Bibliometric analysis of model-based systems engineering in advanced manufacturing

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Abstract

Purpose – Model-based systems engineering (MBSE) is an important approach for the transforming process from "document-centered" to "model centered" systems engineering mode in equipment development, which can effectively shorten the equipment development cycle and improve product design quality. This paper aims to understand if MBSE enables to support manufacturing and equipment development.

Design/methodology/approach – The paper opted a bibliometric analysis of MBSE in domain of advanced manufacturing from different perspectives such as publication volume, research team, sources and keyword co-occurrence.

Findings – Firstly, the application of MBSE in advanced manufacturing can be roughly divided into three stages. And MBSE has been widely implemented globally and has gradually formed several noteworthy teams. Secondly, this article has identified some high-quality sources, with a large number of publications and citations, the most influential publications focus on the practice or guidance of digital twins and intelligent manufacturing. Thirdly, research can be divided into six categories, including systems engineering, digitalization, intelligent manufacturing, product design, model and architecture and MBSE applications.

Research limitations/implications – Because of the chosen research approach, the visualized network tends to lose certain information such as a few keywords may be inaccurately categorized.

Practical implications – This paper comprehensively study the research status of MBSE in advanced manufacturing and forecasts future research trends, emphasizing the combination of intelligent manufacturing and digitization.

Originality/value – This paper fulfills an identified need to understand the current application status and future development trends of MBSE.

Keywords Bibliometric analysis, Digitization, Model-based systems engineering, Manufacturing systems

Paper type Literature review

1. Introduction

Model-based systems engineering (MBSE) is the formal application of modeling to support systems engineering activities such as system requirements analysis, design and validation, starting from the conceptual design stages to the later lifecycle stages. MBSE first appeared from

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academia around 1993 (Wayne, 1993), and after 30 years of development, is now considered a technical solution that can effectively assist engineers in system development particularly for conceptual design and product development using a model-based architecture modeling approach.

The main application of MBSE was initially in the aerospace field, which is a typical complex system. As the complexity and uncertainty of aerospace product systems increased rapidly, posing huge challenges to requirement analysis, design and verification (Heihoff-Schwede *et al.*, 2019). MBSE takes the model as the core and provides a full lifecycle perspective from system to components, including requirement analysis, functional analysis and behavior analysis. With the deepening of Industry 4.0 and intelligent manufacturing, MBSE has gradually begun to be applied in manufacturing industries such as electric vehicles (Kirpes *et al.*, 2019) and smart grids (Brankovic *et al.*, 2023), and emerged many new connotations integrated with lean manufacturing and intelligent manufacturing concepts due to its digital characteristics. Vahid Khalil *et al.* (2020) proposed an agile MBSE for future digital products, and Tliba (Salehi, 2020) proposed an approach applying MBSE to flexible manufacturing and reconfigurable manufacturing systems.

However, it is a challenge for researchers to use and to analyze the large and growing MBSE research literature effectively (Bornmann and Mutz, 2015), particularly in the domain of advanced manufacturing. In order to help researchers better collect and organize the development status and technological connotations of MBSE, this paper uses the bibliometric analysis to systematically analyze the relevant literature about the application of MBSE in manufacturing systems. We identify the most influential authors and sources as they represent the forefront of the theoretical and technological research. This paper analyzes the current situation and interrelationships between research hotspots to track future development trends, which can better guide the digitization of manufacturing and empower intelligent manufacturing.

This paper is organized as follows. Section 2 discusses the data sources and research methodology. Section 3 presents the analysis results. Finally, Section 4 concludes this article.

2. Data sources and research methodology

2.1 Data sources

This paper collected publications related to MBSE and manufacturing systems from 1993 to 2023, as the first related literature was published in 1993 and our search was conducted in November 2023. In terms of database selection, Web Of Science is a high-quality data base, but Mongeon's research (Mongeon and Paul-Hus, 2016), Vivek's research (Singh *et al.*, 2021) and our practice indicate that Scopus comprising of 40,385 journal entries has a wider database coverage than Web Of Science which is comprised of 13,610 journal entries. Therefore, the publications searched in this paper are sourced from Scopus.

