Bibliometric Analysis of Model-Based Systems Engineering: Past, Current, and Future

Zihang Li, Guoxin Wang, Jinzhi Lu, *Member, IEEE*, Didem Gürdür Broo, *Senior Member, IEEE*, Dimitris Kiritsis, and Yan Yan

***Abstract*—Model-based systems engineering (MBSE) is considered an important approach for understanding multidomain fields and is widely used in complex systems such as aerospace. In this article, a detailed survey of MBSE literature was conducted from its commencement to the present trends through bibliometric analysis. Some bibliometric tools were used to implement a visual network analysis of MBSE-related manuscripts. The results of the bibliometric study revealed the interrelationship and distribution of researchers in multidomain fields. The authorized sources of MBSE papers were also assorted. The current practices of MBSE were analyzed. The future directions for MBSE based on the current practices were discussed. We found that MBSE's research has been conducted by many research teams with distinctive characteristics, and the top publishing sources in this field have emerged. Research on MBSE focuses on system engineering, languages, system of systems, and digitalization. The development of new technologies such as next-generation modeling languages is improving current practical problems. The findings of this study may help researchers gain a faster and more comprehensive understanding of the current and future developments in MBSE.**

***Index Terms*—Bibliometric analysis, digitalization, model-based systems engineering (MBSE), modeling language, systems engineering.**

I. Introduction

The rapid increase in the complexity and the uncertainty of systems has posed a challenge to system engineers in terms of factors such as requirement analysis, design, tradeoff, and validation [1]. Model-based systems engineering (MBSE), which emerged around 1993 from the industry as well as from the academia [2], is considered effective in meeting these challenges, especially in the aerospace field [3], [4]. MBSE uses models as the technical baseline to formalize the practice of system development from conceptual design to operation [5]. MBSE is associated with systems engineering of model-based engineering, focusing on behavioral analysis, system architecture, requirement traceability, performance analysis, simulation, test, etc. The scope of MBSE includes multiple modeling domains across the life cycle, from system of systems (SoS) to individual components. Existing studies have limited their review of MBSE to a single aspect, such as tools, languages, methodologies, etc. The lack of a macroanalysis of the existing literature renders it difficult to comprehensively assess the current modern methods in MBSE. This study aims to catalog bibliographical information from the MBSE literature starting from 1993 to comprehensively analyze the research teams, publishing sources, current practices, and future directions, and provide a macro perspective on evaluating the latest techniques in MBSE. For example, the scale of MBSE development can be inferred from the number of large research teams formed.

However, it is a challenge for researchers to use and analyze the large and growing MBSE research literature effectively [6]. Due to the lack of effective methods and tools, it is difficult for researchers to transform the information into views of MBSE [7]. This study uses a bibliometric analysis to implement a comprehensive literature review of MBSE and provide incentives for further MBSE research. Bibliometric analysis refers to a visual big-data analysis approach for publication review using a statistical method, which is useful for identifying the interrelationships among the data [8], [9]. In many research fields, researchers have adopted bibliometric analyses to identify authors, sources, and status of their domains [10]–[17], such as the comprehensive analysis of the relationship between thermal comfort and building control [14]. By using bibliometric analysis to investigate MBSE publications, this study aims to identify the most influential authors and sources. We analyze the status and interrelationships between research hotspots to explore directions for future research. Thus, we enable MBSE researchers to gain a more comprehensive understanding of the latest sophisticated methods in MBSE. This study aims to enhance researchers' confidence in MBSE, guide researchers to reasonably formulate technical routes, and develop next-generation technology of MBSE.

The rest of this article is organized as follows. A summary of MBSE and bibliometrics developments is presented in Section II. The research methodology is discussed in Section III. The results of the analysis are presented in Section IV. The findings are discussed in Section V. Finally, Section VI concludes this article.

Manuscript received 31 October 2021; revised 22 April 2022; accepted 23 June 2022. Date of publication 13 July 2022; date of current version 5 January 2024. This work was supported in part by the National Natural Science Foundation of China under Grant 51975056. Review of this manuscript was arranged by Department Editor Y. Zhou. *(Corresponding author: Jinzhi Lu.)*

Zihang Li, Guoxin Wang, and Yan Yan are with the School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China (e-mail: 3120200350@bit.edu.cn; wangguoxin@bit.edu.cn; yanyan331@bit.edu.cn).

Jinzhi Lu is with the Research scientist at ICT4SM Lab, EPFL, 1015 Lausanne, Switzerland (e-mail: jinzhi.lu@epfl.ch).

Didem Gürdür Broo is with the Research scientist at Center for Design Research, Department of Engineering, Stanford University, CA 94305 USA (e-mail: didem@stanford.edu).

Dimitris Kiritsis is with the Professor at ICT4SM Lab, EPFL, 1015 Lausanne, Switzerland (e-mail: dimitris.kiritsis@epfl.ch).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TEM.2022.3186637.

Digital Object Identifier 10.1109/TEM.2022.3186637

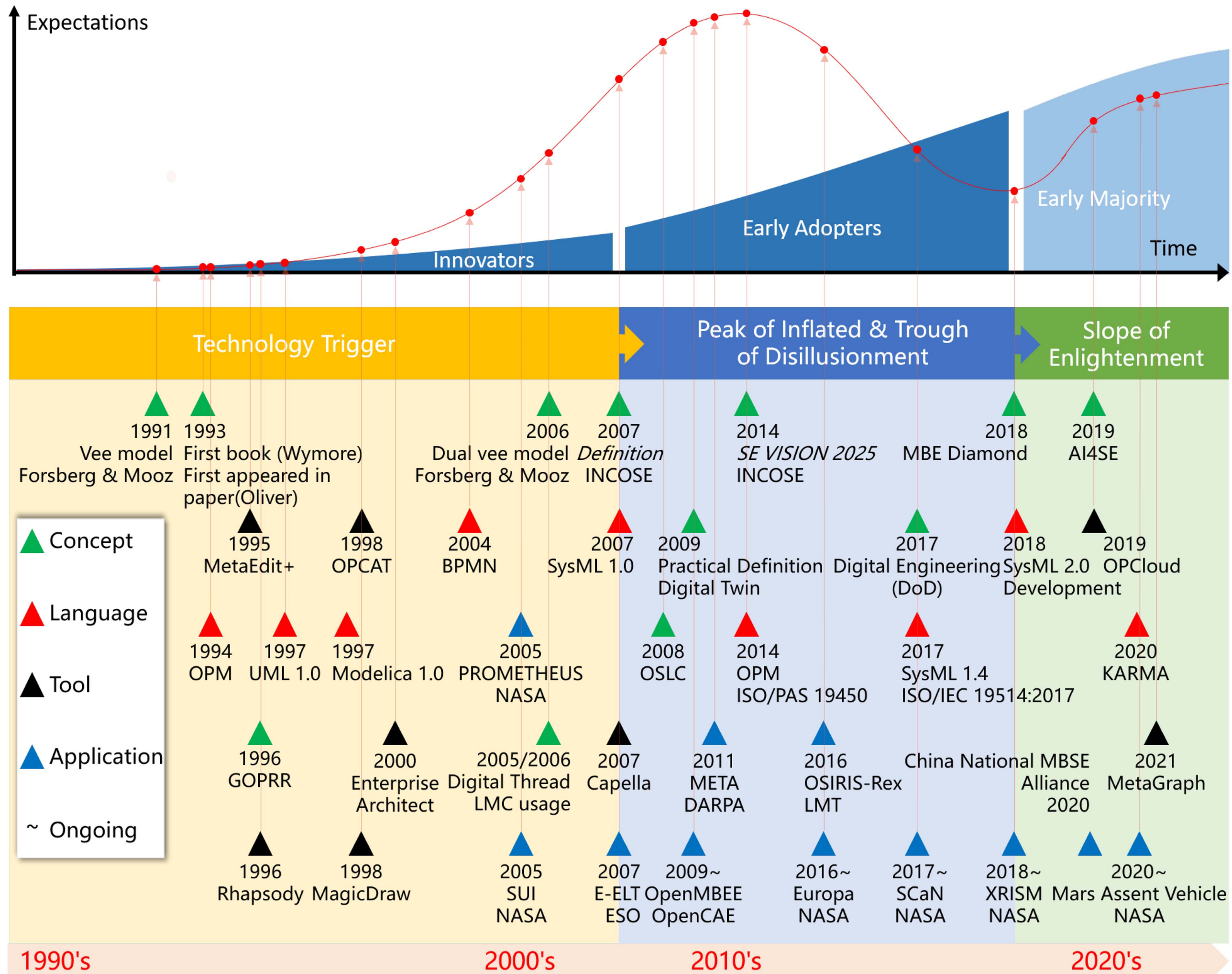

Fig. 1. Timeline of MBSE.

II. Related Works

A. Overview on the Development of MBSE

After nearly 30 years of development, MBSE has become a valuable novel trend in the field of systems engineering. Following traditional viewpoints [18], this study sorts out the development of MBSE in terms of its tools, language, concepts, and applications. The term concept expands the original methodology term to include the MBSE methodology and some new concepts that have emerged. Development stage definitions refer to The historical perspective of MBSE [19]. It suggests viewing the technical lifecycle of MBSE against the Gartner hype-curve [20], which includes five phases:

1) technology trigger—when technology is introduced in the early stages and rapidly expanded thereafter;
2) peak of inflated expectations—when several achievements are accomplished while encountering several challenges;
3) trough of disillusionment—when several problems arise and people lose confidence;
4) slope of enlightenment—when second- and third-generation technologies emerge with more extensive applications;
5) plateau of productivity—when technology becomes mainstream and is recognized by the market.

