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Analysis of the MBE&MBD Integration as a Tool for Value Creation in Industries

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Title
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Abstract

The thesis explores the current state of Model-based Enterprise (MBE) and Model-based Definition (MBD) in the industrial sector. The study consists of two main parts. The first part is a literature-based study on MBE and MBD's modern principles and market situation in the industrial sector. The second part of the thesis includes original data collected through a survey addressed to different manufacturing companies. It was designed to obtain real-world experience, perceived benefits, and current levels of implementation of MBE/MBD technologies in practice. The responses were analyzed, and conclusions were made about trends and future expectations. Both parts of the thesis aim to give a clear picture of the present and future role of MBE and MBD in modern manufacturing.

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thesis, academic writing, abstract, MBD, MBE, Model-based Definition, Model-based Enterprise

Contents

Abbreviations

2D Two-dimensional
3D Three-dimensional
BOM Bill of Materials
CAD Computer-aided design
CAM Computer-aided Manufacturing
GD&T Geometric Dimensioning and Tolerancing
IoT Internet of Things
MBD Model-based Definition
MBE Model-based Enterprise
PLM Product lifecycle management
PMI Product manufacturing information
SME Small and medium enterprises

Introduction

Nowadays, competition between companies within industrial sectors is increasing rapidly. Consequently, manufacturers are always looking for the most efficient methods to organize data storage and exchange to enhance efficiency, improve value-adding, reduce costs, and maximize final product quality. An increasing number of companies tend to become digitalized and implement the newest technologies to exceed their competitors. Therefore, embracing the newest digital technologies has been a key factor for success that enables organizations to organize data management.

Model-based enterprise (MBE) and Model-Based Definition (MBD) approaches were developed as a solution to the problem. These practices are supposed to update industrial processes by eliminating traditional, document-based processes and adopting digital models, which allow for better communication, data completeness, and process automation. As industries transition to more intelligent and interconnected manufacturing ecosystems, a better comprehension of the role and impact of MBE and MBD becomes ever more crucial.

The development of MBE and MBD has evolved significantly over the past few decades. Initially, product development was largely drawing-centric, relying on 2D representations. However, with the advent of CAD technologies and the need for higher precision and efficiency, the industry gradually shifted towards 3D models. MBD emerged as a method to embed all product manufacturing information directly into 3D models, while MBE expanded the concept to include model usage across the entire engineering lifecycle.

The goal of the thesis is to research the current state of Model-Based Enterprises and Model-Based Definition as tools for companies in the industrial sector. We will try to define the modern view of these tools and find out the key drivers, challenges, and benefits of implementing them. We will also explore how these methods provide value and produce competitive advantages for manufacturing companies.

Knowledge-based research on MBE & MBD

1.1 Models

MBE and MBD are the subject of our study, both revolving around the idea of a 'model.' Thus, it is essential first to clarify what a 'model' is.

A model is a representation or idealization of the structure, behavior, operation, or other characteristics of a real-world system (Lubell, Chen, Horst, Frechette & Huang 2012, 3). Lubell et al. (2012, 3) split models into computational and descriptive groups. A computational model is meant to be used by a computer. That is why it has a machine-readable format. Descriptive models are made in a human-readable format for people's consumption. One of MBE's core principles is to create an interconnection between descriptive computational models with the help of CAD. As a result, the CAD model has an understandable view for humans to read and utilize. At the same time, it can also be read by engineering software. For instance, while human engineers can study a model developed in Creo software with 3D graphics and annotations, it can also be imported into automated production systems. (Lubell et al. 2012, 3.)

A model is an approximation, representation, or idealization of selected aspects of the structure, behavior, operation, or other characteristics of a real-world process, concept, or system (Frechette 2011, 2). Frechette (2011, 2) specifies that a model is a digital artifact created to be used in software applications. He states that models can have four different definitions depending on their features and applications. Firstly, a model as a representation of a product includes all the information about the product's attributes that support manufacturing, usage, and support. For example, a 3D model of an engine part in CAD format describes all the information about the part's materials, geometry, standards, and production process. Frechette (2011, 2) indicates that this is the most common usage of the term "model" in the context of manufacturing enterprise. Secondly, models can represent a process. It is a mathematical representation of physical activity. For instance, a mathematical model can represent the conveyor line on a production site. This way, you can analyze the line's efficiency, find bottlenecks, etc. Thirdly, some models are integration enablers. It is a type of model that provides data transfer between engineering sites and businesses. For example, the BOM model can be used to transfer information about product components from an engineering team using a CAD system to the procurement department using an ERP system. Fourthly, the model sometimes means a predictor behavior. It calculates a possible outcome from given conditions. A weather predictor is an example of such a model. (Frechette 2011, 2.)

1.2 2D CAD and 3D CAD comparison

A traditional working method in the industry used to be 2D drawings for a long time until computers became commonplace for us. Later, 2D CAD programs almost entirely replaced the traditional paper 2D drawings. The main reason is that it sped the process of creating 2D drawings by making it more straightforward to modify and change. Afterwards, 3D CAD programs appeared and came into use in the 1990s. (English 2021.)

Computer-aided design can be defined as the use of computer systems to assist in creating, modifying, analyzing, or optimizing a design. It consists of two parts: hardware and software. Hardware usually includes computers, graphic display terminals, and input and output devices. The software consists of computer programs to implement computer graphics on the system and application programs to facilitate the engineering functions of the user company. (Narayan, Rao & Sarcar 2008, 3)

2D CAD drawings have several advantages. They are cost-effective compared to 3D CAD models as they require far fewer resources to create, especially for simple components (Draftings Australia 2022).

However, many experts point out that despite the fact that 2D drawings utilization has quite many advantages, it causes particular problems that companies regularly face to.

To begin with, 2D drawings lack sufficient interactivity, which makes them more difficult for people to understand. They can only provide a flat view, which means you cannot see depth and perspective clearly enough. Moreover, it is impossible to rotate a depicted object as you can do with a 3D view. (Draftings Australia 2022.)

Additionally, 2D drawings have restricted options for simulation. It is impossible to simulate many real-world conditions, such as fluid flow, strain, stress, air flow, etc., on a flat 2D drawing (Mellionard, 2024).

While 2D CAD systems are often more cost-effective for simple tasks and legacy workflows, their limitations in interactivity, depth perception, and simulation capabilities hinder their utility in complex manufacturing environments. In contrast, 3D CAD provides a comprehensive digital representation, enabling direct simulation, better visualization, and enhanced design communication.

Aspect	2D CAD	3D CAD
Visualization	Flat, limited perspectives	Full spatial representation
Interactivity	Low (requires multiple views)	High (rotation, zoom, cross-sectioning)
Simulation capabilities	Very limited	Integrated stress, fluid, and motion analysis
Data richness	Minimal	Includes metadata
Ease of learning	Faster for simple drafting	The learning curve is steep but more powerful in long-distance
Cost efficiency	Lower initial cost	Higher cost but greater ROI in complex systems

Table 1. 2D CAD and 3D CAD comparison table.

Figure 1 represents the comparative analysis of 2D CAD and 3D CAD that was made based on the received insights.

According to Draftings Australia (2022), although 2D CAD can be sufficient for basic components, it cannot support modern digital workflows that rely on real-time data and model-based automation.

In this way, there is no doubt that industrial organizations have a great reason to adopt 3D model technologies within the framework of MBE & MBD conepts, even though they have a great resistance to abandon 2D in the nearest future altogether.

1.3 Reasons for the research

Despite the growing interest in digital transformation, the integration of MBE and MBD remains uneven across industries. Although many large corporations have adopted these frameworks, Finnish and other Nordic SMEs often lack the awareness, technical readiness, and infrastructure to implement the systems effectively.

Most of the existing research on MBE & MBD originates from the United States aerospace and defense sectors companies such as Boeing or Lockheed Martin. It leaves a knowledge gap in how these methods are adopted in Nordic manufacturing environments. Moreover, obviously, there is a lack of practical, survey-based data regarding MBE & MBD implementation in Finland. (Corallo et al., 2022; Lubell et al., 2012).

At the academic level, engineering programs often still prefer 2D drafting and legacy tools, failing to align with the skills demanded by modern model-centric enterprises (Uski & Ellman 2023). This research also supports curriculum development in industrial management and mechanical engineering programmes by highlighting the practical needs and digital trends in the modern manufacturing field.

Furthermore, this thesis aims to provide industry-specific insights into how MBE & MBD can drive competitive advantage by analysing generated value creation, cost efficiency, sustainability, and improved quality. Through a literature review and survey data from Finnish manufacturers, this work addresses both theoretical and practical gaps.

1.4 Industry 4.0

The development and implementation of MBD and MBE concepts are closely linked to the broader paradigm shift known as Industry 4.0. This term refers to the fourth industrial revolution, characterized by the integration of cyber-physical systems, the Internet of Things (IoT), cloud computing, and smart data across all stages of the value chain. The primary objective of Industry 4.0 is to create “smart factories” where decentralized decisions are made in real time and production systems are capable of self-optimization and adaptation (Kagermann, Wahlster & Helbig 2013, 5-6).