2.2 Research methodology

As shown in Figure 1, the research in this paper is divided into four steps: (1) data collection, (2) data processing, (3) data analysis and (4) data results. The details are as follows:

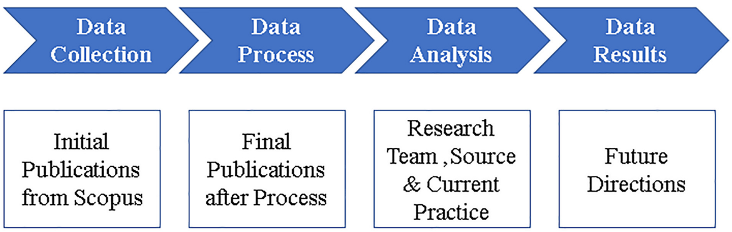

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Figure 1.
Research steps

(1) Data collection:

This paper used an advanced search function in Scopus with input: ALL ("MBSE") OR ("Model based System Engineering (MBSE)") AND ALL ("manufacturing system"). Then we exported all data including title, abstract, keywords and other information to a Comma-Separated Values (CSV) file.

(2) Data processing:

The consistency of statistical data can ensure the reliability of bibliometric analysis results. Therefore, the collected data was further filtered and processed. The processing focused on the consistency of keywords. For example, different publications have different opinions on whether to add "s" after words such as "system" and "twin". In order to make the visualization results more credible, this article uses a unified "model-based systems engineering" and "digital twin" to maintain consistency in terms.

(3) Data analysis:

Vosviewer is a knowledge graph software that can be used for scientific bibliometric analysis and visualization. It uses co-occurrence clustering to construct and visualize the network, showcasing the structure and collaboration of knowledge domains. The bibliometric analysis of relevant literature in the fields of MBSE and manufacturing was conducted on VOSViewer, which can analyze the interrelationships between nodes including author, source and keywords by a distance based network. Strongly correlated nodes closed to each other will form a cluster and be classified according to different colors. In addition, the size of each node in the network is positively correlated with its weight, representing the number of references, citation frequency, etc.

(4) Data results

Through the co-occurrence clustering algorithm of Vosviewer, relevant network visualization results can be obtained. Analyzing the current application and team cooperation of MBSE in the domain of advanced manufacturing, which can enable researchers to effectively obtain current research progress and judge future development directions.

3. Bibliometrics analysis for MBSE

3.1 Overview

This study collected 1128 publications from 1993 to 2023, as shown in Figure 2. The horizontal axis represents the year, and the vertical axis represents the number of all publications in that year. The color of the points represents the total number of citations count in that year, with specific intervals shown in the legend. The size of the points is determined by the average number of citations in that year.

The time distribution of the number of publications reflects the research progress and development trends. The total number of publications per year did not exceed 20 until 2014. In Figure 2, the point circled in red represents the data from 2008. Since 2008 which was an important turning point, the total number of publications per year has steadily increased, reaching a peak of 255 in 2022. After that, research on MBSE in manufacturing has entered a new stage, largely due to The International Council on Systems Engineering (INCOSE's) definition of MBSE and its vision for the future development of systems engineering (Li *et al.*, 2022).

As shown in Figure 2, the average number of citations per year increased from 29 in 2006 to a peak exceeding 40 in 2020, indicating the publication of much highly cited literature. There are four years in which the average number of citations exceeds 20, namely 2006, 2016,

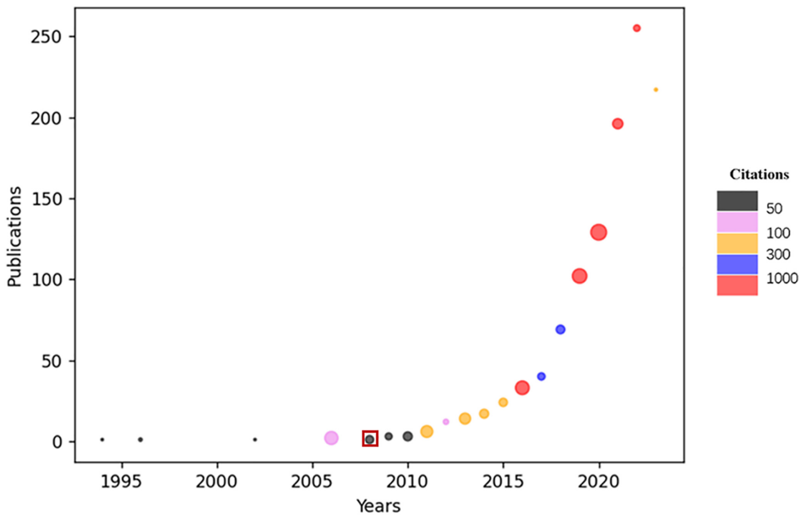

Figure 2.
Publication overview

Source(s): Authors' own work

2019 and 2020. The most frequently cited literature in these years is *Model Composition* (Sarjoughian and Mayer, 2016), *Design Structure Matrix extensions and Innovations: A Survey and New Opportunities* (Browning, 2016), *Digital Twin in Industry: State of the Art* (Tao *et al.*, 2019), *Literature review of Industry 4.0 and related technologies* (Oztemel and Gursev, 2020).