By reviewing the latest modern techniques in MBSE and defining the stages of the hype-curve, we assess the evolution of MBSE. As depicted in Fig. 1, the vertical axis of the coordinate system represents people's expectations for MBSE, and the horizontal axis represents the timeline. This study argues that the development of MBSE over the past 30 years can be divided into three stages. The reasons for such a division instead of using the original five stages are as follows.

1) Regarding the technology trigger and the peak of inflated expectations, challenges or technical inadequacies were noted early on [21]. Therefore, the trough of disillusionment was either short or did not occur at all. Thus, we put the peak of inflated expectations and the trough of disillusionment together.
2) It is now in the early stage of developing and applying the second-generation technology, which has not yet entered the plateau of productivity. Therefore, we did not represent the stage of plateau of productivity in the figure.

First, during the technology trigger, MBSE was a novel concept that did not garner attention. A few researchers began to explore MBSE and were then called innovators. In 1993, the concept of MBSE was introduced in a conference paper at the International Council on Systems Engineering (INCOSE), International Symposium (IS), and a scientific book by Oliver

[22]. His conceptual model of MBSE described the systems engineering processes. In the same year, Wayne [2] published his book, titled "Model-based Systems Engineering," which introduced the terms related to systems engineering and a basic mathematical theory for discrete system simulation. Moreover, the appearance of modeling languages, such as object process methodology (OPM) [23], unified modeling language (UML) [24], and SysML [25], and modeling tools, such as Rhapsody [26], Magic Draw [27], Enterprise Architecture [28], and Capella [29], have transitioned MBSE from theory to practice and laid a foundation for its application. The difference between MetaEdit+ and the previous tools is that the former uses the Graph, Object, Property, Relationship, Role (GOPRR) conceptual data model as a generic meta–meta model, that is, as a language, rather than directly using a modeling language [30].

The introduction of the precise definition of the MBSE concept in 2007 marked the beginning of the peak of inflated expectations and trough of disillusionment. At this stage, more researchers explored MBSE and were termed early adopters. The definition as per systems engineering (SE) Vision 2020 [31], proposed by INCOSE in 2006 is

"Model-based systems engineering is the formalized application of modeling to support system requirements, design, analysis, and V & V activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases."

New techniques emerged at this stage. INCOSE published *SE VISION 2025* [32] as a guide for systems engineering practitioners. Open services for lifecycle collaboration (OSLC) [33] is a lined data specification that integrates all heterogeneous data throughout the product lifecycle. Moreover, the Department of Defense (DoD) embraced digital engineering as a strategy, in which MBSE played a significant role [34]. Simultaneously, the concept of a digital twin was proposed to provide a virtual representation in the system lifecycle [35]. Importantly, the modeling languages and tools were mature at this stage and met the basic requirements of researchers. The NASA, European Space Agency (ESA), Lockheed Martin, and other organizations have already executed a wide range of practical applications and achieved remarkable results.

Currently, we are at the slope-of-enlightenment stage. It will be the most widely utilized period in the entire lifecycle of MBSE (from emergence to backwardness); the symbolic product of the previous stage, SysML, has become one of the most widely recognized languages in the field [36]. After soliciting the opinions of researchers on the applications of MBSE and SysML for more than a decade, researchers in 2018 officially transferred SysML v2.0 to the R & D stage to improve the accuracy, expressiveness, and usability of SysML v1 [37]. Similar to SysML 2.0, OPM's second-generation modeling environment, OPCloud [38], was also launched. It not only supported conceptual modeling, but also possessed detailed quantitative design capabilities. In addition, the emergence of further associations between digital technologies and concepts in the previous stage has drawn the attention of researchers to the combination of virtual and physical worlds. Taking MBE Diamond [39] as an example, it is an evolution of the systems engineering V model. The bottom half is composed of the design and delivery of the physical model, which is the embodiment of the original V model. The top half is embodied by a virtual model and a digital twin, including modeling and simulation. The physical design and model simulation are linked by a digital thread [40] inside the diamond model. The concept of AI4SE [41] was proposed to integrate AI into systems engineering to efficiently process an enormous volume of data during the product lifecycle. We view both as signs of the beginning of this period. The KARMA [42] language and its modeling tool, MetaGraph [43], are second-generation modeling products developed by the Beijing Institute of Technology, EPFL, and Zhongke Honeycomb Technology Co., LTD. The modeling tool was proposed to achieve unified modeling of multiple languages and improve its expression ability and modeling efficiency using Graph, Object, Point, Property, Relationship, and Role (GOPPRRE) [44], an extension of GOPRR [30]).

According to the expanded three pillars of MBSE [18], we can summarize a relatively complete development of MBSE. However, the relationship between the research topics, the collaboration of researchers, etc., cannot be quantitatively judged by this method. In addition, qualitative analysis is more subjective and its accuracy needs to be supported by quantitative analysis. There is a lack of research in this area of MBSE. Therefore, this article uses bibliometrics to explore MBSE researchers' collaboration, sources, and the definitions of practice topics, as well as their internal linkages and future trends. Furthermore, in response to the timeline of MBSE development summarized qualitatively in this section, this article will also aim to answer three research questions using quantitative methods:

RQ1: Is the upgrade of the modeling language relevant for MBSE at this stage? What is the direction of the upgrade?

RQ2: Are new concepts such as digital engineering, digital twin, and artificial intelligence becoming separate research areas for MBSE, and how are they related to the future development of MBSE?

RQ3: Are the application areas of MBSE still in aerospace?

B. Bibliometrics and MBSE Reviews

Bibliometrics is a field that uses statistical methods to evaluate academic productions quantitatively [45]. Compared with the peer review's limited investigation area, the bibliometric method scales the micro area to a macro investigation area by reviewing unlimited publications [46]. Bibliometrics has been widely applied in different academic research areas [47]. Currently, studies on bibliometrics include two types. One is the research on the tools and algorithms of bibliometrics, and the other is the research on specific fields or journals using bibliometrics.

Some researchers focus on developing visualized networks of bibliometric data to give a clearer and more specific understanding of the data. Anfossi *et al.* [48] described an algorithm that can combine the citations and source indicators of a publication to comprehensively evaluate and display the rank of all publications by the two-dimensional (2-D) space using linear or higher-order curves. The research promotes the efficiency and accuracy of research production. Zhang *et al.* [49] proposed an algorithm that describes the subjects, actions, and objects (SAO) retrieved from titles and abstracts as vectors and constructed a tri-layer SAO to visualize their semantic relationships. The research successfully provided some clues for understanding China's research systems.

Meanwhile, a large number of field-specific bibliometric reviews have been published. Wu *et al.* [50] proposed a new bibliometric framework to explore the evolutionary pattern of digital transformation. Through the analysis of 10179 publications, Wu summarized the necessary capabilities of digital

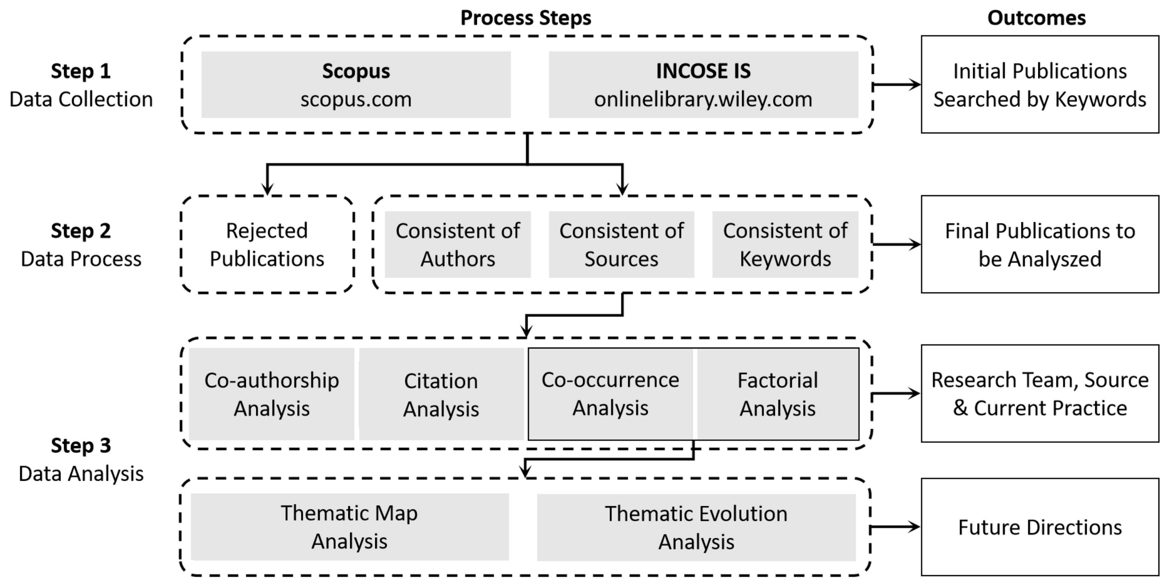

Fig. 2. Research methodology.

transformation. Mejia *et al.* [51] surveyed the academic field distribution of publications that use bibliometrics. The results show that bibliometrics is mainly used in management, public health, sustainability, and medical fields. Zhang *et al.* [52] designed an intelligent bibliometric framework to identify the relationship between predecessor-descendant in research topics and applied it to the study of the relationship between data science and policy. In their journal-specific bibliometric study, Telis *et al.* [16] used bibliometric analyses to measure the most prominent research trends as reflected in the journal GENETICS.

