It is a tool designed to help in assessing the capability level of an organization implementing MBE practices and methods in the following areas [27]: design activities, change management and data management activities, manufacturing planning activities, quality requirements and planning activities, miscellaneous enterprise activities.

The purpose of the model was defined as the development of a tool to calculate the MBE maturity level of organizations in the industrial sector that want to understand what they can improve. In these terms, the model provides a descriptive picture of the organization allowing for the as-is scenario assessment. The model is structured in seven maturity levels ranging from L0 to L6, in particular: L0 drawing centric – no connection to any models; L1 model centric – drawing derived from model but disconnected; L2 model centric – model managed with drawing; L3 model based definition – model contains some PMI (Product and Manufacturing Information) and drawing is supplemental; L4 model based definition – model contains complete product definition in PMI; L5 model based enterprise – model is used in some non-traditional activities; L6 model based enterprise – model drive all associated activities.

The study of the NIST's model allowed the understanding of the level of detail to structure an original maturity model, including the business areas to assess, the maturity levels and the categorization of these levels. Moreover, concepts related to clarity, comprehensiveness and easy-of-use are considered to facilitate its deployment. The following section presents the proposed maturity model: the Core-MBE maturity model.

3 The Core-MBE Maturity Model

Both models are designed for descriptive purposes by allowing the maturity of the company's as-is scenario to be assessed, but they can also be adopted for prescriptive purposes to assess the target to-be score

The development of the Core-MBE maturity model has been driven considering the methodologies for a maturity model development suggested by [14] and [19]. In this way both the structure and the content of the model improve in terms of methodological reliability and robustness. Moreover, the Core-MBE maturity model is inspired by the model provided by NIST in order to create an easier-to-read guide for companies to use it effectively. For instance, both models have been designed for descriptive purposes and to take a picture of the as-is status of a company. But the Core-MBE maturity model has been provided to also be adopted for prescriptive purposes in order to asses some targets to reach in a desired to-be scenario. Moreover, it was born from an integration of knowledge referenced on existing maturity models, comprehensive methodologies and design principles. All of these elements contribute to shape the innovativeness of the Core-MBE maturity model.

The Core-MBE framework consists in the maturity model itself and a complementary structured questionnaire useful to collect data from the applicative scenario. The maturity model is composed by four levels of maturity that can exclusively represent the status of an organization. These levels are sequential and a gradual improvement from a level to the next one is usually expected. Incremental improvement actions, rather than disruptive changes or breakthrough impacts, can ensure more easily a maturity improvement in a specific area selected by an organization.

The four maturity levels are:

- Level 0: Drawing Centric
  The design and manufacturing processes of the organization rely on traditional 2D drawing and depend on skills and experiences of people. There is no use of 3D models. The Bill of Materials (BoMs) – both engineering BoM (EBoM) and manufacturing BoM (MBoM) – are not linked with any CAD tools. Engineering analysis and calculations are based on manual and ad-hoc methods, as well as the transmission of product information among activities or departments. Model or drawing data are manually created, modified and sent to external partners or suppliers. The organization is not aware of the potential value it could achieve

by using 3D models and consequently does not intend to invest in such technologies.

- Level 1: Model Centric
  The organization begins to use 3D models. The drawing is still the master practice, but both drawings and models are managed together. The EBoM and MBoM are integrated and connected with CAD models. Some forward enterprises reuse and exchange CAD data in collaboration in their ecosystem. Companies begin to realize the potential value of using 3D models and are interested in investing in these technologies.
- Level 2: Model Based Definition
  The organization reaches an important level of maturity where the model can contain the comprehensive PMI and drawings are no longer used. 3D CAD models with annotations is the main source of the product definition. In some cases, supplementary drawing still exists to capture information that is not available in the model. Technologies are well integrated within departments but may not be globally. In addition, the company has an optimal degree of governance of the 3D models.
- Level 3: Model Based Enterprise
  The 3D CAD model with annotations is the master of the product definition, and represent the only source of truth for the all internal tasks, including decision making activities. The organization is configured as an extended enterprise that is seamlessly connected both within as outside its boundaries, involving all the partners and stakeholders of its supply chain. Drawings no longer exist and up-to-date view of the product definition is shared commonly in accordance with access rights.