The color of the points representing the data from 2019 to 2022 is red, which means that the total number of citations in recent years has been at a high level, exceeding 1000. At the same time, the number of publications has also rapidly increased. The color of the points representing 2023 is yellow, and the total number of citations for that year is between 100 and 300. At the same time, the size of that point is significantly smaller than previous years, indicating that the average citation for that year is relatively low. This may be due to the short publication time or indicating that some cutting-edge concepts in MBSE are still waiting for practical verification in the advanced manufacturing.

3.2 Research team analysis

The co-author analysis can be used to retrieve and analyze key research teams and their collaborative relationships. In order to better show the visual network between active research teams, this paper sets a threshold of 5 publications, with 93 of 3013 authors meeting this requirement. Some of the 93 authors have no affiliations with other authors, thus the largest network of affiliations includes 58 authors. After the cluster computing of VOSviewer, nodes with closely relationships have the same color, resulting in 8 active teams in the MBSE and manufacturing as shown in Figure 3. Each node represents an author, and the size of the node represents the total number of publications by that author. The largest research team is represented by liu. j, wang. s (blue cluster), which has 19 members and collaborates with four other research teams in the network. The second largest research team is represented by Vogel Heuser (Hehenberger *et al.*, 2016) (yellow cluster), which has a collaborative relationship with two other research teams in the network.

As shown in Figure 4, it represents the activity level of each research team from 2019 to 2022, representing the color from purple to green to yellow. It can be seen that teams represented

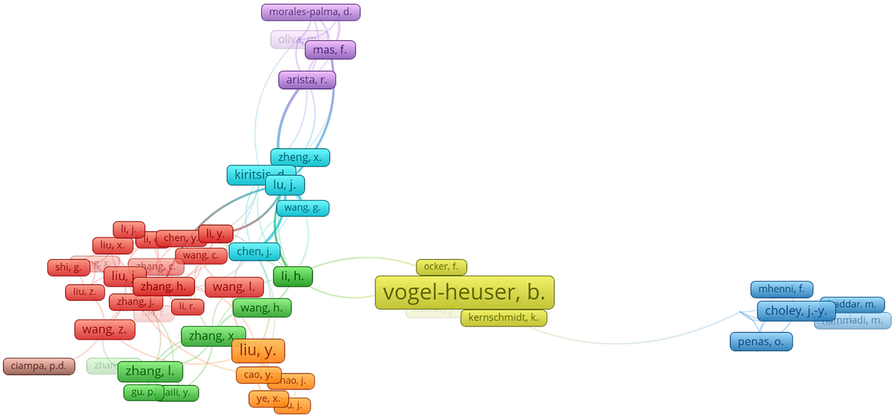

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Figure 3.
Authorship collaborative network

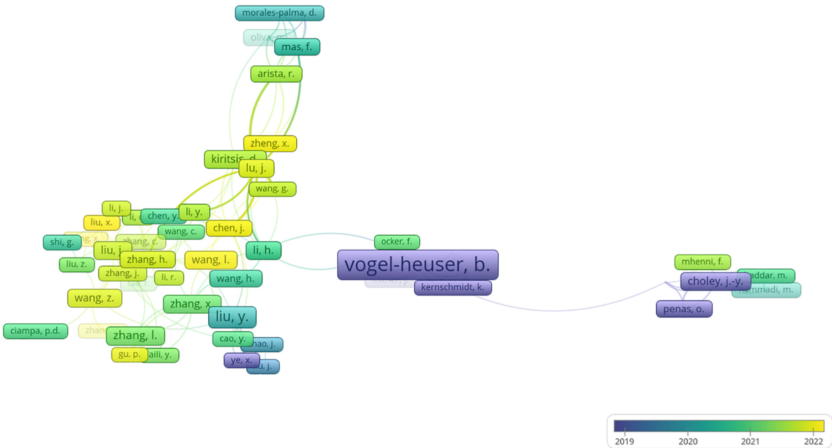

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Figure 4.
Research team activity

by Lu *et al.* (2020) and teams represented by Zhang *et al.* (2023) and Yang *et al.* (2023) have been relatively active in recent years. It can be inferred that their research is dedicated to promoting the latest and even the next generation technologies of MBSE to manufacturing.