MBSE has developed for nearly 30 years from prototype concept to now and has been covered in many kinds of academic publications. Sufficient MBSE publications have been published, so it is necessary and effective to make a bibliometric study on MBSE. Thus far, MBSE reviews have focused on specific technologies or applications. Several researchers have reviewed the MBSE literature. Rashid [53] rigorously analyzed the application of MBSE tools to support the development of embedded systems and suggested methods to select tools in different scenarios. Linnosmaa [54] discussed the advantages of system modeling languages SysML and AADL in the area of security analysis. Torres [55] reviewed the application and approaches to across-domain model management in the field of MBSE. Dridi [56] reviewed the effective application of MBSE in systems engineering. Lu [57] surveyed the development trend of MBSE from the perspective of tool-chain development using questionnaires. Schmidt [58] reviewed the literature on a general definition of the term "system model." Henderson [59] empirically analyzed the advantages of MBSE. Cameron *et al.* [60] studied the practical role and utility of MBSE in engineering practice. These reviews in the literature have not thoroughly investigated MBSE in the entire period since its conception and as a field.

There is also no substantial progress in the bibliometric research of MBSE. A few studies have comprehensively reviewed MBSE using bibliometrics, but limitations still exist. For example, Akundi *et al.* [61] focused on the current research status through text mining of a large number of MBSE literature abstracts but did not provide a meticulous analysis of the current humanistic cooperation, journals, and future development. Li *et al.* [62] thoroughly explored MBSE using the bibliometric method. However, they restricted the sample size to literature published from 2016 to 2021; therefore, the amount of data acquired was small.

To summarize, it is necessary to use bibliometrics to quantitatively assess the evolution of MBSE, including collaborations, key sources, topic distribution, development trends, and the research questions mentioned above. Driven by research gaps in this area, this study presents a comprehensive bibliometric analysis of MBSE literature since 1993.

III. Research Methodology

The methodology of research on the development of MBSE is illustrated in Fig. 2. The research in this study is divided into three steps: 1) data collection, 2) data processing, and 3) data analysis. The details are as follows:

A. Data Collection

In this step, we collected publications related to MBSE from 1993 to 2022 because the first relevant publication was in 1993 and our search date was March 20, 2022.

For the choice of database, Google Scholar was dropped due to its low data quality and its inability to output bibliometric data [63]. Although Web of Science (WOS) is also a high-quality database [64], the research by Mongeon [63] and our practice together show that Scopus has a wider databases coverage than WOS. Thus, relevant research publications in this study were sourced from Scopus [65]. Meanwhile, during the search process, we found that the Scopus database only includes studies published by the INCOSE IS from 2005 to 2013, whereas most publications before 2005 were from INCOSE IS. Given that INCOSE IS is an important MBSE-related conference held by INCOSE, particularly regarding the research related to defining and envisioning MBSE, it was essential to add the missing INCOSE IS publications to the dataset. Thus, we collected the remaining publications from 1993 to 2022 published by the INCOSE IS from the Wiley Online Library [66].

Two terms were searched, "MBSE" and "Model-based Systems Engineering." First, we collected publications from Scopus and exported them to a CSV file. The search strategy was as follows:

(ALL (MBSE) OR ALL ("Model-based Systems Engineering") AND PUBYEAR $>$ 1992 AND PUBYEAR $<$ 2023)

The search parameter ALL in Scopus includes all search fields such as title, abstract, keywords, affiliation, funding information, reference, and conference. Employing this search strategy, we ensured the comprehensiveness of the search.

Second, we collected publications from Wiley Online Library using the same search strategy as above. The search strategy in Wiley Online Library was as follows:

[All: "Model-based Systems Engineering"] OR [All: MBSE] AND [Journal: INCOSE International Symposium]

Regarding the inconsistency in the number of citations that may occur between the two databases, we compared the citations of 99 INCOSE IS publications included in Scopus with those in Wiley Online Library. The results show that the citations of the INCOSE IS publications in Scopus are generally slightly greater than those of the INCOSE IS publications in Wiley Online Library, but the average citations deviation per publication is only 0.57. Therefore, although the citations to the remaining INCOSE IS publications we supplemented by Wiley Online Library may have been lower than the actual level of Scopus, they would not significantly affect the results.

Finally, we collected all the searched publications (not only from Scopus but also from other sources) and recorded them in a. CSV file using the Scopus information standard format.

B. Data Processing

Because the bibliometric analysis required consistency in statistical data, we filtered the collected dataset by the following steps to gain the final bibliometric data:

1) Rejected publications: There are two reasons to remove the following publications. First, due to its mechanism, Scopus includes different types of publications. We deleted some of these, including conference reviews, erratum, and repeated publications. Second, we found that the abbreviation "MBSE" does not specifically refer to "Model-based systems engineering." It may also refer to terms such as "multiband single echo" [67], which is an acronym in medicine, or "multiscale base-scale entropy "[68], which is a term in fault diagnosis, as well as other terms such as "modified basic scale entropy," "maximum breast surface expansion," "mel-bands spectral energy," and "multiburst sliding encoding." Thus, we deleted the publications that included these terms.
2) Cleaning the dataset for consistency in author names: Inconsistency in author names is mainly caused by the inconsistent descriptions of citations in the different sources of MBSE publications. We used the format of author names in the Scopus library as the standard for unification. For authors who were not listed in the Scopus library, we used the format that appeared most often. However, the author naming format in bibliometric data is a combination of a surname and all first name initials, which still lead to some duplicate names, especially for Chinese authors. Therefore, we also focused on authors with more publications, unified by using the full name or adding more first name letters. For example, by comparing bibliometric data, we identified Lu in initial data as two authors, Lu J.Z. [44] and Lu J.D. [69].
3) Cleaning the dataset for consistency among sources: the sources of conference papers were mostly defined by the year and session. For example, the source title of IEEE ISSE 2020 is "ISSE 2020 - 6th IEEE International Symposium on Systems Engineering Proceeding," which is different from the source title of the same conference in 2019—"ISSE 2019—5th IEEE International Symposium on Systems Engineering, Proceedings." We deleted the year and session of the conference and retained the main title of the source in a unified format.
4) Cleaning the dataset for consistency in keywords: A large amount of data poses an important research challenge—terminology uniformity. For example, several publications do not concur on whether to add "s" or "-" in "model-based systems engineering," "systems modeling language," "systems thinking," "system of systems," etc. Among them, the frequency of inconsistent keywords with "Model-based Systems Engineering" is approximately 200 times, which is in contrast to MBSE, which brings unambiguous expressions. Therefore, such keywords were unified before visualizing data. For example, we used MBSE to unify the terms consistent with the meaning of "Model-based Systems Engineering."

C. Data Analysis

We used VOSViewer [70] and BibliometriX [71] to implement a bibliometric analysis of MBSE. By using the distance-based network of VOSViewer, we analyzed the interrelationships between nodes, which represented the authors, sources, keywords, and so forth. Strongly related nodes were close to each other. Several highly related nodes formed clusters, which were classified by different colors. Additionally, the size of each node in the network was positively related to the weight. The weight value was used to express the number of documents, citations, etc. We used BibliometriX tools to provide features that VOSViewer lacks, such as thematic maps [72] and factorial analysis. The visualization methods that we used were described as follows.