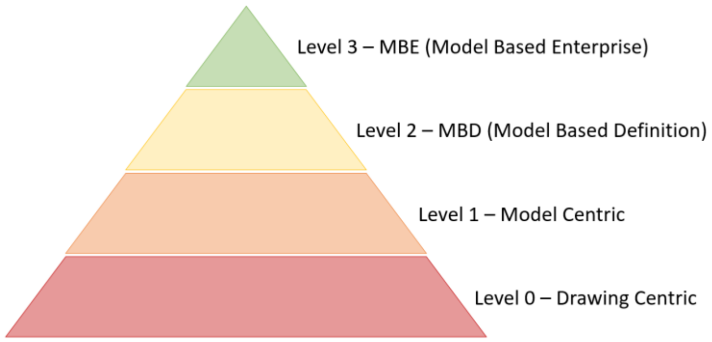

Fig. 1. Maturity levels of Core-MBE maturity model.

The maturity model has been defined in relation to the specific target objectives for industrial realities referring to the already existing maturity models. In this way, it is possible to detail and refine the contents under examination and to make the model easy to use respect to already existing models.

The second component of the Core-MBE framework is the questionnaire. It has been developed to collect useful data for the model application and the maturity evaluation. The questionnaire can be submitted online or offline, since it is detailed in all parts, including sections, questions and answers modalities. As for the NIST's maturity model, the Core-MBE maturity model focuses on some specific topic to investigate within organizations. The questionnaire is intended to help organizations to measure their current level of MBE maturity, based on how the company implements: design processes, change and configuration management practices, data management process, production planning, quality and inspection activities, collaboration and data exchange.

Firstly, the questionnaire is structured with a brief description of the topic (i.e. MBD ad MBE approaches), including the scope and the composition and the description of the maturity levels. Then, a preliminary section (interviewee data) is designed to gather information about the company and the interviewees. This data will not influence the maturity of the organization. Basically, the questionnaire should be completed by professional figures who know how the design and production processes, including the relative data, are managed within the company.

Following, six sections are designed to investigate specific topics:

- Design data – This section mainly explores how the company documents product information and how it manages design data, annotations, and BoMs.
- Technical data packages – They are a set of electronic files (e.g. 3D models, annotations and PMI, BoMs) created to describe a product or item in a way that is appropriate for transferring information into purchasing, production, engineering, and logistics support activities.
- Change and configuration management data – The focus is to investigate how the company manage and control the change and configuration management processes, including relative data and documents.
- Manufacturing data and planning activities – It aims to explore manufacturing operations and planning activities and how data are transferred from engineering to manufacturing areas.
- Quality and inspection activities – This section explores how manufacturing verification, part inspection and product acceptance activities are managed.
- Collaboration and data exchange – It is investigated how and whether the company collaborates and exchange data with partners and stakeholders.

The all sections aim to gather information about the specific business activities that can be encompassed for the evaluation of MBD and MBE approaches are. 33 structured closed-ended questions have been defined in order to have exclusive answers. Each question can have a different number of answers. To each answer a corresponding ascending maturity level is assigned on the basis of the maturity status. To facilitate the evaluation of the maturity of the organization, an appropriate matrix scheme has been designed. In addition, there are some questions that also have the answer "other". These are included to give interviewees the possibility to add additional information to better detail his company status. Furthermore, a final section "notes" allows for suggesting some improvement actions of the questionnaire such as missing elements to consider.

Based on the collected answer, the maturity level is calculated. A score is assigned for each answer: Level 0: 1 pt.; Level 1: 2 pt.; Level 2: 3 pt.; Level 3: 4 pt. Once the score has been assigned to all 33 questions, it can be calculated the average of each section in order to be independent in terms of number of questions in each section. The final score can be obtained by averaging the partial results of the all sections and converting it in percentage in order to establish the maturity level at which the company belongs. In particular, the ranges of each maturity level can be expressed as follow: Level 0 (Drawing Centric) - from 0% to 25%; Level 1 (Model Centric) - from 25% to 50%; Level 2 (Model Based Definition) - from 50% to 75%; Level 3 (Model Based Enterprise) - from 75% to 100%. Since the descriptive purpose of the Core-MBE framework, only the final result about the maturity level of MBD and MBE approaches can be communicated to the organization. In fact, no additional information can be provided such as improvement actions or suggestions, because it goes beyond the scope of the model. On the other hand, imaging a to-be scenario, companies could adopt the Core-MBE framework with prescriptive purposes to just identify the desired maturity level of the organization itself or of specific internal topics.