This paper collected geographic information from literature by VOSviewer, as shown in Figure 5. A threshold of 2 publications was set, with 63 of 92 countries meeting this requirement. The total number of publications in Germany is 226, accounting for 20.0% of the total, followed by China (18.1%), the United States (16.8%), France (7.9%) and Italy (5.7%). Europe, China and the United States account for over 80% of all publications, making them leaders in advanced manufacturing and indicating rapid development and wide application in MBSE.

3.3 Source analysis

Based on citation analysis in VOSviewer, this paper reveals the connections between the sources of these publications. A threshold of 5 publications was set, and 47 of 528 sources

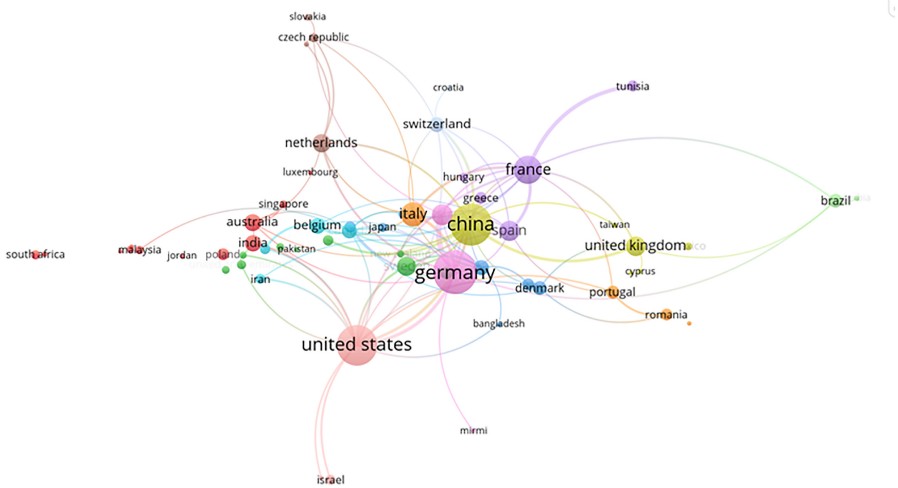

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Figure 5.
Researcher distribution

meeting the criteria. The results are shown in Figure 6. Citation analysis is the process of counting the number of citations in a publication. Therefore, the larger the node size in the network, the higher the average number of citations from that source.

To provide a detailed illustration of the graph, Table 1 and Table 2 list 9 sources sorted by total citations (TC) and total publications (TP).

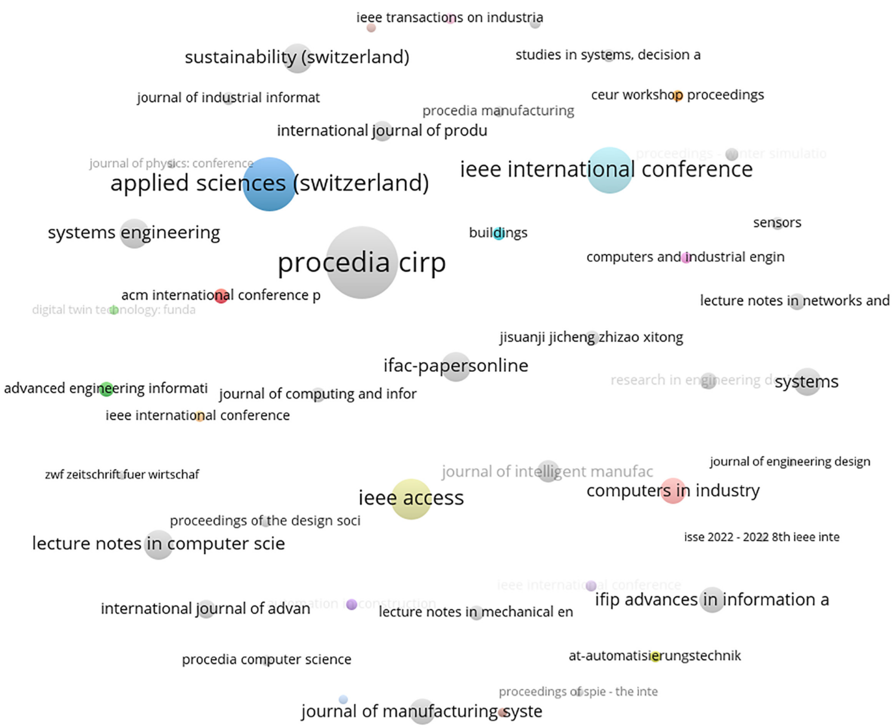
Only three sources appear in the top nine rankings of TC and TP simultaneously, namely *International Federation of Automatic Control (IFAC) Paper online*, *Applied Sciences* (Switzerland) and *IEEE Access*. Among them, the number of publications on *IEEE Transactions on Industrial Information* is 6, with a high citation count of 1599.