1.5 Model-based definition

Model-Based Definition (MBD) is an innovative approach to product design and development that integrates the main PMI directly into a 3D model (Pajula 2016). In contrast to traditional processes involving 2D drawings to communicate dimensions, tolerances, and specifications, MBD implants all relevant data into the model itself. The model is then referenced for the entire product life cycle from design to manufacturing and quality control. As a result, MBD enhances productivity, reduces errors, and fosters better teamwork in organizations, as well as with suppliers and stakeholders. (Lubell et al. 2012)

MBD promotes a clean approach by utilizing dimensions and Geometric Dimensioning and Tolerancing (GD&T) within into the 3D model. This ensures that product specifications are clearly defined and available to all stakeholders. (Reid 2016). Furthermore, MBD shifts the model to become the master source that drives all engineering activities throughout the product’s development and production process.

In addition to improving internal workflows, MBD also plays a vital role in supporting the regularity of the digital flow and enabling downstream automation. The point is that using MBD makes it easier to automate stages, such as production and quality control, because all the necessary data is already in the digital 3D model. This eliminates the need for manual data re-entry and makes the process more streamlined. Using the 3D model as a primary source of truth, MBD enables integration with other digital tools and systems such as CAM, PLM, and simulation software. This not only reduces redundancy and manual rework but also supports traceability, compliance, and data-driven decision making across the value chain. As industries continue to evolve towards Industry 4.0, adopting MBD is becoming a key strategic step towards achieving complete digital transformation.

MBD relies on several key principles. MBD's core concept centers on 3D-Centric Representation, where the three-dimensional model serves as the whole product definition. This wide model includes not only geometry but also size, tolerances, material requirements, surface treatments, and assembly guidelines, creating a clear design representation that improves communication. Through data integration, MBD combines product design specifications and manufacturing requirements into a unified model. This ensures data consistency and accessibility.

The approach significantly improves collaboration and communication by providing a single digital model that design, manufacturing, and quality teams can use at the same time. This rids interpretation issues and manual format conversions, with any model modifications being instantly visible to all stakeholders.

A key goal of MBD is the elimination of 2D drawings by involving all essential information directly into the 3D model. This reducing errors and inconsistencies between teams and provide materials and data for everyone involved in the project.

MBD enables Automation and Efficiency by leveraging computer tools for processes like CNC machining and manufacturing, which increases accuracy while reducing time expenditures and costs associated with manual errors. The Model-Based Inspection capabilities improve production quality processes. The annotated 3D model helps automated measurements during manufacturing, and embedded specifications can be directly applied during inspection, helping prevent quality issues before they arise.

Finally, MBD simplifies Product Lifecycle Management by effectively monitoring changes throughout the product's life cycle. Changes to the model are captured immediately and distributed to relevant team, ensuring everyone works with current and accurate information (Bijnens 2019).

1.5.1 Benefits of adopting MBD

Companies find they can no longer focus on a single area. To be competitive, they must consider various factors such as performance, innovation, quality, and personalization.

MBD provides several advantages, particularly when dealing with life updates and changes in 3D modeling. Since all changes are made directly in the 3D model, no additional updates are necessary. This significantly contributes to increased efficiency (Rannanpää 2020). According to a Boucher (2017) study, companies that have adopted MBD report fewer manufacturing errors, less rework, and improved communication with suppliers.

Employees are more satisfied with their work, as they spend less time on tedious tasks related to 2D drawings and focus on more value-added activities. Time savings are also reported in the design process, and product information access has become more effective. Boucher (2017) found that 89% of MBD adopters are satisfied or extremely satisfied, with none being dissatisfied.

A diagram in Figure 1 (Boucher 2017) below describes the design time of the product. So, 21% of the time is spent on creating 2D drawings, and 12% on making changes to 2D drawings. In total, 33% of all the time is spent creating or making 2D drawings. Today's manufacturers have to work harder than ever to stay competitive, and considering that a third of the time goes to 2D drawings and mainly involves documenting what is already in the 3D model, that is much time wasted on non-value-added efforts. Opportunities for improvement are significant. This is where the concept of MBD becomes essential.

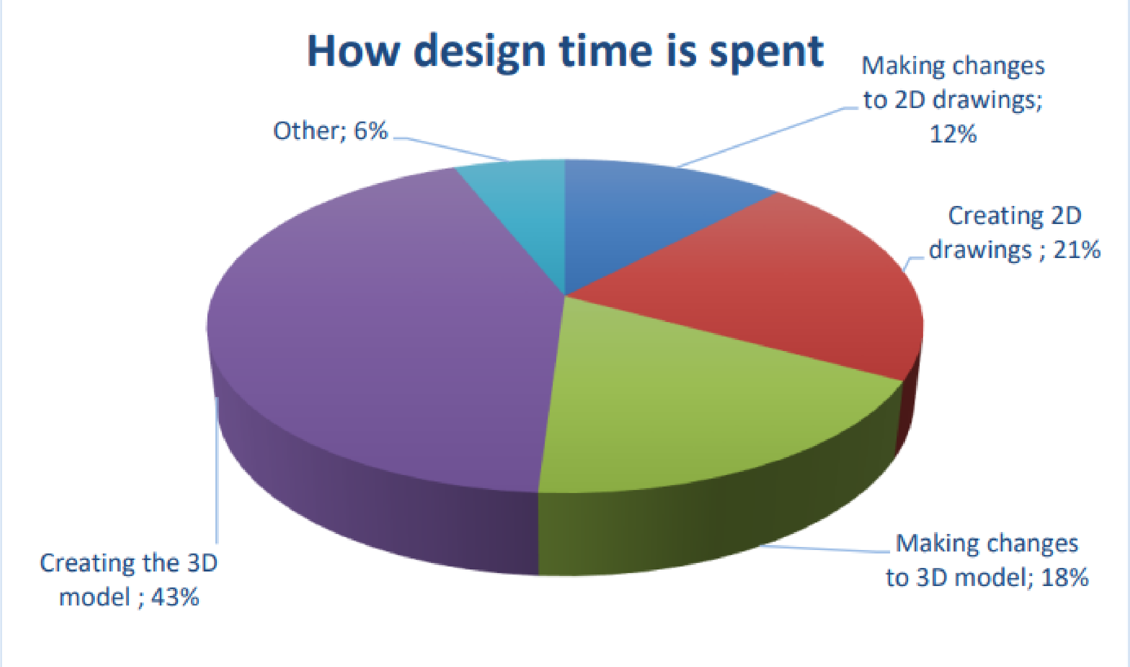


Figure 1. How design time is spent (Boucher 2017, p. 5).

Young engineers, in particular, prefer 3D models to 2D drawings, often seeing the latter as outdated. The 3D model provides a more comprehensive understanding and more intuitive representation of the product, compared to the multiple views needed to interpret a 2D drawing (Rannanpää 2020). Moreover, MBD solutions are accessible even on affordable devices, as many visualization tools are suitable with standard tablets, reducing hardware costs (Boucher 2017). MBD also helps save on data storage, as it uses less space compared to 2D drawings. The same data can be efficiently reused across departments, cutting down on printed materials and improving overall workflow (Adamski 2010).

Another important benefit of MBD lies in its positive environmental impact. By reducing documentation paper use, MBD reduces both the costs and minimizes

the ecological harm associated with paper production — a process that consumes natural resources and releases harmful chemicals. Digital workflows, in turn, support more sustainable and resource-efficient practices (Rannanpää 2020).
So, let us summarize the main advantages of using CAD models in production:

1. Increased Accuracy: A single, defined source of information minimizes errors related to interpreting multiple documents.

2. Faster Time to Market: Streamlined processes and reduced communication overhead lead to faster product development cycles.

3. Cost Reduction: MBD reduces costs by minimizing errors, rework, and reliance on 2D drawings.

4. Improved Quality Control: Clear, unambiguous product definitions improve inspection accuracy and reduce defects.

MBD represents a significant departure from traditional design and manufacturing methods, leveraging the power of 3D models to centralize and streamline product definition and communication. By integrating design, manufacturing, and inspection data into the 3D model, MBD increases efficiency, reduces errors, and facilitates better collaboration throughout the product lifecycle. This approach is increasingly important in modern product development, where accuracy and speed are critical to competitive advantage.

1.5.2 Challenges and recommendations for adopting MBD

Although companies tend to appreciate MBD once it is implemented, the initial stage does come with some challenges. However, with proper planning, these issues can be minimized.

As with any significant change to an established process, the biggest problem is often overcoming resistance to change. Most other challenges (Figure 3) are secondary and can typically be overcome by taking steps to overcome the resistance to change.

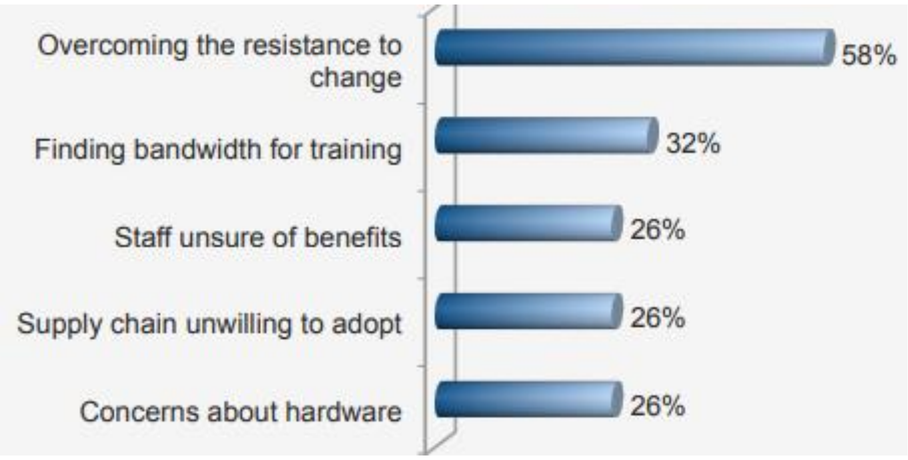


Figure 2. Challenges of Implementing MBD (Boucher 2017).