1) Co-authorship analysis: The relatedness of nodes (author) was determined based on the number of their coauthored documents. Thus, we obtained the main research teams working on MBSE.
2) Citation analysis: The relatedness of nodes (source) was determined based on the number of citations among each other. Thus, we obtained the main sources of MBSE publications.
3) Co-occurrence analysis: The relatedness of nodes (keywords) is determined based on the number of documents in which they occur together. Thus, we obtained the research cluster of MBSE.
4) Factorial analysis: Similar to co-occurrence analysis, the distance of keywords was related to the number of articles that used them at the same time. We identified MBSE subfields by reducing the dimensions of data.
5) Text analysis: This is another type of co-occurrence analysis based on abstracts and titles. Thus, we unearthed a few textual details other than the keywords obtained in the previous co-occurrence analysis step.
6) Thematic map: Based on the co-occurrence analysis, the centrality and density were used to classify the research

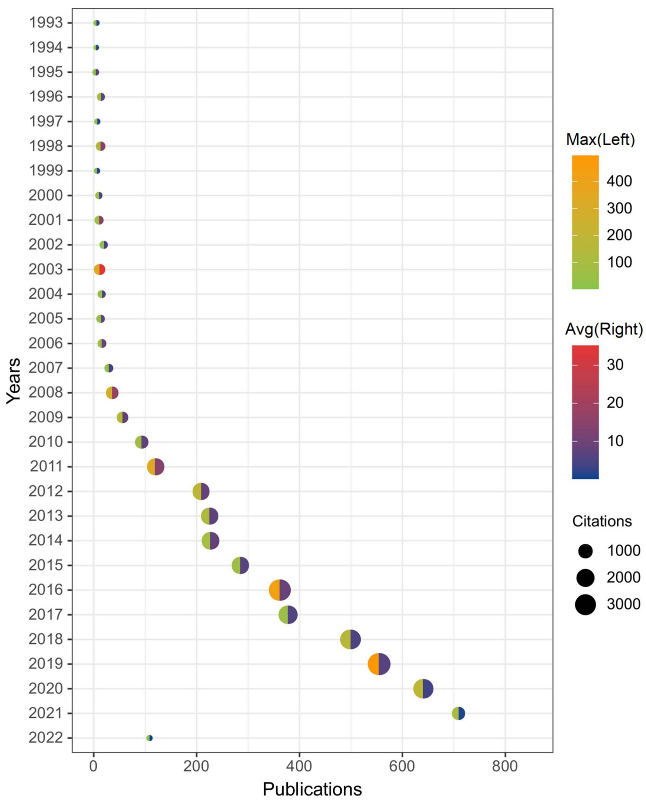

Fig. 3. Publications overview.

clusters. Thus, we obtained the impact of each topic on overall research and future trends.

Through this analysis, we collected the data of researchers in MBSE and the authorized sources of publications to judge the overall scenario of MBSE development and enable researchers to obtain research related to MBSE efficiently. In addition, we summarized the latest techniques of MBSE and discussed future directions. The results are presented in the following section.

IV. Findings

In this section, the findings are presented and discussed from different perspectives: Subsection A provides an overview of the publication's bibliometric data. Subsection B describes the research team, distribution, and activity of the MBSE researchers. Subsection C provides noteworthy information on the MBSE sources. Subsection D presents the current MBSE practices. Subsection E discusses the future directions of MBSE.

A. Overview

This study collected a total of 4675 publications from 1993 to 2022, as depicted in Fig. 3. The color on the left side of the point was determined by the value of citations for the most cited publications in a year, and the color on the right side was determined by the average number of citations in a year. The size of the point represents the total number of citations in the selected year. The abscissa corresponding to the point indicates the number of publications in that year.

In terms of the publication count, the number of publications never reached 20 before 2007. In 2007, as an inflection point, the total number of MBSE publications reached 29 and began to increase steadily on an annual basis (the half-year data of 2022 was included in this study), peaking at 709 in 2021. In other words, since 2007, research on MBSE has entered a new stage, which is largely due to INCOSE's definition of MBSE and its vision for the future development of systems engineering. The result of bibliometric data is consistent with the research in Section II that shows that a large number of researchers have begun to pay attention to MBSE. The development of MBSE entered the peak of inflated expectations and trough of disillusionment stage in 2007.

As shown in Fig. 3, from 2008 to now, at least one study was cited between 50 and 100 times each year, and the most cited study was published in 2019, reaching 496 citations. In 2008, the average citation number peaked at nearly 18 and the median was 5, indicating the publishing of numerous highly cited studies. From 2008 to 2014, the average number of citations for seven consecutive years exceeded seven, which was the longest period from 1993 to 2022. The largest leap in the number of publications was in 2018, which means that MBSE entered a new phase in 2018, consistent with the information provided in Section II.

In recent years, the total number of citations (the size of the point) has remained high; this is due to the simultaneous high growth in the number of publications. However, the average number of citations is lower, which may be due to the short publication time. Compared with publications that remained published for a long time, the number of citations of published studies in recent years was not fully reflected in the latest publications; however, there are still some highly cited publications and the average number of citations in the past five years (2017–2021) was around 4.

B. Research Team Analysis

The co-authorship analysis was used to analyze the key research teams and their interrelationships. To clarify the visualization network among research teams, we set authors with at least five publications to appear in the network. Consequently, authors who did not meet this criterion were filtered out. Subsequently, 490 of the 9825 authors met this requirement. VOSViewer's clustering algorithm groups the nodes that are closely related to a cluster with the same color. In addition, we set the threshold for a cluster to constitute at least three authors.

Fig. 4 illustrates the coauthorship network, from which we obtained 49 teams for the MBSE field. Each node represents an author, and the node size represents the number of publications. The location of the clusters in Fig. 4 is arbitrary and is not an important metric.

Twenty-two teams were connected by extensive cross-team collaboration, which constituted the majority in Fig. 4. The associations between the teams are marked in red, and at least 35 different associations appeared. In addition, the team in the black circle indicates that it had few contacts with the authors outside the circle. Although there are 27 teams not connected with the largest coauthorship cluster (the majority), five large teams had more than seven members, which is more than the number of some teams in the majority. This indicates that MBSE produces distinct research characteristics divided by the research team, which in turn means that at least 10 categories of technologies are recognized in the MBSE community. Thus, MBSE is in a significant expansion stage [62]. The largest research team is the one represented by Vogel-Heuser [73], which not only has the

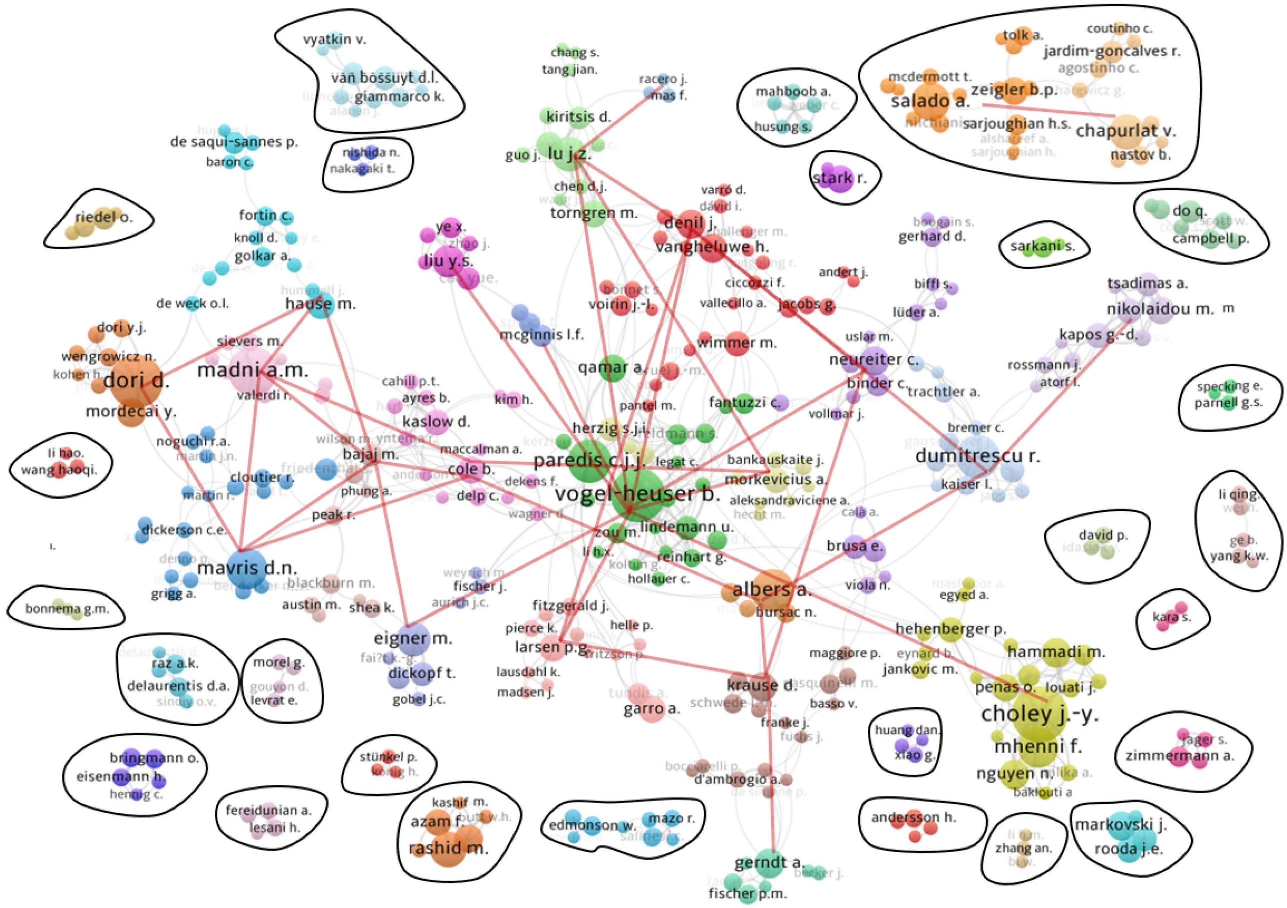

Fig. 4. Authorship collaborative network.

second largest group base (with 22 core members) but has also collaborated with nine research teams.