Table 3 lists the top ten most cited publications among all, with 7 articles and 3 reviews. These publications mainly focus on digital twin, which also reflects the research hotspots and cutting-edge applications of MBSE in advanced manufacturing. The most cited article was published in 2019 on *IEEE Journal of Industrial Informatics* (Tao *et al.*, 2019), with 1503 citations.

3.4 Current state of the art analysis

Cluster analysis of co-occurrence keywords in literature based on VOSviewer can provide a clearer understanding of the current practice of MBSE in advanced manufacturing. This paper sets the keyword co-occurrence frequency of 7 times as the threshold, and 68 of 2831 keywords meeting the criteria. Co-occurrence keywords refer to keywords that appear together in the same literature. As shown in Figure 7, the resulting co-occurrence network consists of 6 clusters. This paper defines the theme of each cluster based on its keywords, and the details are shown in Table 4.

Red cluster accounts for 31.1% of all keywords, with the theme word of systems engineering. Essentially, the manufacturing systems are complex systems that couples multiple elements of human, machine, material, method and environment managed by systems engineering. And MBSE is a holistic system engineering approach centered on evolutionary system models (Madni and Sievers, 2018). MBSE is widely applied in conceptual design and functional modeling in systems engineering. System thinking is the foundation of



Source(s): Authors' own work

Figure 6. Source citation analysis

Rank	Source	TP	TC
1	*Procedia Crip*	39	360
2	*Applied Sciences*(switzerland)	29	468
3	*IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*	25	237
4	*IEEE Access*	22	1761
5	*IFAC Papers online*	16	74
6	*Lecture Notes in Computer Science*	16	100
7	*Systems Engineering*	16	128
8	*Sustainability*	16	189
9	*Systems*	15	113

Source(s): Authors' own work

Table 1. Top 9 sources according to TP

systems engineering and the fundamental idea of observing and defining systems of interest (Cloutier *et al.*, 2014). Ontology can obtain explicit and implicit domain knowledge from historical records and domain experts (Arista *et al.*, 2023). And through knowledge graphs, design knowledge integration can be better reused and innovated, promoting further development of MBSE (Zhu *et al.*, 2023).

The theme word for orange cluster is digitalization. Digitization is a trend driven by the Internet of things in the background of Industry 4.0. Researchers have proposed many new

Rank	Source	TP	TC
1	*IEEE Access*	22	1761
2	*IEEE Transactions on Industrial Information*	6	1599
3	*Journal of Intelligent Manufacturing*	12	1469
4	*Journal of Manufacturing Systems*	14	1130
5	*Computers in industry*	14	944
6	*Applied Sciences*(switzerland)	29	468
7	*Procedia crip*	39	360
8	*International Journal of Production Research*	11	266
9	*Crip annals*	5	246

Source(s): Authors' own work

Table 2.
Top 9 sources according to TC

Rank	Title	Year	Source	Citation	Type
1	Digital Twin in Industry: State-of-the-Art	2019	*IEEE Transactions on Industrial Informatics*	1503	Article
2	Literature review of Industry 4.0 and related technologies	2020	*Journal of Intelligent Manufacturing*	1003	Review
3	Characterising the Digital Twin: A systematic literature review	2020	*CIRP Journal of Manufacturing Science and Technology*	799	Article
4	Digital Twin: Enabling Technologies, Challenges and Open Research	2020	*IEEE Access*	750	Article
5	Review of digital twin about concepts, technologies and industrial applications	2021	*Journal of Manufacturing Systems*	556	Article
6	A survey on digital twin: Definitions, characteristics, applications and design implications	2019	*IEEE Access*	517	Review
7	A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives	2020	*Journal of Intelligent Manufacturing*	297	Review
8	Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities	2016	*IEEE Transactions on Engineering Management*	243	Article
9	Digital twin paradigm: A systematic literature review	2021	*Computers in Industry*	238	Article
	Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios and Architectural Models	2020	*Proceedings of the IEEE*	238	Article