Training is needed to ensure that both staff and suppliers understand the benefits of MBD. However, the problem lies in finding the time for this training. Fortunately, once MBD is successfully implemented, the resulting cost savings, thanks to reduced rework and fewer manufacturing errors, make it a good investment of time.

Hardware requirements are another consideration. While high-end CAD workstations can be expensive, many MBD solutions do not demand top-tier hardware. In fact, several options can run on affordable tablets, helping to keep hardware costs down.

Another concern is the hardware needed to access 3D models. While a full CAD workstation can be expensive, many MBD solutions do not require the best workstations. In fact, many can run on lower-cost tablets, minimizing the hardware investment.

To successfully implement MBD, it is recommended to take some steps:

1. Think of MBD as a strategy to improve the efficiency of engineering processes. It allows engineers to focus on creating quality designs rather than routine drawings.

2. When implementing MBD, consider all employees and departments that can benefit from access to the engineering model. Their participation is important when developing the implementation plan.

3. Ensure that internal teams have access to the necessary resources to facilitate the adoption and use of MBD.

4. Implementation to suppliers may require additional effort. It is important to work closely with them and explain the new approach's benefits.

5. All users of MBD, including those who will only work with the final data, should be trained accordingly.

1.6 Model coordinate systems

To ensure clear and consistent digital product definitions, the structure of coordinate systems within a design model plays a crucial role. The design model must include at least one model coordinate system, represented by three crossing, mutually perpendicular axes originating from a common point. Each axis should be clearly labeled, with the positive direction indicated (Figure 3). Unless stated otherwise, the coordinate system is assumed to be right-handed (see Figure 4). The CAD model should define the relationship between the absolute coordinate system and the model coordinate system(s), while the technical documentation must establish the connection between the model coordinate system(s) and the datum system(s) used for geometric specifications. (SFS-ISO 16792 2021, 14-15.)

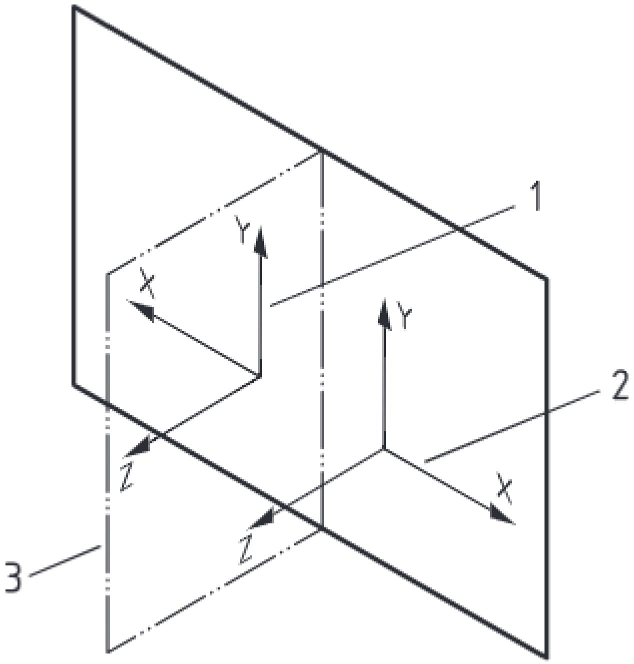


Figure 3. Mirror-image relationship. (SFS-ISO 16792 2021, 14.)

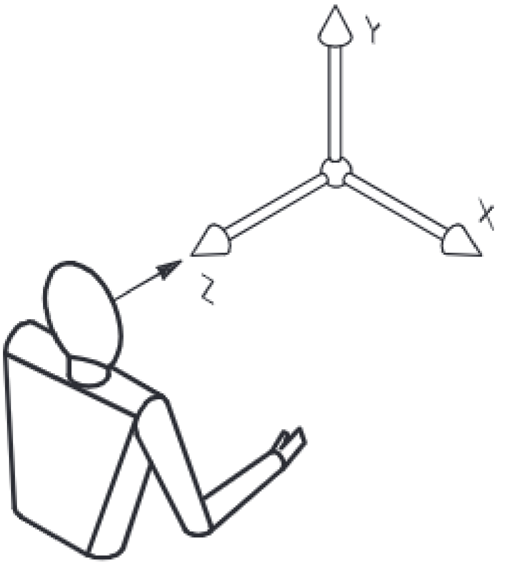


Figure 4. Recognizing the right-hand coordinate system. (SFS-ISO 16792 2021, 14.)

1.7 Model-based enterprise

MBE and MBD are closely related concepts, although there is an essential distinction between them. While MBD refers to focusing on the implementation of 3D CAD models and all associated hardware, software, and documentation on the manufacturing site to transition the company from traditional 2D drawings to a single source of information, MBE implies a broader concept in which MBD plays a key role.

According to Corallo, Vecchio, Lezzi and Luperto (2022, 1), MBE is an organization that utilizes modeling technologies to analyze and manage the product on each phase of its lifecycle including product design, production, support and retirement.

MBE is using MBD by various departments and stakeholders, internal and external to a company, throughout the product's lifecycle. It connects all the product data into a digital thread. (Astheimer 2021, 17.)

MBE is an engineering strategy that aims to clarify design intent during the manufacturing process. (Rannanpää 2020, 5.)

MBE is an organization that applies modeling and simulation technologies to integrate and manage all its technical and business processes related to production, support, and product retirement. The data that is created once should be used by every data consumer. This approach allows a single data asset, like a 3D CAD model, to be transferred from one department to another without additional work. It improves data flow, reduces costs, and helps with documentation management. (Frechette 2011, 2-3.)

MBE is a method of organizing and managing business processes that involves creating and using digital models to represent the various aspects of the enterprise.

The complete change to MBE is supposed to apply digital models as a single source of truth in the company's workflow. (PTC 2025)

One of the MBE features is organizing all the information flow within the company into a “Digital thread”. In accordance with Yasar (2024), a digital thread is a data-driven communication framework that connects isolated manufacturing process elements and provides an integrated view of an asset throughout the manufacturing lifecycle. (Yasar 2024)

PTC determines six levels of the MBE adoption journey:

0. A company is drawing-centric

1. The company switched to a model-centric approach and started to use a neutral file for manufacturing.

2. The company has started to use native CAD models in manufacturing

3. The company is MBD organization, using the annotated model and a lightweight viewable

4. Manufacturing is fully integrated into the process

5. The company is considered an MBE as the internal enterprise becomes integrated.

6. The company’s manufacturing, internal, and external enterprises are integrated. (PTC 2024, 9.)

The Business Research Company (2025) states that one of the reasons for MBE to develop rapidly over the last few years is the implementation of "digital twin” technology as a part of the Industry 4.0 advent. (The Business Research Company 2025).

“Digital twin” is a virtual representation of an object or system that reflects a physical object accurately. It covers the whole product lifecycle and updates based on real-time data with the help of simulation, machine learning, and reasoning. Digital twin significantly improves the process of decision-making. It became a key technology approach for MBE & MBD applications. (IBM 2021)

The MBE market size has significantly expanded recently. While it was $19.32 billion in 2024, it increased to $22.77 billion in 2025 (The Business Research Company 2025).

A digital twin is a virtual representation of an object or system that reflects a physical object accurately. It covers the whole product lifecycle and updates based on real-time data with the help of simulation, machine learning, and reasoning. Digital twin significantly improves the process of decision-making. It became a key technology approach for MBE & MBD applications. (IBM 2021.)

MBE market has a great tendency for growth. While market revenue of MBE is $13.6 billions in 2024, MarketsadnMarkets (2024) forecasts that MBE market will reach an Estimated Value of $27.1 billion by 2029. (MarketsandMarkets 2024.)

1.8 Value creation in MBE & MBD

The implementation of MBD and MBE offers substantial value creation across multiple dimensions of industrial operations. These benefits are not only technical but also economic, strategic, and environmental, making MBE & MBD a central enabler of digital transformation in modern manufacturing.

1. Cost Reduction. By reducing reliance on 2D drawings and minimizing rework, MBD significantly cuts manufacturing costs. Studies show that MBD can reduce rework-related costs by up to 60% due to better communication and fewer interpretation errors in production documentation (Boucher 2017).

   Additionally, MBE automates design-to-manufacturing workflows, reducing manual labor and administrative costs across departments (Lubell et al. 2012).

2. Increased Productivity. MBE connects product design, manufacturing, and quality systems through a digital thread, enabling faster development cycles and concurrent engineering. This leads to shorter time-to-market for new products. According to PTC (2025), companies using MBE frameworks report up to 30% faster product development times and 40% fewer design iterations (PTC 2025).