4 The Core-MBE Maturity Model application

In order to test the usefulness and the validity of the Core-MBE maturity model and the complementary assessment tool in evaluating the maturity of MBD and MBE approaches, an empirical evidence has been planned focusing the attention on two case studies. The first one represents a SME industrial company operating in the manufacturing sector of medium-light carpentry and that deals with the main realization of fork-lifts. The second one refers to a large aerospace company that operates in the design, production and maintenance of civil and military aeronautical components and systems.

By submitting the questionnaire to them, preliminary information has been collected about the companies (i.e. size and industrial sector) and the interviewees (i.e. role and years of experience in the company), as shown in the table below.

Table 1. Information about case studies.

	Carpentry company	Aerospace company	
Industry	Mechanical carpentry	Aerospace	
Size	150	5500	
Interviewee role	Cost planning manager	Engineering team leader	Technical project manager
Experience	9 years	13 years	2 years

Mechanical Carpentry Company

For the carpentry company, it has been possible to gather only one questionnaire that has been fulfilled by a figure with the role of cost planning manager. The company entrusted to him the assessment activity since his knowledge on the topic of MBD and MBE and his awareness about the design and manufacturing processes as well as the practices of product data management. He stated the usefulness of the framework due to the fact that it pushes people to reflect about the level of maturity of MBD and MBE approaches, routine activities and practices that could also be improved such as in terms of standardization and collaboration.

After the analysis of his answers, it has been possible to declare that the maturity of the company corresponds to the “model centric” level, in view of the result of 45,5%. Therefore, considering the Core-MBE maturity model and its structure, the organization status consists in an initial understanding of the potential value coming from the usage of 3D models. However, drawings are still considered as the authoritative sources of product information.

The company receives customer orders through primary 3D CAD models and supplemental drawings. PDF and STEP (Standard for the Exchange of Product model data) files are used for data exchange. The technical teams of the company adopt 3D models for the product geometric definition but the complementary PMI and annotations are described on 2D supports. Design data and annotations are defined as text on 2D drawings and are managed in a separate database that is not connected with the PLM (Product Lifecycle Management) enterprise system. Moreover, calculations and engineering analysis are carried out manually on spreadsheets, and the engineering bill of material is manually defined into the ERP (Enterprise Resource Planning) system. Also, both the delivery and the collection of technical data packages are processed in ad-hoc manner, as well as the configuration management and the document management processes are managed manually. Releases and potential changes are managed with a kind of structured model-based reference.

Regarding the manufacturing operation and the planning activities, the MBoM considers the CAD product tree but some components are often added manually. Manufacturing models are mainly used with supplemental drawings. There are no digital associations between design models and manufacturing data. In fact, also the manufacturing data are managed in a separate database. The manufacturing process relies on 2D drawings but models, images and text are used for work instructions. The drawings and models are used to drive the quality inspection of products, while raw materials are monitored with 2D supports. Also in this case, data are managed in a separate database that is not integrated with the PLM or the ERP systems. Design data are provided with digital drawings and defined in the EBoM, which are accessible through the PLM system. But this information is not automatically connected with manufacturing suppliers who could, for example, streamline the supply chain.

Aerospace Company

Within the aerospace company, the questionnaire has been fulfilled by two professional figures: a technical project manager and an engineering team leader. The former allowed the evaluation of the maturity of MBD and MBE approaches considering the main business contract program, while the latter was focused on other small programs. It is important to consider this aspect because of the remarkable different maturity that has been assessed in these two contexts and, for this reason, it was chosen to discuss the result separately. In both cases, the interviewees have recognized the usefulness of such assessment activities and of the Core-MBE framework as well, considering their effects in terms of increasing awareness of some specific topics and stimulation for continue business improvement.

The analysis of the first questionnaire returned a total score of 81%, which corresponds to the "model based enterprise" maturity level. The company is seamlessly connected both within and outside its business, including the whole ecosystem such as vendors, suppliers, and customers, and 3D models represents the main source of product data.

The 2D drawing is almost all deleted and represents just an output of 3D models which contains the full product definition, including geometric information, annotations and PMI. Moreover, design data and models, as well as the EBoM and TDP, are fully managed within the PLM system that is also integrated with the CAD tools used by designer. The configuration management and the document management are handled in structured way within the PLM, as well as release and change processes. Regarding the manufacturing operations and planning activity, the MBoM is strongly associated with the CAD product tree and MBoM components. 3D models are used to generate process plans and work instructions which also rely on pictures and texts. Digital associations exist between design models and manufacturing data, since the adoption of CAD and PLM systems as the authoritative sources of information. Both drawings and models are used to define the process of quality inspection for both incoming materials and products. The quality requirements are fully managed in the ERP and MES (Manufacturing Execution System) systems. Structured policies are adopted in order to ensure in accordance with the role of the users the access to product data, which is mainly segregated with respect to data attributes. Some PMI and other data can be accessible by downstream groups through the PLM system. Product information and 3D models are often exported and manually sent to external suppliers, which are also used for procurement requirements. CAD, PDF and STEP files are used for information exchange. Both 3D images and 2D depictions are used and elaborated to create technical manuals.