Source(s): Authors' own work

Table 3.
Top highest citations publications

technological applications by combining new digital technology concepts with MBSE. Manufacturing digital thread takes a model-based approach to describe both each step as well as the connectivity and interoperability of manufacturing processes, both digital and physical (Liu *et al.*, 2023). Digital thread and digital twin serve the entire production lifecycle based on models, laying the foundation for achieving production paradigms that meet the requirements of intelligent manufacturing. The US Department of Defense released its Digital Engineering Strategy in 2018, which for the first time defines digital engineering as an integrated digital approach that uses authoritative system data and models as an interdisciplinary continuum to support lifecycle activities from concept to obsolescence (Department of Defense, 2018). This is an extension of MBSE in the digital age.

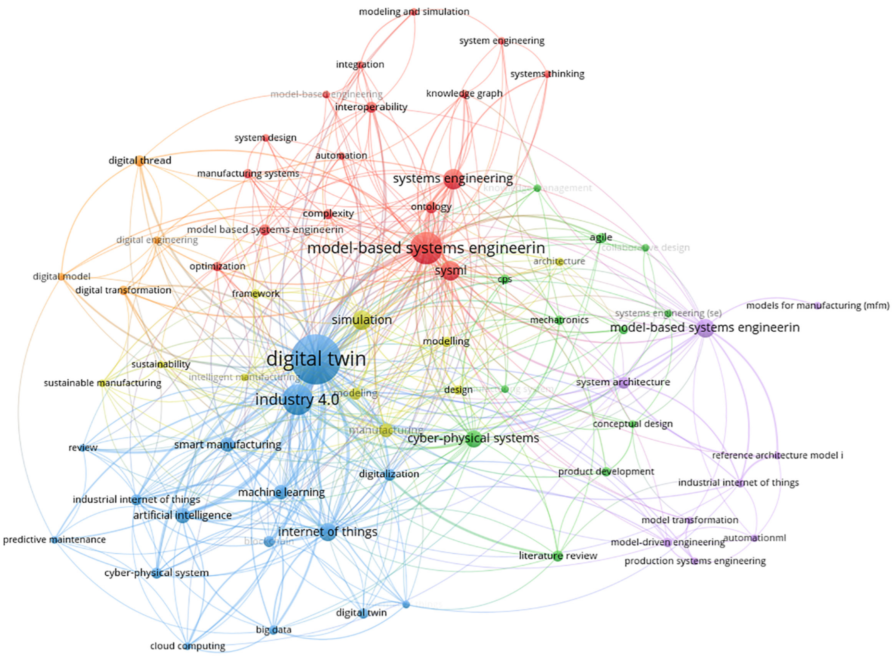


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Figure 7.
Co-occurrence keywords network

The theme of blue cluster is intelligent manufacturing, which accounted for 41.4% of all keywords. In terms of frequency, it is the most in all clusters. Since the 21st century, the emergence of information technologies such as cloud computing, the Internet of things, digital twin and big data has promoted the transformation and upgrading of the manufacturing towards a new generation of intelligent manufacturing. Digital twin was initially defined in 2007, but occupy 9 of the top 10 cited literature in Table 3. The operation content of digital twin comes from the system model constructed through MBSE, therefore, digital twins are known as the possible core of MBSE in the future (Madni *et al.*, 2019). The interconnection and optimization of distributed and heterogeneous manufacturing resources and manufacturing services realized through the full manufacturing process and full lifecycle data has become a trend in the development of the manufacturing. Therefore, major manufacturing countries around the world have proposed different strategic plans to seize the commanding heights of future manufacturing, such as the industrial internet advocated by the United States (Evans and Annunziata, 2012), Industry 4.0 proposed by Germany (Kagermann, 2015) and Made in China (2025) promoted by China (Tan, 2017). Liu *et al.* (2021) constructed a comprehensive digital twin (DT) model for the shop floor by using system modeling language, the modeling method "MagicGrid," and the "V model" of systems engineering. An orchestration method (Brusa *et al.*, 2023) was proposed to implement integrated multi-disciplinary simulation through the combination of DT and MBSE.