To evaluate the activity of each research team, we constructed statistics on the annual publications issued by all teams. Because the distinguishing feature of a team is coauthorship, counting the annual publications of all members of the team simultaneously would cause serious duplication. To avoid data duplication, we considered the authors with the highest number of publications in each cluster as the representative to count the number of publications in each year. Fig. 5 illustrates the annual publications of 10 representative authors with the highest number of publications among the representatives from the 49 clusters in Fig. 4. The size of the point (value) in Fig. 5 refers to the number of publications by the author in a year. In terms of the average number of publications, these primary research teams increased their output over time, which is consistent with the overall results. Dori sustained outputs throughout the entire period from 2008 to 2022. Although Choley and Vogel ranked in the top two in terms of TP, their publications were mainly from 2014 and beyond. Inferring from the studies published in recent years, Lu and Albers [74] have the highest number of papers published in the last three years, indicating that their research may be related to the next-generation technology of MBSE. Further, these researchers focus on digital twins, mechatronic system design, ontology, industry 4.0, etc.

For the geographical analysis, we used VOSViewer to collect geographic information of publications. The author's geographical location was calculated based on the location of the institution or organization and not their nationality. Fig. 6 presents the results. The majority of MBSE researchers were from the United States (25.1%), followed by Germany (14.2%), France (9.0%), and China (8.0%). Researchers in the United States, Europe, and China accounted for 80% of the total researchers, which are also regions with rapid development in the aerospace industry, with institutions such as NASA, ESA, and China Aerospace Science and Technology Corporation (CASC). Taking the Netherlands as an example, where the European Space Research and Technology Centre (ESTEC) is located, 10 publications we collected from the country were authored by researchers from the ESA or ESTEC. In addition, we found that MBSE software companies also drove regional MBSE research. A software development facility named No Magic is located in the EU (Kaunas, Lithuania), and 7 of the 22 publications from Lithuania are authored by researchers from this facility.

C. Source Analysis

MBSE publications are currently published in more than a thousand sources, including journals, conferences, and books. Based on the citation analysis of VOSViewer, this study examines the number and strength of citation connections among these sources. In general, publications are from sources in systems engineering, simulation, manufacturing, aerospace, computer science, and technology, etc. The left side of Fig. 7 shows

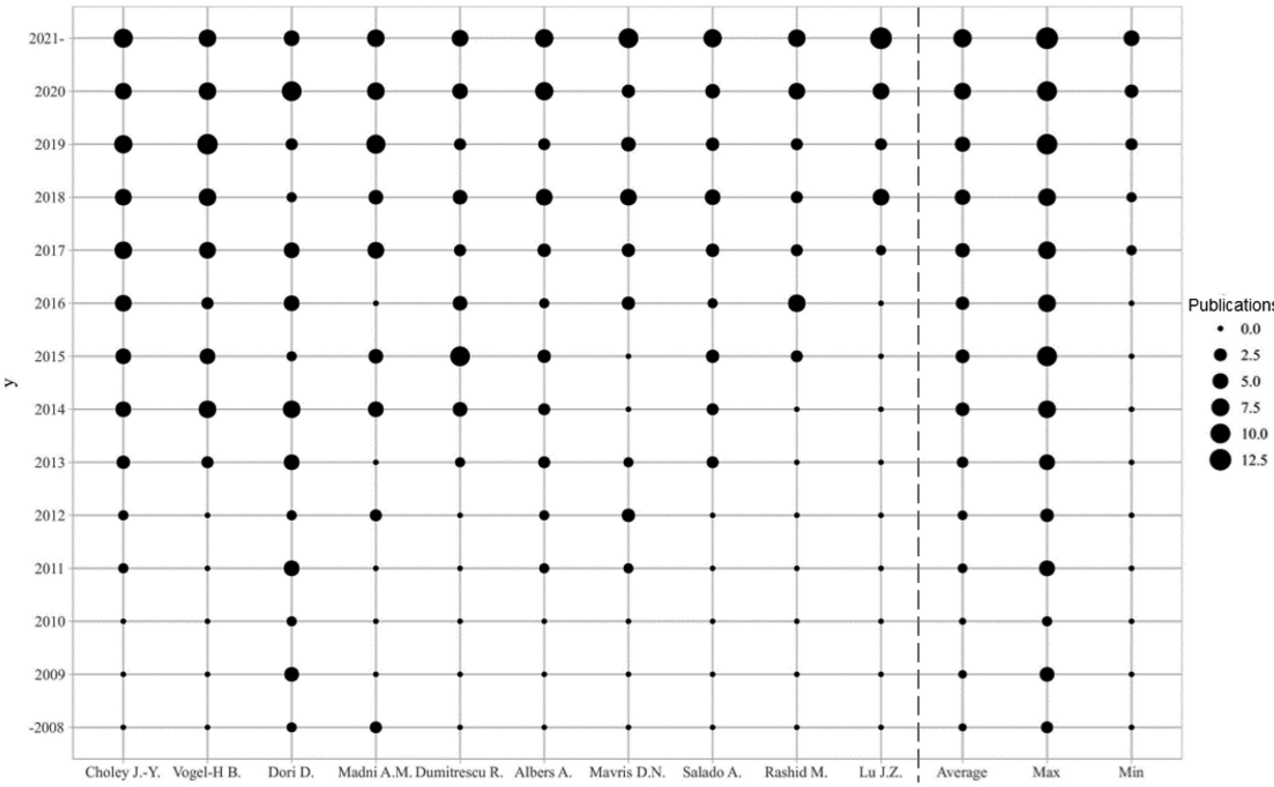

Fig. 5. Annual publication of the team's core authors.

the complete source analysis results to give an overall judgment. To provide a clearer picture of the noteworthy sources, the minimum publication threshold of each source was set to 17, which implies that only the sources that reach the threshold would appear on the network. Among the 1174 sources, 45 (3.8%) met the constraints. The number of publications produced by these 45 sources accounts for 51.6% of all publications. All these sources were connected to each other due to mutual citations, and there were no independent sources. Fig. 7 illustrates the citation network of the 45 sources on the right side. Each node in the network represents a different source, the size of which represents the number of publications. The palette represents the average number of citations to a source.

According to the rules of citation analysis, the links between two nodes indicate that they have a "cite each other" or mutual-citation relationship. Each link has a strength that indicates the number of such relationships. Therefore, the higher the total strength of a node, the stronger the relationship between that node and the other nodes, which signifies the importance of the node. *Systems engineering* links with most sources and has the highest strength at 294, which demonstrates its high recognizability. The second echelon consisted of four sources, *Procedia Computer Science, Systems, IEEE Aerospace Conference, IEEE Systems Journal*, each of which has a strength of over 80.

To provide a detailed analysis of Fig. 7, Tables I and II lists 10 sources ranked by total citations (TC) and total publications (TP). The INCOSE IS ranks top 2 in both TP and TC, proving it an important publishing source in MBSE. Seven sources appear simultaneously in the top 10 of TC and TP rankings. *Systems Engineering* has published only 113 studies and received 1257 citations. In addition, the *IEEE System Journal* has reached 441 citations with 43 publications, which proves the high quality of its content. *IEEE Transactions on Industrial Informatics* is highly cited and deserves the attention of researchers, despite the small number of MBSE-related publications that have been published so far. *International Astronautical Congress, (IAC)* has a higher TP with a significantly lower TC, which means that the papers published in the IAC tend to receive fewer citations than the other sources listed in Table II. In addition to the top

TABLE I
TOP 10 SOURCES ACCORDING TO TC

Rank	Source (Sort by TC)	TC	TP	TC/TP
1	*Systems Engineering*	1257	113	11.12
2	*INCOSE International Symposium*	919	409	2.25
3	*Procedia Computer Science*	756	100	7.56
4	*IEEE Transactions on Industrial Informatics*	742	9	82.44
5	*Lecture Notes in Computer Science*	687	133	5.17
6	*IEEE Aerospace Conference*	627	109	5.75
7	*International Systems Conference*	570	142	4.01
8	*IEEE Access*	551	38	14.5
9	*Procedia CIRP*	487	77	6.32
10	*IEEE Systems Journal*	441	43	10.26

TABLE II
TOP 10 SOURCES ACCORDING TO TP

Rank	Source (Sort by TP)	TP	TC	TC/TP
1	*INCOSE International Symposium*	409	919	2.25
2	*International Systems Conference*	142	570	4.01
3	*Lecture Notes in Computer Science*	133	687	5.17
4	*International Symposium on Systems Engineering*	117	350	2.99
5	*Systems Engineering*	113	1257	11.12
6	*IEEE Aerospace Conference*	109	627	5.75
7	*Procedia Computer Science*	100	756	7.56
8	*System of Systems Engineering Conference*	81	354	4.37
9	*Procedia CIRP*	77	487	6.32
10	*International Astronautical Congress*	67	57	0.85