The analysis of the second questionnaire returned a total score of 29%, which corresponds to the "model centric" maturity level. In this case, the organization seems to just gain the awareness about the potential of 3D models, even if drawings are massively adopted. In fact, drawing contents are manually validated, PMI and annotations are defined as texts, and even if engineering analysis are carried out on CAD models, the EBoM is defined manually within the ERP system and then imported in the PLM system. The product configuration and the management of documents are manually handled using applications not integrated with the PLM system, while releases and changes are exclusively drawing-based. The MBoM is manually created through the fulfilment of item lists with the support of drawings; then manufacturing data are stored and managed in the PLM system where also some design models and data exist. The drawings are used for quality inspection and verification for both parts and raw materials, but quality requirement data are not integrated in the PLM system.

Finally, considering that the two assessment cases belong to the same aerospace company, it could be useful to summarize the general level of maturity of MBD and MBE approaches. By averaging the two partial results, it is possible to define that the overall maturity of the company corresponds to the "model based definition" level.

5 Conclusion

Enabling technologies and useful aligned methodologies are essential to support the digitization phenomena and the increasingly complex and dynamic market as well as the progressively interconnected and collaborative business environment. For these reasons, model-based approaches, including the Model-Based Enterprise (MBE), are considered to improve the quality of engineering activities in accordance with the concepts of fully integration of product data and adoption of 3D models. Compared to traditional approaches, they can significantly contribute to cut internal costs and reduce time to market. The main problem faced in this research is connected to the lack of accurate procedures to be applied; companies struggle to understand what Model Based Definition is, and on which Model Based Enterprise is based; their knowledge and awareness depends on the level of maturity that exist within their business structure. Starting from these issues this research allowed the clarification of these concepts and the definition of their relationships along the product lifecycle management. In addition, the aim of the research was to define an original framework for assessing the maturity of model-based approaches and, in particular, of MBD and MBE. The Core-MBE maturity model and the questionnaire have been developed and applied for validation purpose. The research has demonstrated that the framework can be applied in different industrial sectors and to assess a company in its overall perspective or by considering specific applications.

Heterogeneous maturity levels emerged from the case studies. A very high level of maturity has been assessed for the aerospace company considering the main contract programs (81%), while for the other small programs a lower level (29%) has been identified. This scenario can be justified by strategic choices oriented to a more structured maturity for the core business that, considering the structure of a global extended enterprise, need to rely on effective interactions and strong collaborations in the whole ecosystem. By averaging these results, it is anyway possible to declare a comprehensive medium-high level of maturity with a massive adoption of 3D models and a decreasing usage of drawings. Considering the aerospace case study, the fulfillment of more questionnaires allowed the better understanding and evaluation of the company. Moreover, it has highlighted some useful considerations related to the application of the Core-MBE framework.

On the other side, referring to the mechanical carpentry case study, it has been possible to identify a medium level of MBE maturity (45,5%). Only one response has been collected from the empirical evidence. This level of maturity can be interpreted in line with the general business structure. Considering the size of the company and its narrower business, other technological initiatives could be invested respect to model-based approaches that anyway appears to be quite mature.

The empirical evidence allowed to test and validate the usefulness of the Core-MBE framework which collected positive feedback from interviewees. However, the research suffers some limitations due to a limitative case study applications and their qualitative approach, which also impact on results generalizability. In addition, since the descriptive purpose for which the framework has been designed, other explorative applications could be carried out to shape the future maturity desired by the companies.

In fact, only descriptive statements can be extracted from the application of the framework. Future improvements can be oriented in the evolution path from descriptive to prescriptive to comparative purposes. Moreover, further improvement actions could be based on suggestions received by interviewees.

Concluding, it is also possible to state that the research provides academic implications considering the knowledge enhancement about the topic of MBD and MBE, as well as practical implications due to its usefulness in stimulating the maturity awareness of industrial companies.

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