3. Improved Quality and Accuracy. Embedding PMI into 3D models enhances clarity and reduces interpretation ambiguity. MBD improves first-pass yield and inspection accuracy, as automated tools can extract

GD&T data directly from the model. What is more, that quality assurance costs can be reduced by up to 50% with model-based inspection processes.

4. Better Collaboration and Data Reuse. MBE enables real-time data sharing across engineering, production, and supply chain functions. The 3D model becomes the single source of truth accessible to all stakeholders. This reduces the overhead of document conversions and ensures everyone is working from the same up-to-date information, improving supplier coordination and change management.

5. Sustainability and Environmental Benefits. Paperless workflows enabled by MBD reduce paper consumption and lower carbon footprints associated with traditional design documentation—additionally, the ability to simulate designs digitally before manufacturing reduces material waste. Digital twins and predictive maintenance, both supported by MBE, further contribute to energy efficiency and resource optimization. (IBM 2021.)

6. Strategic Competitive Advantage. Companies adopting MBD & MBE position themselves for future readiness. They align with Industry 4.0 principles, facilitate certification compliance (e.g., AS9100), and build scalable platforms for integration with AI, AR/VR, and IoT. This enhances adaptability in volatile markets and strengthens resilience against disruptions.

As these findings suggest, the adoption of MBE and MBD is not merely a technical upgrade but a strategic investment in competitiveness, sustainability, and long-term value generation.

1.9 Lockheed Martin case study for MBE & MBD

Lockheed Martin is one of the most well-known aerospace and defense companies in the world. Over the years, it has been a leader in adopting modern digital practices, including MBE and MBD. These approaches have helped the company move away from paper-based processes and toward fully digital, model-centered workflows. (Lockheed Martin 2025, p. 3)

The best example of this transformation is how Lockheed Martin introduced MBE and MBD across its supplier network and internal manufacturing processes. The company realized that as products became more complex, traditional 2D drawings were no longer enough. That is when they started using annotated 3D models, complete with all the needed PMI, as the primary communication method between engineering and production teams. (Lockheed Martin 2025, p. 8–9.)

By shifting to MBD, Lockheed Martin removed the need for separate 2D drawings. This helped reduce misunderstandings between departments and made it easier to catch and correct problems early. These 3D models are now used to share precise design details like tolerances, materials, and inspection data. (Lockheed Martin 2025, p. 8–9).

Alongside MBD, Lockheed Martin implemented an entire MBE system. This involved creating a digital thread, which connects all the data about a product from design to production, inspection, and maintenance. The goal was to have one continuous flow of information so that updates and changes could be tracked and used by different teams without losing important details. (Lockheed Martin 2025, p. 6–7, 19.)

To make this possible, the company used standard file types like STEP AP242 and QIF, which allow different software and machines to read the model data correctly. These formats help with things like automatic inspection, programming CNC machines, and sharing data across departments and suppliers. (Lockheed Martin 2025, p. 14, 18, 20–21.)

Another key part of Lockheed Martin’s approach was its collaboration with suppliers. The company launched pilot programs to assess whether its partners were ready for MBD and what support they needed. Some suppliers, especially those working with machining, were already familiar with using 3D models, while others, like those making printed circuit boards, needed more help to catch up. (Lockheed Martin 2025, p. 12–14.)

To support the transformation to MBD, Lockheed Martin used tools like the External Integration Hub (EIH) to secure data sharing and the iBase-t Manufacturing Execution System (MES) to track real-time production activities. These platforms helped coordinate work and ensure quality across all stages. (Lockheed Martin 2025, p. 10, 28.)

However, the transition was not easy. One of the biggest challenges was getting employees to shift from paper-based workflows to digital tools. Many engineers, technicians, and suppliers were more familiar with using 2D drawings, so LM had to invest in training focused on interpreting and using model-based data. The company used tools like MBDVidia and partnered with external organizations such as the Connecticut Center for Advanced Technology (CCAT) to support supplier and internal workforce development. These resources helped users learn how to work with formats like STEP AP242, 3D PDFs, and QIF files (Lockheed Martin 2025, p. 22–24).

Another challenge was making sure suppliers could also use model-based processes. Some of them were still printing 2D drawings from 3D models, which broke the digital flow. Lockheed Martin worked with these suppliers to explain the benefits of staying fully digital and helped them adjust their workflows. (Lockheed Martin 2025, p. 13–14, 24.)

In the end, the results of adopting MBE and MBD were impressive. Lockheed Martin saw programming times for machines and inspections drop by up to 90%. Engineering cycle times were reduced by two to three times, and suppliers reported less manual work when filling out first article inspection forms because much of the data came straight from the models. (Lockheed Martin 2025, p. 5, 14.)

The overall impact was good: less scrap and rework, better on-time delivery, and improved first-pass yield. For example, Lockheed Martin’s Clearwater facility reported a 46.9% reduction in scrap and rework costs after adopting these model-based practices. (Lockheed Martin 2025, p. 5.)

Lockheed Martin’s case shows how MBE and MBD are part of a bigger strategy to modernize the way manufacturing companies work. With strong leadership, good planning, and a commitment to training and collaboration, even large organizations can successfully make the shift to digital and get real business benefits from it. (Lockheed Martin 2025, p. 6–7, 28.)

1.10 Visualization programs

In the design and manufacturing of products, productive communication between designers, engineers, and manufacturers is critical. To support this, several visualization and collaboration tools have been developed to share 2D and 3D models. This section introduces three commonly used tools—eDrawings, JT2Go, and 3D PDF—each of which has unique features for viewing, sharing, and interacting with CAD data. These tools help to make engineering data more accessible across devices and users.

“eDrawings” is a communication tool for sharing 2D and 3D drawings between the designers and the manufacturers. eDrawings and SolidWorks are both owned by Dassault Systèmes. eDrawings can read files straight from SolidWorks in DWG format. NX is not compatible with eDrawings. eDrawings supports AR and VR technology. It also has a version for computers, tablets, and mobile devices. An eDrawings file is created with the eDrawings Publisher add-in, which works with most CAD programs. An eDrawings file is rather compressed, and it can easily be sent via email, etc. (eDrawings, n.d.)

“JT2Go” is a visualization program for JT files. This program is created by Siemens NX. This program is compatible with Android, iOS, and Windows computers. (Rapinoja 2016).

“3D PDF” is created by Adobe. A 2D PDF that includes text and pictures is a standard format. A couple of years ago, 3D information could be imported into a PDF file. It is possible to show PMI and 3D model picture information in the 3D pictures PDF file. In PDF file format, it is also possible to create an attachment file, such as a 3D model (native or STEP), measurement protocols (XLS or PDF), and manufacturing instructions. This format is highly popular because it can be viewed on smartphones and tablets. (Rapinoja 2016).

Next, we will take a closer look at the Creo6 application example.

1.10.1 Creo6 example

Creo 6 is a unified CAD/CAM/CAE platform for 3D design, developed by PTC (Parametric Technology Corporation). It allows the creation and analysis of 3D product models using a parametric approach (complemented by direct modeling). According to Parametric Technology Corporation, Creo combines a "powerful, proven toolset" with the newest technologies, such as generative design, real-time simulation, advanced manufacturing, augmented reality (AR), smart sensors, actuators, and other devices. Originally known as Pro/ENGINEER (Wildfire), the system was rebranded as Creo and has since received regular updates. Overall, Creo is intended to automate product development of various complexities, from mechanical components and assemblies to consumer goods and complex technical systems.

Creo 6 offers a wide range of tools and modules for design and manufacturing tasks. Key components include (PTC 2019):

1. 3D modeling – create parts and assemblies with parametric relationships, and use freeform surface modeling. It also includes support for frame structures, fasteners, and analytical shapes.

2. Drawing Generation (2D projections) – automatically generates orthographic drawings from 3D models and ensures consistency between models and documentation (Model-Based Definition).

3. Assembly Management – tools for working with large assemblies and components, as well as kinematic and mechanism analysis.

4. Specialized Add-ons – tools for sheet metal design, mold and plastic part development, hybrid surface modeling, direct modeling (Flexible Modeling), and an Additive Manufacturing module for preparing models for 3D printing.

5. Analysis and Simulation – CAE tools for structural, thermal, and modal analysis (Creo Simulate), also with Creo Simulation Live technology for real-time strength feedback during modeling. Integration with ANSYS extensions is supported for more advanced simulations. Additional tools include shape optimization, fatigue analysis, mold filling simulation, and so on.

6. Augmented Reality (AR) – The AR Design Share module enables the creation and viewing of AR experiences. Users can visualize 3D models in real-world environments via tablets, smartphones, or HoloLens for collaborative design and review.

7. Manufacturing Tools – CAM modules for CNC programming, tools for additive manufacturing, technical illustrations (Creo Illustrate), and tooling/prototyping support.

8. Additional capabilities include data import and export from other CAD systems, electronic schematics (Creo Schematics), generative design, design validation (Performance Advisor), and more. A range of

extensions allows the system to be customized to specific needs (e.g., simulation, rendering, MBD, tolerance analysis).

To summarize, Creo 6 integrates all stages of product development—from conceptual modeling and 2D drawings to engineering analysis, manufacturing preparation, and AR-based review.