The theme word for green cluster is product design. Small batch, personalized and complex customized products bring problems such as low level of design intelligence and difficulty in design verification. It is urgent to adopt standardized models throughout the entire product design process. Knowledge engineering, with knowledge management as its

Cluster	Topic	Keywords	Occ	Total
Red	System engineering	Automation	8	
		Complexity	12	
		Integration	8	
		Interoperability	14	
		Knowledge graph	9	
		Manufacturing systems	17	
		Model-based engineering	50	
		Model-based system engineering	180	
		Ontology	17	457
		Optimization	10	
		Sysml	45	
		System design	7	
		System engineering	65	
		Systems thinking	7	
		Model and simulation	8	
Blue	Smart manufacturing	Artificial intelligence	27	
		Big data	11	
		Cloud computing	7	
		Industrial Internet of things	9	
		Internet of things	45	
		Machine learning	25	289
		Industry 4.0	111	
		Predictive maintenance	7	
		Review	8	
		Smart manufacturing	24	
		Block chain	15	
Green	Product design	Agile	12	
		Collaborative design	8	
		Concepted design	8	
		Cyber-physical system	60	
		Design methodology	9	138
		Knowledge management	7	
		Literature review	14	
		Mechatronics	10	
		product development	10	
Yellow	MBSE Application	Architecture	9	
		Design	10	
		Framework	11	
		Intelligent manufacturing	8	
		Manufacturing	21	149
		Modeling	29	
		Simulation	46	
		Sustainability	8	
		Sustainability manufacturing	7	
Purple	Model and Architecture	Automation	7	
		Model transformation	7	
		Model for manufacturing	8	
		Production systems engineering	7	54
		Reference architecture	8	
		Systems architecture	17	
Orange	Digitalization	Digital engineering	8	
		Digital model	7	
		Digital thread	14	56
		Digital transformation	10	
		Digitalization	17	

Source(s): Authors' own work

Table 4.
Co-occurrence keywords Cluster

core, can complement MBSE by integrating design knowledge through reuse and innovation, achieving formal modeling and process analysis of the entire system, and forming an intelligent design technology system (Wu *et al.*, 2022).

The theme words of the earthy yellow cluster are the application of MBSE. Design verification is an important link in the product development process, which can improve the quality of product design and reduce the cost of design changes in the later stage. One of the purposes of modeling is to verify and validate (Reilley *et al.*, 2016). The focus of simulation not only includes directly establishing simulation models in simulation software, but also converting system models into simulation models (Guo *et al.*, 2020). This new technology also includes studying discrete event system simulation using activity diagrams, state machine diagrams, etc (Alshareef *et al.*, 2020). Through MBSE, forward design can be achieved starting from requirements, using models to reflect user needs. This application can effectively solve decision-making challenges (Russell, 2012), and reduce the risk of delayed delivery, resulting in sustainable manufacturing.

The theme word for purple cluster is the model and architecture. The design of manufacturing systems, especially intelligent manufacturing systems, cannot be separated from the design of system architecture models. Automation can be empowered by constructing models for manufacturing. The industry 4.0 reference architecture model (RAMI 4.0) was published by the German Committee for Standardization of Electrical, Electronics and Information Technology in 2015 (Institute of Comprehensive Technology and Economics for Mechanical Industry Instruments and Meter, 2015). It combines the entire lifecycle and value chain with the hierarchical structure of Industry 4.0, providing maximum flexibility for describing and implementing Industry 4.0. Developing MBSE based on RAMI 4.0 can better address the increased complexity of production systems caused by cyber physical systems (CPS) or IoT (Binder *et al.*, 2021) and address the design and manufacturing issues of specific domain systems.