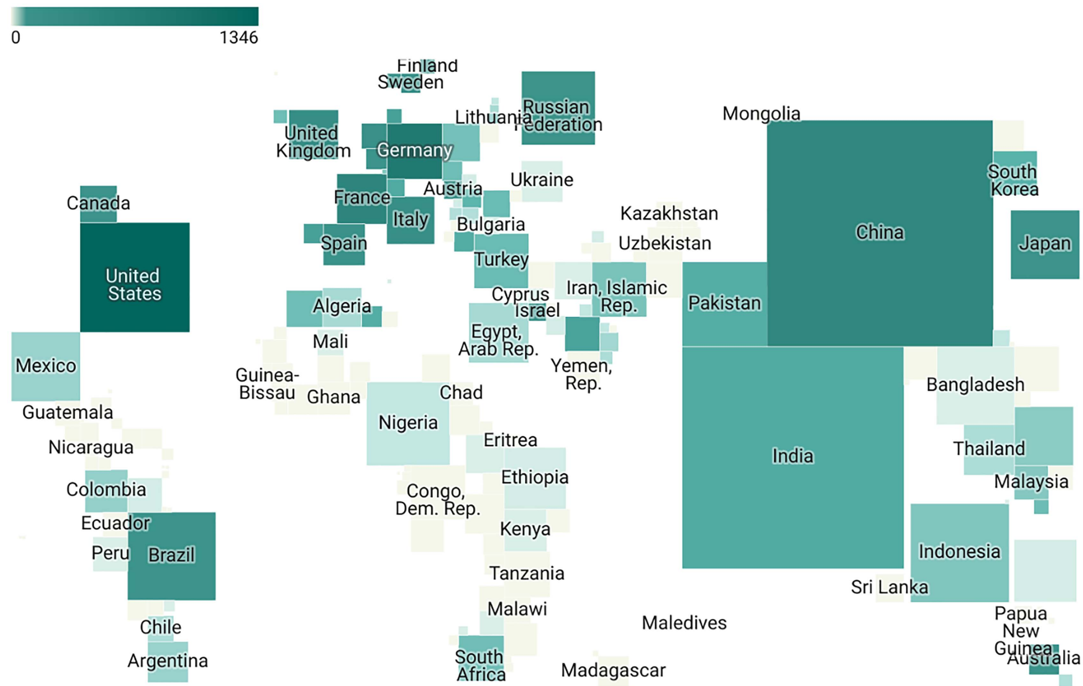

Fig. 6. Researcher distribution.

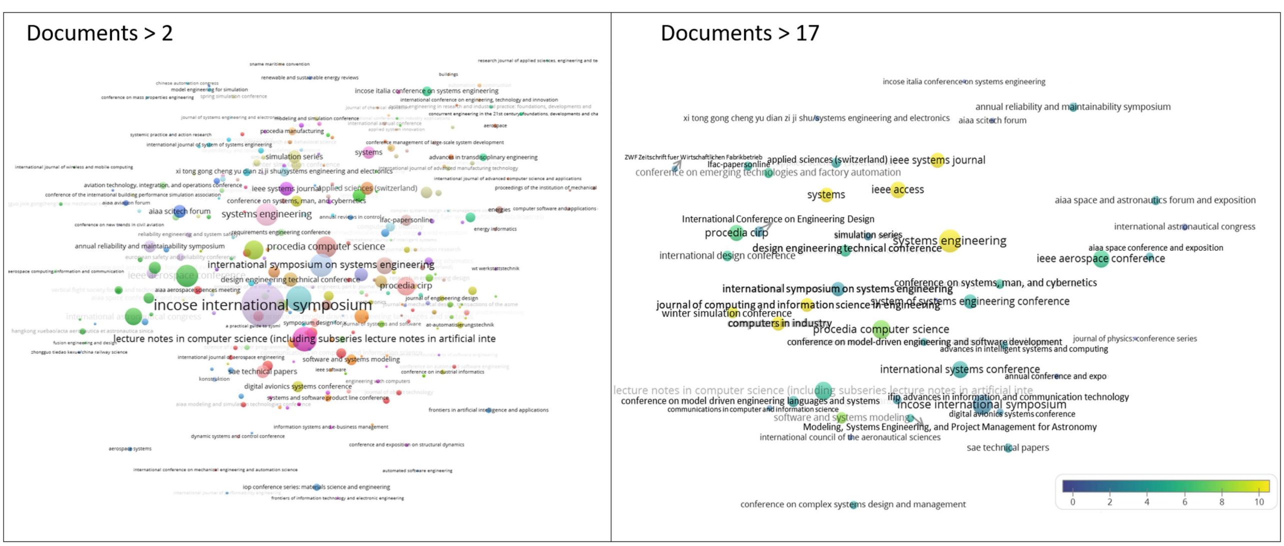

Fig. 7. Source citation analysis network.

10 TP/TC sources in Tables I and II, a few sources with a lower total number yet high notability can be found in Fig. 7.

Table III lists the top 10 most-cited MBSE publications, which are mostly from journals. Barring three books, all of these publications were research and review articles. Ten most-cited articles reflect the current trend of MBSE and correspond to the three phases of Section II at a ratio of 1:5:4. During the technology trigger phase, researchers were more concerned with the definition of concepts, but these studies did not attract more researchers. In the peak of inflated expectations and trough of disillusionment phase, MBSE started to move toward applied practice, which also attracted more researchers. The current slope-of-enlightenment phase, where researchers are beginning to explore MBSE in combination with new technologies, such as the digital twin, has also attracted the most research. With 496 citations, the most cited article was published in IEEE Transactions on Industrial Informatics (Tao F., etc.) [75] in 2019.

D. Current Practices

The cluster analysis of co-occurrence keywords was performed to obtain the current practice. Because the strategy involved searching with MBSE as a keyword, "MBSE" occurred 1104 times, which is significantly more frequent than any other related keyword. As illustrated in the upper-left corner of Fig. 8, MBSE links with 76.7 % of the other keywords that occur at least

TABLE III
TOP 10 HIGHEST CITATIONS PUBLICATIONS

Rank	Title	Year	Source	Cited by	Type
1	Digital Twin in Industry: State-of-the-Art[75]	2019	IEEE Transactions on Industrial Informatics	496	Journal
2	Digital twin-the simulation aspect[76]	2016	Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and Their Designers	430	Book
3	Systems Engineering Principles and Practice: Second Edition[77]	2011	Systems Engineering Principles and Practice: Second Edition	339	Book
4	A review of the development of Smart Grid technologies[78]	2016	Renewable and Sustainable Energy Reviews	333	Journal
5	System of systems engineering[79]	2003	Engineering Management Journal	322	Journal
6	A Practical Guide to SysML[80]	2008	A Practical Guide to SysML	283	Book
7	Characterizing the Digital Twin: A systematic literature review[81]	2020	CIRP Journal of Manufacturing Science and Technology	191	Journal
8	Leveraging digital twin technology in model-based systems engineering[82]	2019	Systems	188	Journal
9	A survey on smart grid technologies and applications[83]	2020	Renewable Energy	184	Journal
10	Model-based systems engineering: An emerging approach for modern systems[84]	2012	IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews	180	Journal

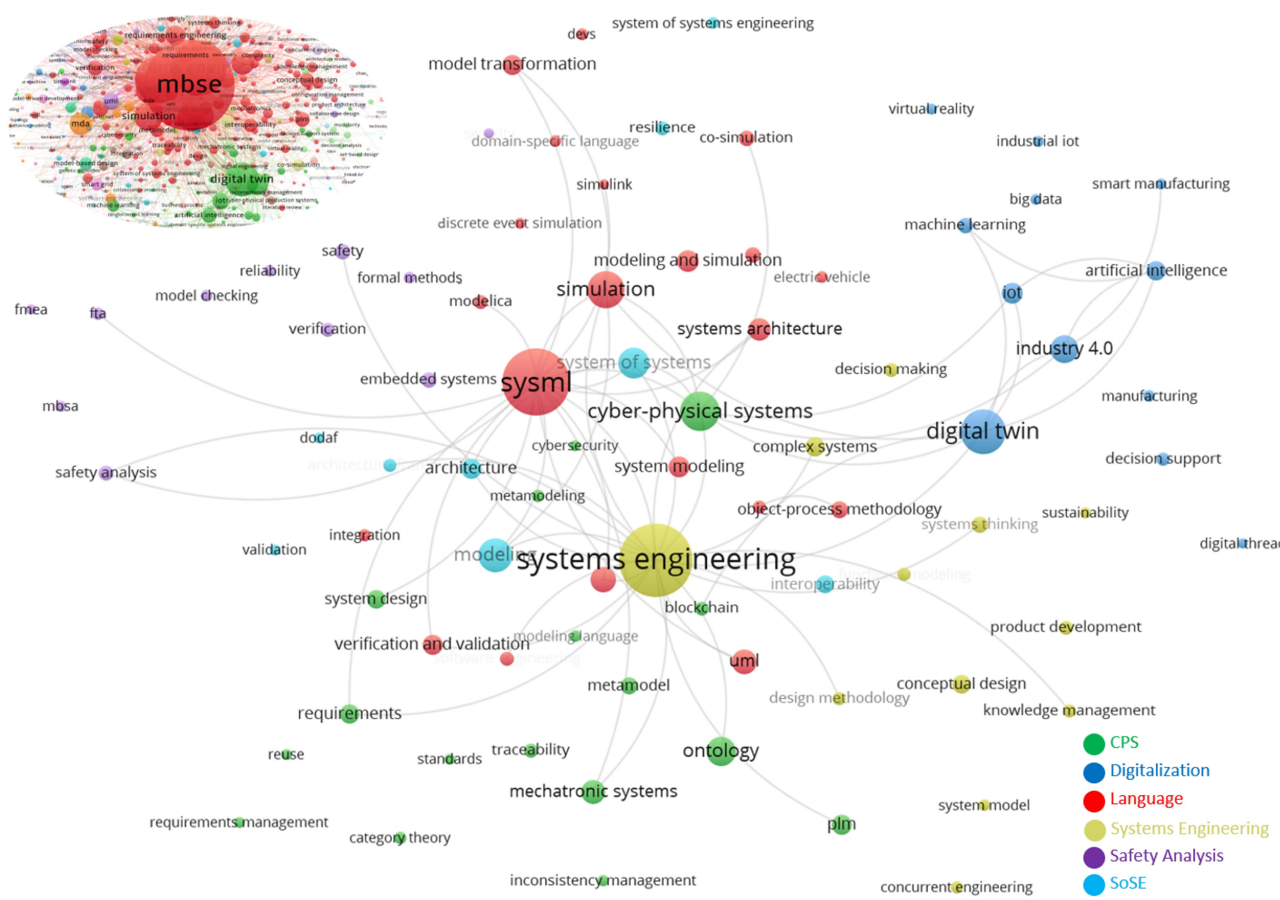

Fig. 8. Keywords co-occurrences analysis network.