Compared to previous versions (e.g., Creo 5), version 6 introduced several significant enhancements and new features (PTC 2019):

1. Real-Time Simulation (Creo Simulation Live) – a new technology providing quick feedback on structural analysis results during model modifications. This speeds up the design process by enabling early error detection and design optimization.

2. Augmented Reality Enhancements – improved AR capabilities, including access rights management for AR experiences, support for model access via links, QR codes, and better full viewing on mobile devices.

3. Additive Manufacturing Enhancements – increased flexibility with net structures, including new patterns, and the ability to create and customize user-defined lattices using model parameters. Added tools for orientation analysis and 3D print optimization (support minimization, time saving), and enhanced 3MF file support for printer data exchange.

4. UI and Performance Updates – Refreshed user interface with contextual mini toolbars for feature creation/editing, modernized feature dashboards, improved model tree, and navigation. Performance optimizations have enhanced update speeds for complex models and assemblies.

5. Tool Extensions – Improvements to existing extensions: added intelligent fasteners (Fastener Extension), enhanced wire and pipe routing tools (Cabling and Tubing), improved geometry handling in imported data (Multi-CAD), extended Shrinkwrap features for assembly simplification, and various UI refinements.

All these updates make Creo 6 more efficient and user-friendly for designers, combining simulation automation with a modern interface.

Creo 6 is widely used across numerous industries. Typical applications include:

1. Automotive industry – design of vehicle parts and assemblies

2. Aerospace and defense – modeling aircraft, missiles, and satellite components

3. Industrial machinery – machine tools, equipment, and robotics

4. Medical electronics and equipment

5. Consumer products – home appliances and electronics

By integrating CAD/CAM/CAE/AR tools, many companies rely on Creo for designing complex, connected products that require an end-to-end workflow from concept to manufacturing (EACPDS 2025).

Creo 6 is designed for the Windows environment. Supported operating systems include:

1. 64-bit versions of Windows 7/8.1/10 (Professional/Enterprise)
2. Windows Server 2012/2016 (for batch processing)

Creo is only available for Windows; no official versions exist for Linux or macOS. Licensing is proprietary and available via subscription or enterprise agreements (including academic and student versions).

Creo 6 has many advantages and useful features:

1. Extensive tools for 3D design and engineering analysis, including built-in FEA/CFD (Finite Element Analysis and Computational Fluid Dynamics) and advanced additive manufacturing features.

2. Modular and scalable system—additional extensions for simulation, visualization, AR, etc.

3. A model-centric approach enables rapid updates to designs and related documentation.

4. Combines traditional strengths with modern tech (AR/IIoT), making Creo a market leader.

5. High customizability—parameterization, scripting, programmable sketches. (PTC 2019.)

However, there are some disadvantages users have mentioned: (SoftwareAdvice 2024)

1. Steep learning curve – the extensive toolset and traditional interface may be complex for new users.

2. Requires significant training; users coming from other CAD systems may need time to adapt.

3. Resource-intensive – high-end CPUs and OpenGL 4.0+ GPUs are necessary for large assemblies.

4. Cost – commercial licenses are relatively expensive, and the product is available only on Windows.

5. Some users find the interface and specific commands outdated or clumsy.

Nonetheless, due to its capabilities, integration with other PTC systems, and ongoing feature development, Creo 6 remains a leading solution for industrial 3D design and multifunctional engineering.

1.11 Future trends and opportunities in MBE & MBD

By 2030–2040, manufacturing will be transformed by deep digitalization and advanced technologies installed in MBE and MBD. The future of MBE and MBD integration lies in the adoption of advanced technologies such as artificial intelligence, machine learning, cloud computing, and augmented reality. These innovations will further improve design automation, predictive maintenance, and real-time collaboration.

Artificial intelligence (AI) and machine learning (ML) will be integral to future MBE-driven manufacturing. In design, generative design and optimization processes will explore vast solution spaces at machine speed, iterating through thousands of simulations to optimize shapes, materials, and configurations. For example, generative design systems can automatically adjust part geometry between simulations, making new lightweight and cost-efficient designs that often outperform human-generated ones. Across industries, AI design has already demonstrated significant gains: McKinsey reports that generative design can cut product weight by 10–50%, reduce parts cost by 6–20%, and shorten development time by 30–50% (McKinsey & Company 2020). In an MBE & MBD case, these AI tools will act directly on the comprehensive digital model of the product, producing optimized designs that automatically update the Model-Based Definition (3D CAD/CAE) and Bill of Materials. Such AI-augmented design will accelerate time-to-market and improve performance without manual redesign. Computer-vision AI will be pervasive on the shop floor: high-resolution cameras plus ML defect-classifiers will inspect parts in real-time, flagging anomalies far more accurately than the human eye and can correlate slight design variations with field failure rates or find the root cause of a quality issue by sifting through production logs (KSMVision, n.d). What is more, intelligent scheduling software will reorganize workflows instantly to adapt to changing demands or machine availability, enabling mass customization without sacrificing efficiency.

Computers and tablets are the most common digital tools for the visualization of drawings in factories today. VR and AR technology have been expanding a lot over the past years in many different environments. AR and VR technologies will deepen the interaction between humans and digital models. Engineers will use VR to perform immersive design reviews and process simulations, while AR will guide technicians with real-time overlays during maintenance and assembly.

The AR glasses that include a camera can, for example, recognize the frame in reality and show a virtual 3D picture where the components should be placed. These tools will support safer, faster training and enable remote collaboration, making the digital model a more tangible and operational tool throughout the product lifecycle. AR/VR will thus close the gap between the virtual and physical domains of MBE (Malowany 2024)

Digital twins will serve as the dynamic basis of simulation-based engineering, linking physical systems to their virtual counterparts. Every product, process, and asset will have a twin that is continuously updated through sensor data and simulation feedback (IEEE Transmitter 2022). These twins will support optimization, predictive analytics, and cross-domain validation throughout the lifecycle. When embedded within an MBE framework, they enable a closed-loop system in which data-driven insights refine both design and operations. Integration across product, production, and supply-chain twins is expected to reduce total lifecycle costs by up to 70% (Metrology.news 2023).
The Industrial Internet of Things (IIoT) will connect machines, sensors, and systems across the factory floor and supply chain. This real-time connectivity enables complete transparency and traceability, empowering predictive maintenance, adaptive scheduling, and quality assurance. High-speed networks like private 5G will support these data-intensive applications, while standardized IIoT frameworks will ensure interoperability. The convergence of IIoT with MBE will form a digital nervous system that continuously feeds actionable insights into the model (Diekmann & Kolur 2024).

As MBE systems become more interconnected, cybersecurity becomes paramount. End-to-end encryption, secure authentication, and real-time intrusion detection will protect the integrity of digital models and operational systems. Concurrently, robust data governance frameworks will ensure data quality, provenance, and semantic consistency across domains. Together, these safeguards will protect the digital infrastructure of MBE & MBD while enabling compliant and reliable data sharing (Locke 2025).

In the future, all these technologies will evolve MBE & MBD into an intelligent, self-improving ecosystem. AI, AR/VR, and digital twins will not only support but also co-create and optimize designs. Cloud-edge architectures and IIoT will ensure real-time, actionable feedback loops. Cybersecurity will secure the data layer, while predictive insights and simulation-based engineering will enable agile, resilient manufacturing. MBE will no longer be a methodology—it will be the operating system of the future factory.

MBE & MBD survey conduction

It was decided that a survey among Finnish manufacturing companies should be conducted. The survey was developed by the students in Webropol application. The survey was sent to company representatives with job positions connected with the production site, such as product manager, R&D, and others. The representatives' contacts were found through companies' websites, LinkedIn, or mutual connections. Companies' experience with MBD, MBE, and model utilization is expected to be valuable for the analysis of the Finnish manufacturing market.

Questions for the survey were developed based on the insights from the literature review. The survey scheme is shown in Figure 5. The survey is non-linear because it was assumed that people might utilize MBD principles without knowing the proper terminology. That is why most leading questions were asked after respondents answered that they were unfamiliar with MBD. In addition, the non-linear structure allows people to avoid answering questions about things they are not familiar with. It also helps keep the required time for the survey low, potentially increasing the number of answers.