4. Discussions

This paper conducts a bibliometric analysis of the application of MBSE in the domain of advanced manufacturing:

(1) Overview. Figure 1 shows the annual research trends, which indicate a growing interest among researchers in this application. It will also attract more researchers to join this application. Based on the number and the TC of the publications, we divide the development of this application into three periods. The first period is the embryonic stage (from 1993 to 2006). MBSE technology had just started with poor adoption because of its technical inadequacies (Chami and Bruel, 2018). At the same time, the research of intelligent manufacturing focused on “Genetic algorithm”, “Optimization”, “Expert system” (Yuan *et al.*, 2022) and so on, with great emphasis on manufacturing itself. Therefore, the application of MBSE in the domain of manufacturing was also limited. The second period is the development period (from 2006 to 2016). At this stage, INCOSE precisely defined the concept of MBSE. Researchers started to practice and explore the application of MBSE in manufacturing. Open services for lifecycle collaboration (OSLC) (OSLC, 2008) was proposed to integrate all heterogeneous data throughout the lifecycle. Some modeling tools were applicated in NASA and European Space Agency (ESA), whose modeling languages widely used in complex production system design and verification, such as SysML and Capella. The third period is the explosive period (from 2016 to now). With the maturity of technologies such as big data, industrial IoT and cloud computing, the manufacturing industry is not satisfied with the effectiveness of lean production and

agile manufacturing, starting to explore towards Industry 4.0 and the combination of virtual and physical manufacturing systems. Digitization is an important feature of intelligent manufacturing, and models are an important manifestation of product digitization. The cyber physics system and digital twin based on digital models have sparked research interest in further exploring the integration of MBSE and advanced manufacturing. With the continuous development of technology, how to cope with the new complex characteristics emerging from the integration of the two will be an important research topic.

(2) Research team analysis. Figure 3 shows the 7 major teams of this application with certain achievements and Figure 4 shows their recent activity. Future researchers can quickly understand the cutting-edge developments in this application by studying the publications of the main teams. Figure 5 shows the depth of application in various countries. The more developed the manufacturing industry, the more research progress in this field can be promoted. And the more mature the industrial structure is, the more demands and suitability for digital transformation. MBSE can provide transformation impetus for the manufacturing industry.

(3) Source analysis. Tables 1 and Table 2 show the most active journals in this field. Researchers engaged in MBSE and advanced manufacturing can consider publishing their own articles in corresponding journals in the future. Table 3 shows the top 10 most cited articles, but there are 9 papers on the topic of digital twins, and 3 of them are reviews. It indicates that digital twin, as a current research hotspot, have a wide range of applications in various fields. Many new researchers need to quickly understand the relevant research status through reviews.

(4) Current state-of-the-art analysis. Figure 7 shows the 6 major clusters of application. They are "System Engineering", "Intelligent Manufacturing", "Product Design", "MBSE" Applications, "Digitalization" and "Model and Architecture". Intelligent manufacturing is the largest cluster, encompassing numerous enabling technologies for intelligent manufacturing. In the future, with the continuous enhancement of model integration capabilities, MBSE will truly achieve the integration of product design, production and services throughout the entire lifecycle.

5. Conclusion

MBSE, as a widely used technology in the aerospace field, has developed rapidly in recent years and has begun to expand to other industries. In order to comprehensively understand the application of the latest MBSE technology in advanced manufacturing, this paper conducted a bibliometric analysis of relevant literature from 1993 to 2023. Firstly, in terms of research progress, the application research of MBSE in advanced manufacturing can be roughly divided into three stages. According to the analysis of the research team, MBSE has been widely implemented globally and has gradually formed several noteworthy teams, ranging from collaborative teams to independent teams. All teams have multiple publications with high citation. Secondly, this article has identified some high-quality sources, with a large number of publications and citations. In addition, as shown in the table, the most influential publications focus on the practice or guidance of digital twins and intelligent manufacturing. Thirdly, research can be divided into six categories, including systems engineering, digitalization, intelligent manufacturing, product design, model and architecture and MBSE applications.

It can be seen that MBSE, as a system engineering technology, has begun to be applied in the field of intelligent manufacturing, integrating with emerging technologies such as digital twins and artificial intelligence. The future development of the manufacturing will be based on digitalization. And for MBSE, research focus will be on the following aspects:

(1) With the transition from single delivery to dual delivery mode, digital prototypes for design and manufacturing have also become important products, promoting the rapid construction and widespread application of digital models, and enabling digital models to digitize the entire lifecycle of product design and manufacturing will become an important issue.

(2) Platform tools are an important support for digitization, researching integrated service platforms with multiple languages, stages and fields, integrating next-generation emerging MBSE technology, and laying the foundation for the rapid development of advanced manufacturing industry with independently developed platforms.

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