three times; therefore, it is in the core position. Consequently, the keyword "MBSE" occupied most of the network and covered up other nodes, rendering it difficult to understand. Thus, we removed "MBSE" and some of the keywords with general descriptions from the initial data to promote the visualization efforts.

Fig. 8 depicts a co-occurrence network of authorial keywords (without MBSE co-occurrence), in which the minimum threshold of the frequency of occurrence of keywords is set to 15. Thus, only those keywords with at least 15 occurrences appeared in the network. Moreover, two keywords are linked if they exhibit a co-occurrence of at least seven. Finally, we obtained 82 of the 7386 keywords. In the past 30 years, SysML and Systems Engineering were the most frequently mentioned keywords. SysML is a general-purpose architecture modeling language for systems engineering applications that can strictly reflect systems engineering activities, and it is widely applied by various organizations and institutions [85]–[87]. Systems

Engineering is second only to MBSE in terms of the frequency of occurrence and associations with other nodes, indicating that MBSE is highly relevant to systems engineering activities.

Six clusters were identified that are illustrated by different colors in Fig. 8. Table IV provides more details of the clusters in the figure. We defined the topic of each cluster (the second column of Table IV) according to the keywords in each cluster (the third column of Table IV). Based on the visualization of the current data, we obtained the current practice of MBSE and divided it into six categories:

The red cluster accounted for 31.9% of all keywords. SysML, UML, Modelica, Simulink, and domain-specific languages are MBSE modeling languages. The OPM series was developed by Dori D. This unique modeling approach explains the construction of the system model from a different perspective. It integrates the object-oriented (structure) and process-oriented (behavior) paradigms into a single frame of reference through a combination of graphics and equivalent natural language [88]. Discrete event simulation specification (DEVS) is a popular formalism for modeling complex dynamic systems using discrete-event abstractions [89]. OPM and DEVS as modeling methods are not languages, but both cover the language. Hence, the topic of this cluster is language. In addition to focusing on the language itself, one of the purposes of modeling with modeling languages is for verification and validation [90]. The focus of simulation research not only includes establishing a simulation model directly in the simulation software, but also enables the conversion of system models to simulation models [91]. The novel technology also includes the study of discrete event system simulations using activity diagrams, state machine diagrams, and so forth [92]. A large number of requirement-related keywords is another characteristic of this cluster. The forward design process, which starts with requirements, is an important part of the MBSE focus and is currently used intensively in modeling languages [93].

The green cluster represents the cyber-physical system (CPS). The development of energy, transportation, water, and healthcare systems has significantly benefited from information, communication, and computation through physically engineered systems [94]. CPS is the evolution of mechatronic systems [95]. In the case of the integration of a large number of components, the design of the CPS system focuses on three issues (as shown in Table IV). First, how to effectively manage complex systems has always been an important issue [96]. Research in this area includes studies on product lifecycle management (PLM), inconsistency management, requirements management, and traceability technologies. Second, the ontology appears second only to the CPS in group 2 and is related to its ability to express a standardized information model [97]. The CPS system or rather, the system engineering process, is a multidomain process [98]. To enhance the communication among different stakeholders, it is necessary to unify the description of the multi-domain modeling language through ontologies, in which the metamodeling approach is used [99]. Third, CPS is more vulnerable to attacks [100], [101]; therefore, further measures are required for the cybersecurity of CPS. Based on the aforementioned management and cybersecurity needs, the MBSE sector has also started using blockchain technology [102].

The blue cluster accounted for 13.7% of all keywords. Digitalization is a fundamentally disruptive force triggered by the

TABLE IV
MBSE RESEARCH CLUSTERS

Cluster	Topic	Keywords	Occ	Total
Red	Language	sysml	395	1227
		simulation	139	
		requirements engineering	73	
		uml	69	
		systems architecture	60	
		modeling and simulation	55	
		system modeling	53	
		model transformation	48	
		verification and validation	48	
		object-process methodology	36	
		co-simulation	32	
		smart grid	30	
		modelica	25	
		software engineering	25	
		conceptual modeling	23	
		integration	22	
		devs	21	
		electric vehicle	20	
		domain-specific language	18	
		discrete event simulation	17	
		simulink	15	
Green	CPS	cyber-physical system	157	683
		ontology	95	
		mechatronic systems	65	
		plm	48	
		requirements	46	
		system design	41	
		metamodel	36	
		traceability	27	
		blockchain	25	
		category theory	22	
		metamodeling	22	
		modeling language	18	
		cybersecurity	17	
		inconsistency management	16	
		requirements management	16	
		reuse	16	
		standards	16	
Blue	Digitalization	digital twin	193	526
		industry 4.0	84	
		iot	52	
		artificial intelligence	44	
		machine learging	31	
		decision support	24	
		manufacturing	18	
		virtual reality	17	
		big data	16	
		industrial iot	16	
		smart manufacturing	16	
		digital thread	15	
Yellow	Systems engineering	systems engineering	458	757
		complex systems	44	
		conceptual design	41	
		systems thinking	33	
		product development	27	
		decision making	26	
		design methodology	24	
		knowledge management	24	
		functional modeling	23	
		concurrent engineering	21	
		system model	20	
		sustainability	16	
Purple	Safety analysis	safety	32	242
		embedded systems	30	
		safety analysis	28	
		verification	27	
		fta	21	
		formal method	20	
		model checking	19	
		reliability	18	
		mbsa	17	
		fmea	15	
		security	15	
Azure	SoSE	modeling	122	415
		system of systems	104	
		architecture	48	
		interoperability	39	
		resilience	25	
		architecture framework	24	
		system of systems engineering	20	
		dodaf	17	
		validation	16	

Fourth Industrial Revolution (Industry 4.0) and Internet of Things (IoT) [103]. After 30 years of development, researchers have explored ways to combine MBSE with a range of new concepts brought about by digitalization. The influx of new concepts, such as digital twins, also provides opportunities for MBSE. According to Section II, the digital twin was defined in practice in 2007, but related publications already occupy four of the top 10 cited publications in Table III. The context of the operation of the digital twin is derived from the system model built through MBSE, and therefore, the digital twin is referred to as the core of the possible future of MBSE [82]. The flow of data is also a distinctive feature of digitalization. Digital thread, the technology that integrates heterogeneous models into a unified model, is the guarantee that constitutes an authoritative source of truth (AST) for MBSE [104]. Using this data, machine learning techniques can be employed to drive the self-evolution of models and achieve artificial intelligence. Besides, data-driven modeling and intelligent modeling are the contents of the combination of AI and MBSE [105].

The yellow cluster accounted for 19.7% of all keywords. In essence, MBSE is a holistic systems engineering approach centered on the evolving system model [106]. The keyword data also shows that systems engineering is second only to MBSE in terms of frequency. MBSE is widely used in conceptual design and functional modeling activities of system engineering. Systems thinking is the foundation of systems engineering and is the basic idea of observing and defining systems of interest [107]. Decision-making is also commonly encountered throughout a system's lifecycle. Using MBSE to model the system can effectively solve the decision challenge [108]. Concurrent engineering, complex systems, and product development are the most common systems on this topic. In addition, the sustainability of the system has attracted more attention in terms of system characteristics.

The topic of the purple cluster is safety analysis. MBSE is widely used in the development of complex systems and equipment. Safety analysis in the early stage can reduce the design cost of these systems and improve the development efficiency [109]. Fault tree analysis (FTA) and failure mode and effects analysis (FMEA) adopt a formal method to investigate system safety and reliability. The modeling mode is a combination of the safety analysis and MBSE. From the perspective of application, safety analysis has been widely used in embedded systems. In 2016, some MBSE publications first mentioned a combination of FTA, FMEA, and modeling [110]. The research on safety analysis has increased rapidly since this time. Security is a word similar to safety; it is related to cyberspace, communication, and software security, while safety is mainly related to physical safety [111]. Thus, security may also become another new research cluster in the future.