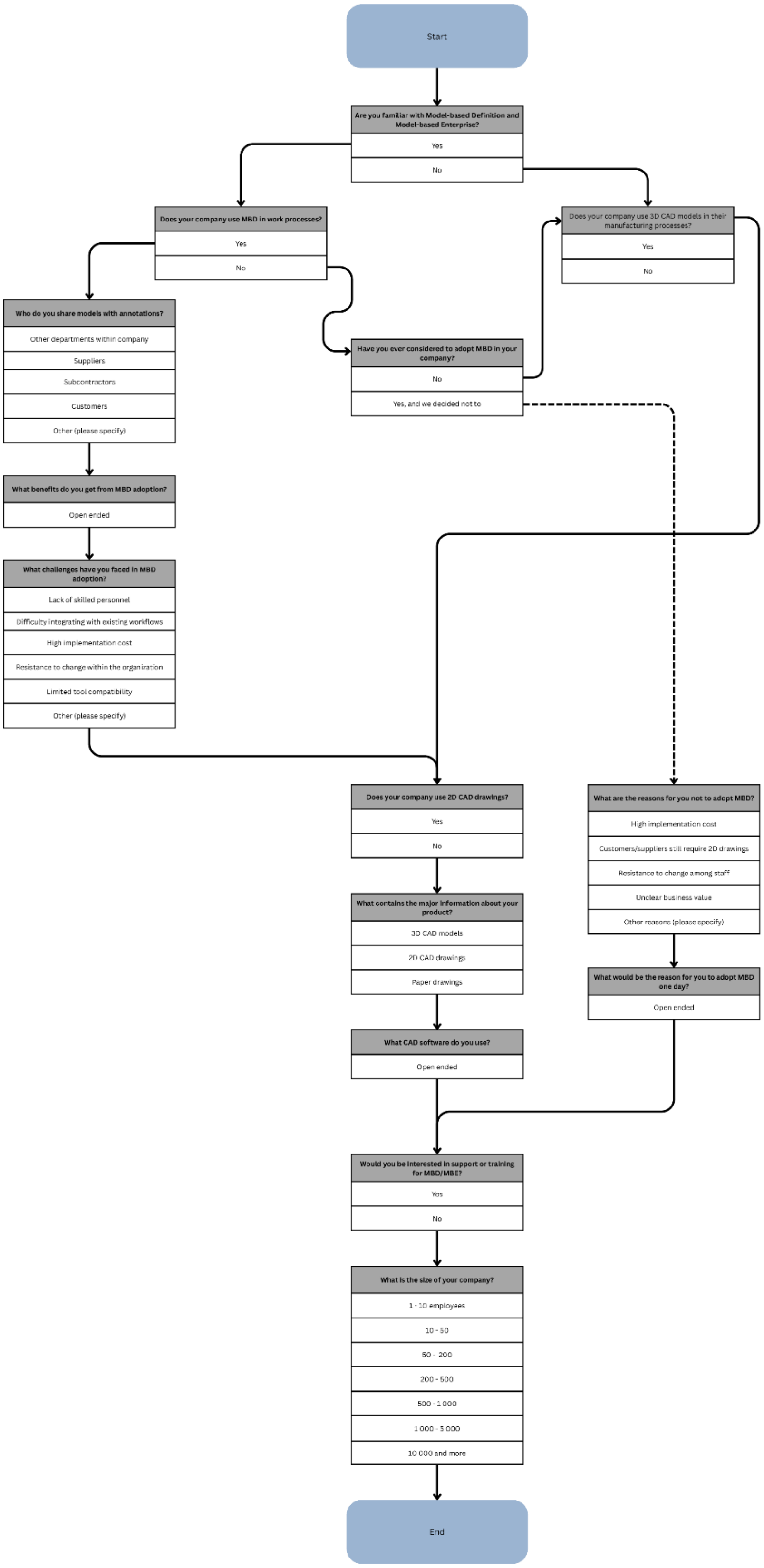


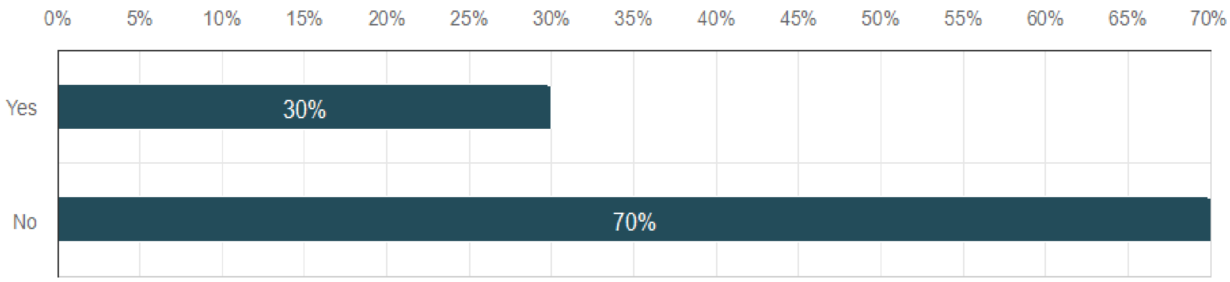
Figure 5. Scheme of the created survey.

MBE & MBD utilization survey results

As a result of the research, ten companies of different sizes shared their experience with model utilization. The next chapter contains the results of the survey.

1. Are you familiar with Model-based Definition and Model-based Enterprise?

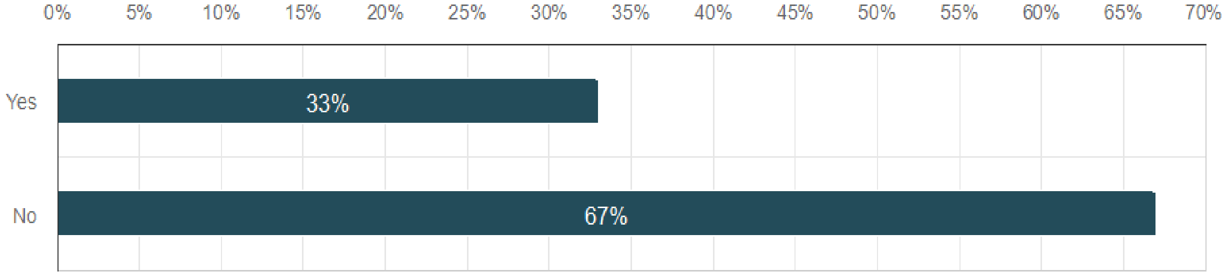
Number of respondents: 10



	n	Percent
Yes	3	30,0%
No	7	70,0%

2. Does your company use MBD in work processes?

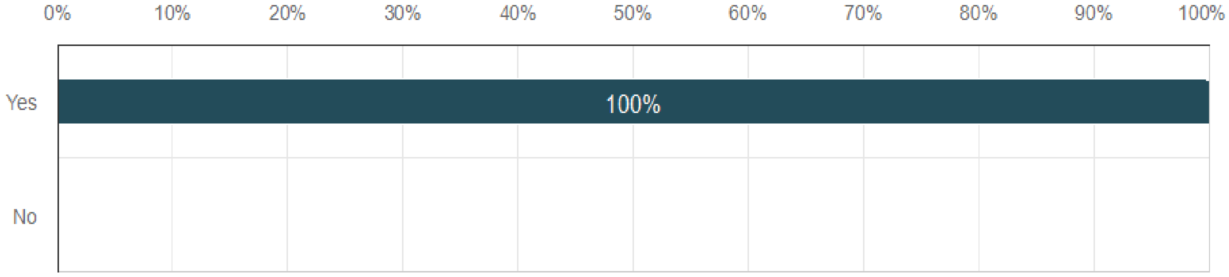
Number of respondents: 3



	n	Percent
Yes	1	33,3%
No	2	66,7%

3. Does your company use 3D CAD models in their manufacturing processes?

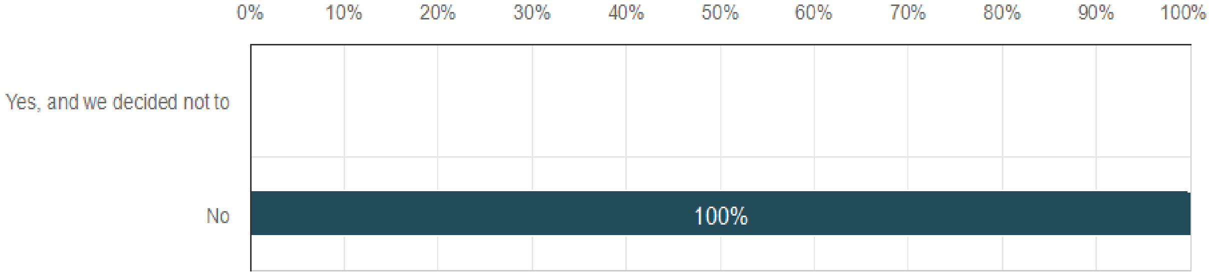
Number of respondents: 9



	n	Percent
Yes	9	100,0%
No	0	0,0%

4. Have you ever considered to adopt MBD in your company?

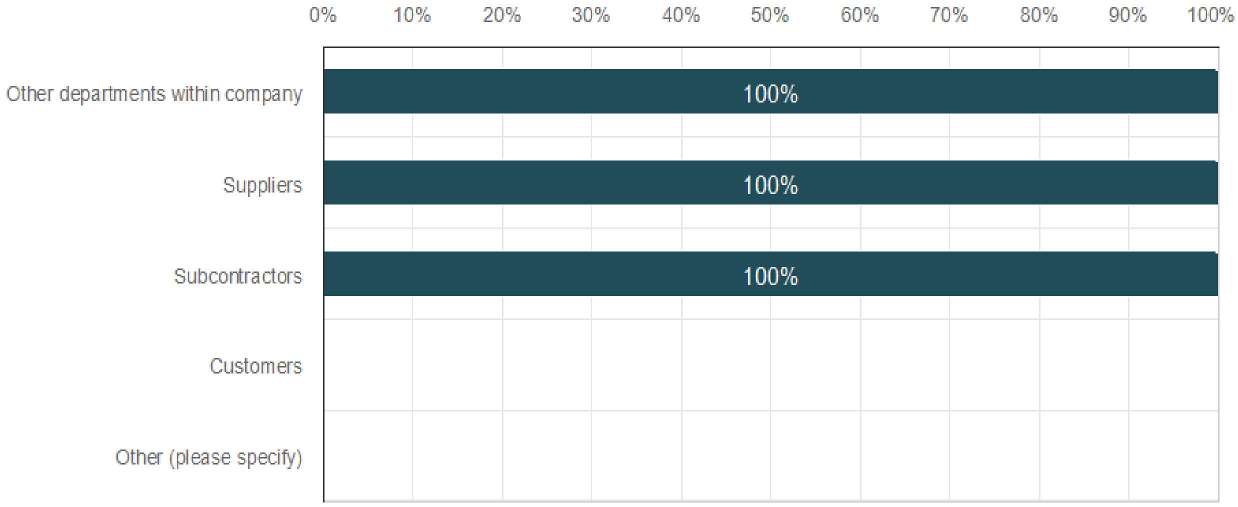
Number of respondents: 2



	n	Percent
Yes, and we decided not to	0	0,0%
No	2	100,0%

5. Who do you share your models with?

Number of respondents: 1, selected answers: 3



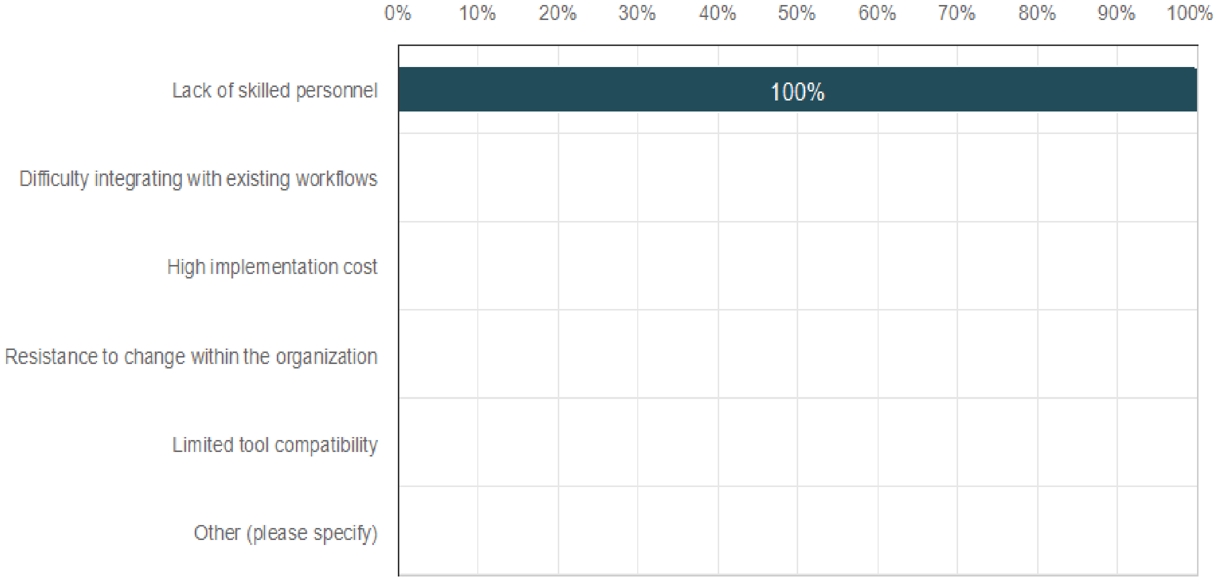
	n	Percent
Other departments within company	1	100,0%
Suppliers	1	100,0%
Subcontractors	1	100,0%
Customers	0	0,0%
Other (please specify)	0	0,0%

Answers given into textfield

Option names	**Text**

6. What challenges have you faced in MBD adoption?

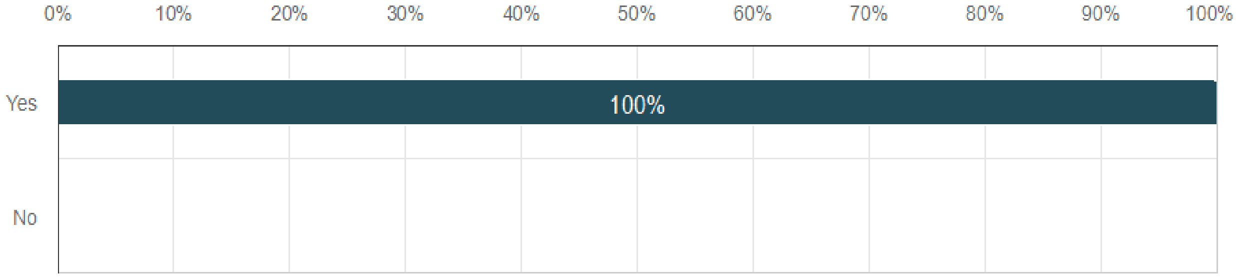
Number of respondents: 1, selected answers: 1



	n	Percent
Lack of skilled personnel	1	100,0%
Difficulty integrating with existing workflows	0	0,0%
High implementation cost	0	0,0%
Resistance to change within the organization	0	0,0%
Limited tool compatibility	0	0,0%
Other (please specify)	0	0,0%

7. Does your company use 2D CAD drawings?

Number of respondents: 10



	n	Percent
Yes	10	100,0%
No	0	0,0%

8. What CAD software do you use?

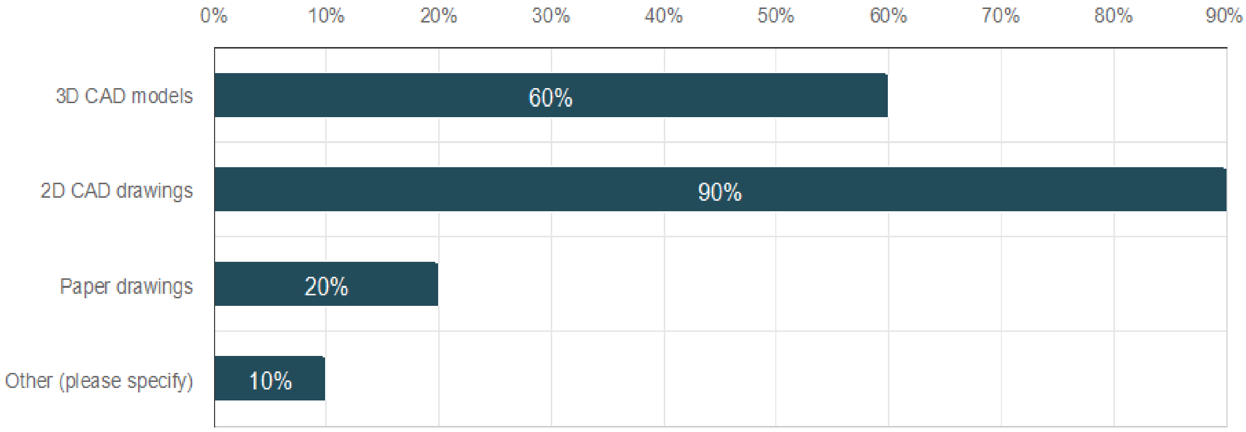
Number of respondents: 10

Responses
Fusion 360
Creo
solid works
Solidworks
Solidworks, Altium
AutoCAD
Calypso/ NX
Creo
Autodesk, vertex kuvien hallinnointiin
AutoCAD 2d ja rhinoceros 3d

Solidworks	3
Creo	2
AutoCAD	2
Fusion 360	1
Altium	1
Calypso	1
NX	1
Vertex kuvien hallinnointiin	1
Rhinoceros 3D	1

9. What contains the major information about your products?

Number of respondents: 10, selected answers: 18



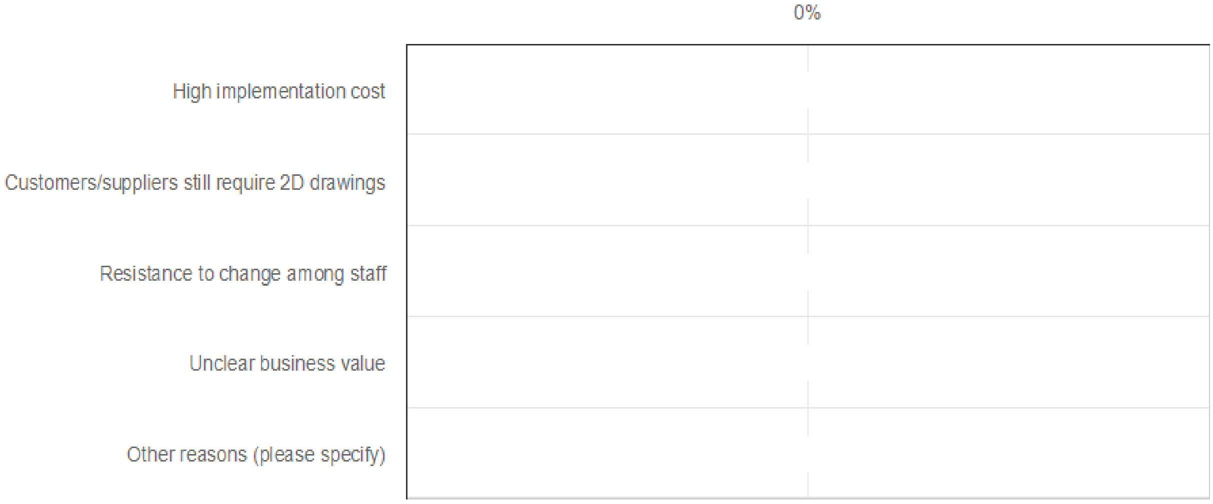
	n	Percent
3D CAD models	6	60,0%
2D CAD drawings	9	90,0%
Paper drawings	2	20,0%
Other (please specify)	1	10,0%

Answers given into textfield

Option names	Text
Other (please specify)	ERP

10. What are the reasons for you not to adopt MBD?

Number of respondents: 0, selected answers: 0



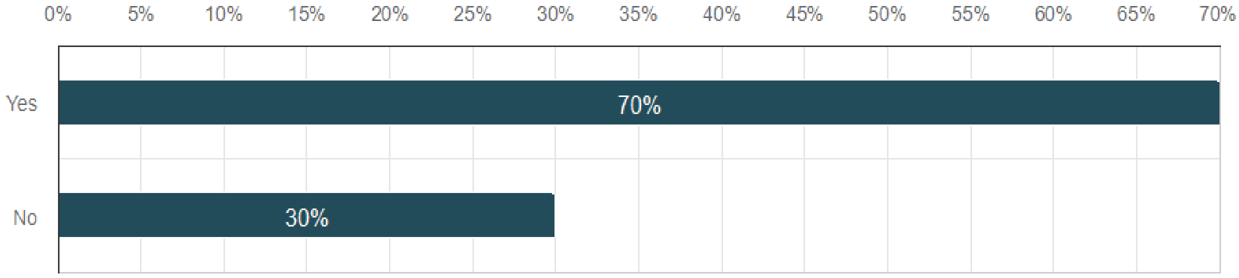
	n	Percent
High implementation cost	0	0,0%
Customers/suppliers still require 2D drawings	0	0,0%
Resistance to change among staff	0	0,0%
Unclear business value	0	0,0%
Other reasons (please specify)	0	0,0%

Answers given into textfield

Option names	**Text**

11. Would you be interested in support or training for MBD/MBE?

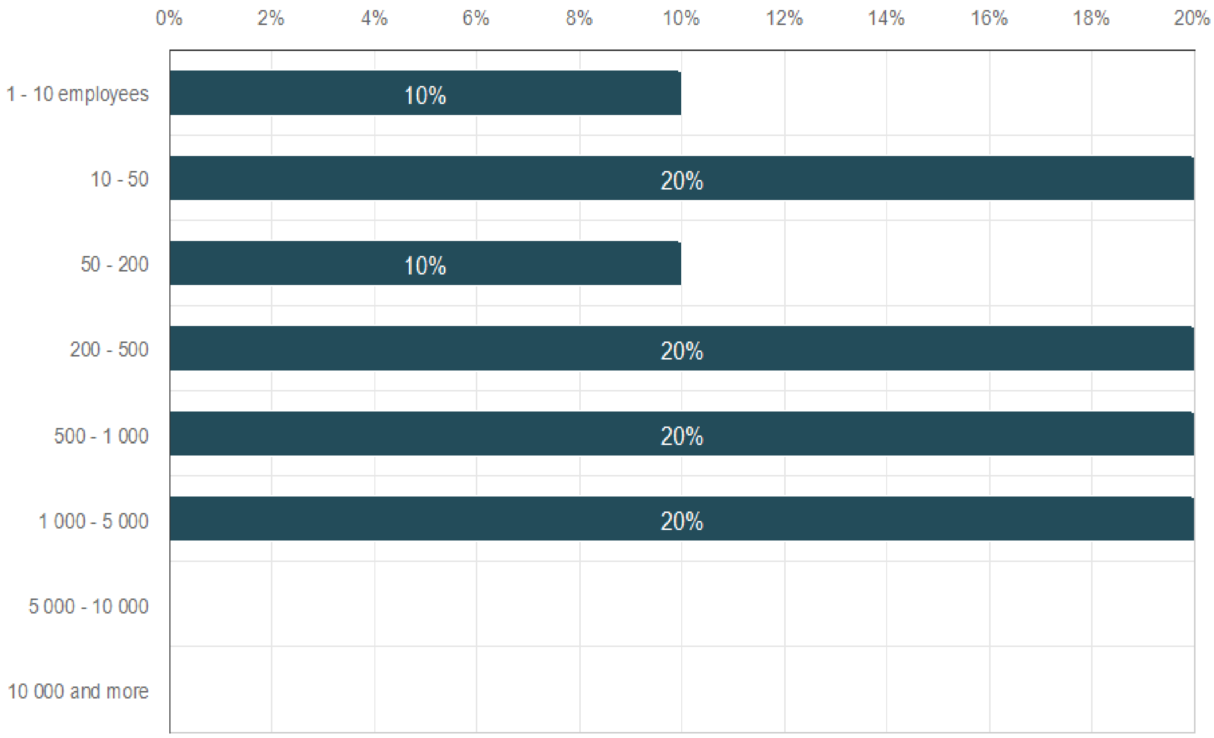
Number of respondents: 10



	n	Percent
Yes	7	70,0%
No	3	30,0%

12. What is the size of your company?

Number of respondents: 10



	n	Percent
1 - 10 employees	1	10,0%
10 - 50	2	20,0%
50 - 200	1	10,0%
200 - 500	2	20,0%
500 - 1 000	2	20,0%
1 000 - 5 000	2	20,0%
5 000 - 10 000	0	0,0%
10 000 and more	0	0,0%

Analysis of the survey results

The survey conducted among Finnish manufacturing companies provided several important insights into the current awareness, implementation, and challenges related to MBD and MBE adoption.

To start with, only 30% of all respondents were familiar with the concepts of MBD & MBE. Only 10% reported that their companies actually implement MBD in their processes. Interestingly, none of the companies that were aware of MBD had considered adopting it more widely. This clearly shows that there is a significant lack of awareness and understanding of these technologies in the Finnish industrial sector.

Despite this, all companies reported using 3D CAD models in their manufacturing processes, which indicates that the technical foundation for MBD exists. However, 100% of respondents also confirmed that they still use 2D CAD drawings. In fact, 90% stated that most of the significant product information is stored in 2D drawings, and 20% of respondents said they continue to use paper drawings as well. This suggests that although digital tools are available, companies are still heavily reliant on traditional documentation methods.

The results also revealed that a wide variety of CAD software is used in the industry, with SolidWorks being the most common, followed by Creo and AutoCAD. Other tools mentioned included Fusion 360, Altium, NX, and Rhinoceros. This software diversity might lead to integration issues between different departments and external partners, making collaboration more difficult.

A key insight is the high level of interest in support and training: 70% of companies expressed that they would be interested in receiving help with MBD or MBE. This is especially relevant when we consider that the one company already using MBD identified "a lack of skilled personnel" as the main challenge. The gap between interest and readiness suggests that companies see the potential of model-based methods but do not yet have the resources or expertise to implement them.

This situation presents a clear opportunity for educational institutions and service providers. More training programs, practical workshops, and consultancy services could help Finnish companies build the necessary competence to move toward model-based processes.

While 3D CAD is widely used, only a small fraction of companies apply MBD in a strategic way. This implies that the most significant barrier is not technology access but the process and organizational transformation required to change how digital tools are used. Without addressing internal workflows and change management, companies are unlikely to benefit from their existing technological capabilities fully.

In summary, the survey results show that Finnish manufacturing companies are technologically equipped for MBD and MBE but organizationally underprepared. There is clear interest and willingness to learn more, but current adoption levels are low due to a lack of knowledge, training, and strategic planning. To support wider MBE and MBD adoption, focused training initiatives and better communication of the business benefits are essential. Bridging this gap could unlock significant improvements in efficiency, data accuracy, and competitive performance.

Conclusion

The research presented in this thesis has explored the current state of MBD & MBE in industrial settings, with a focus on both global developments and the situation in Finnish manufacturing. The findings from the literature review and the survey provide a comprehensive picture of model-based approaches are evolving and what challenges lie ahead.

The literature review revealed that MBD and MBE are important parts of the broader Industry 4.0 transformation. These methods are not just technical upgrades but strategic tools that can enhance data quality, increase productivity, reduce costs, and support sustainable manufacturing. By replacing traditional document-based processes with digital 3D models enriched with all necessary information, companies can improve communication across departments and supply chains while also enabling automation and traceability.

The case study of Lockheed Martin demonstrated how a large organization can successfully implement these practices with the help of careful planning, strong leadership, and a focus on workforce development. Their approach to supplier collaboration, usage of open standards, and investment in infrastructure evidently shows the long-term value of adopting MBE & MBD.

At the same time, the survey of Finnish manufacturing companies highlighted a significant gap between interest in these technologies and their current level of adoption. Although most companies use 3D CAD models, they still rely heavily on 2D drawings for critical information. Only a small number of companies have started to implement MBD, and even less companis have a clear strategy for full MBE integration. Lack of awareness, training, and internal expertise remain the main barriers.

Anyway, the survey also revealed a high level of interest in learning more about MBD and MBE. This presents an excellent opportunity for educational institutions, consultants, and technology providers to support the industrial sector through training programs, pilot projects, and better communication of the benefits. Closing this knowledge and skill gap could unlock significant improvements in efficiency, collaboration, and product quality.

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