The azure cluster accounted for 10.8% of all keywords. It includes SoS and SoS engineering (SoSE). SoSE is more concerned with the study of architecture framework, the most famous of which is the DoD Architecture Framework [112]. Besides, resilience is an important feature for maintaining functionality, stability, and improving the operational efficiency of complex systems, particularly for SoS [113].

In addition to keyword co-occurrence analysis, we used the factorial analysis function of BibliometriX to analyze the potential subfields. The parameters we used for the analysis were multiple correspondence analysis (MCA), auto-clustering, and the maximum number of keywords 50. MCA represents the data as points in low-dimensional Euclidean space techniques to achieve dimensionality reduction [114]. MCA is widely used to analyze a set of variables with similar characteristics and to identify new potential variables [115].

TABLE V
TEXT ANALYSIS OF ABSTRACT AND TITLE

Term	Occurrences	Term	Occurrences
Aircraft	137	Electric Vehicle	50
Satellite	99	OMG	44
ISO	73	Smart Grid	39
Spacecraft	72	Flight	38
INCOSE	71	Cubesat	36
NASA	64	JPL	34
Aerospace	57		

As shown in Fig. 9, factorial analysis divided the keywords into two categories compared to the six clusters obtained by the co-occurrence analysis. According to the factorial analysis rule, the closer two keywords are, the more publications put them together; the farther away, the fewer publications put them together. The red cluster includes traditional MBSE research, such as languages, systems engineering, SoSE, design, verification, etc. This part of the research is mainstream, so most of the publications put these keywords together. Note that the keywords in the blue clusters are not strongly associated with publications from traditional MBSE publications. Therefore, the blue cluster includes the new research represented by digital twins, artificial intelligence, and IoT. Although the blue cluster also has many publications (enough to support it as a cluster), it has fewer keywords, indicating that there is still space for further improvement.

Because most of the authorial keywords are related to technologies or concepts, we used textual analysis for detailed entities. As indicated in Table V, these terms are part of the results of the textual analysis of the structured titles and abstracts. The analysis revealed that the main research area and application of MBSE are aerospace and aircraft, respectively, the main institutions of which include NASA and its affiliate JPL. NASA's CubeSat Launch Initiative provides opportunities for small satellite payloads built by universities, high schools, and nonprofit organizations to fly on upcoming launches, advancing the practice of MBSE theory [116]. In addition to aerospace, MBSE now has major applications in electric vehicles and smart grids [117]. The initiative of MBSE has always been inseparable from the INCOSE, owing to its SE vision 2020 [31] and SE vision 2025 [32], which guided the entire MBSE community. Object Management Group (OMG) is the developer of many important standards such as UML, XML, etc. These two organizations together have introduced the most widely used modeling language in the current MBSE field, SysML. In addition, the ISO standard is very important in the authorized data source advocated by MBSE. ISO 15288 [118] as well as several other ISO standards and specifications have also been mentioned in related studies. For example, Duan *et al.* proposed a hazard analysis method for MBSE based on ISO 26262 [119].

E. Future Directions

In this section, we first analyze the future trends of MBSE research topics from a development status perspective using BibliometriX thematic map analysis. Subsequently, the thematic

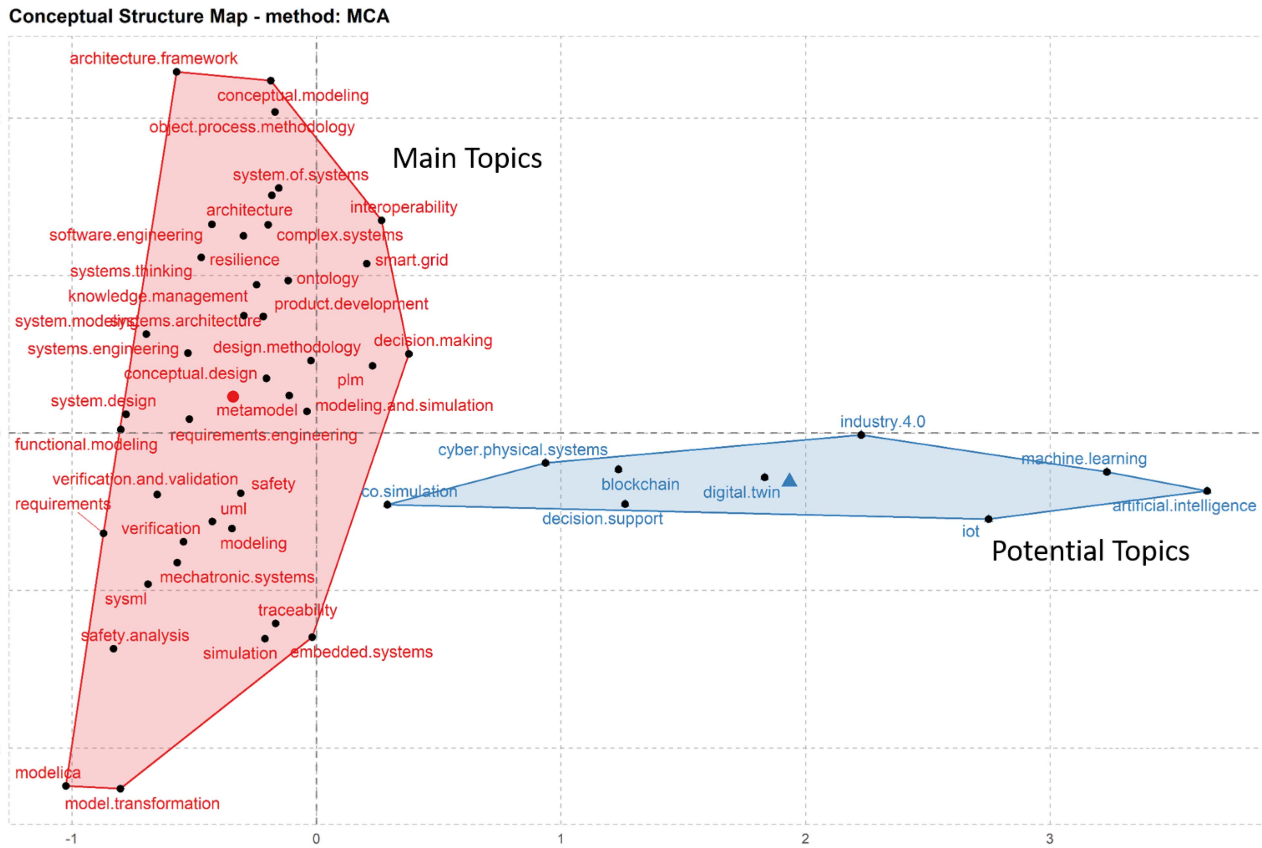

Fig. 9. Factorial analysis.

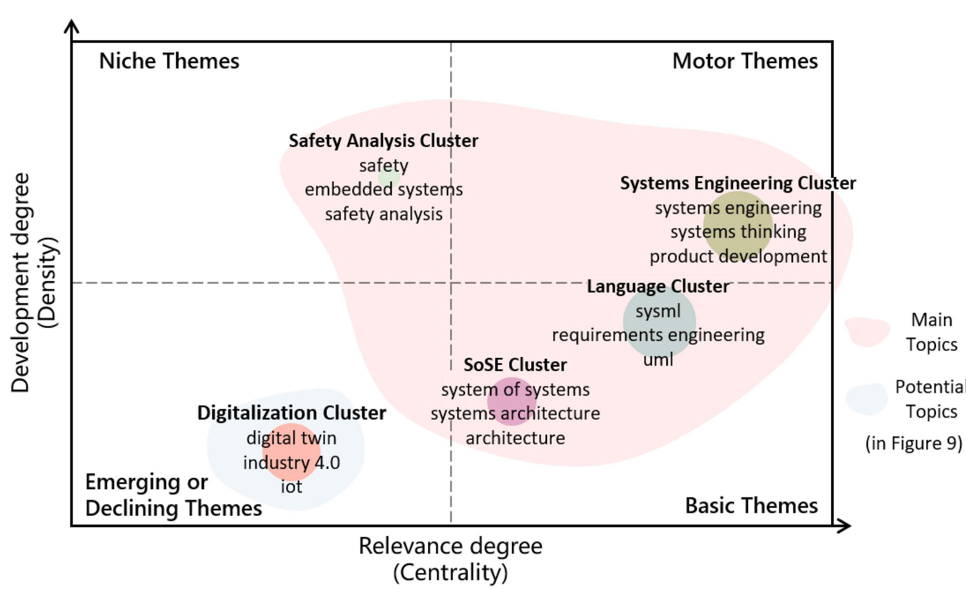

Fig. 10. Thematic MAP of MBSE.

evolution of MBSE research is studied using thematic evolution analysis, and further detailed analysis is given.

Thematic map transforms keyword co-occurrence networks into bivariate maps of centrality and density [120]. The x-axis of the thematic map represents centrality, which is the importance of the topic in the entire research field (determined by the degree of relevance of keywords within the topic to other topics); the y-axis represents density, which is the development of the topic itself (determined by the degree of relevance of each keyword within the topic) [121]. The thematic analysis results maintain strong consistency with Section IV-D. As shown in Fig. 10, each bubble corresponds to the topics in Fig. 8. The two topic sets under the red and blue shading correspond to the Fig. 9. The size of each bubble is proportional to the topic keyword occurrences.

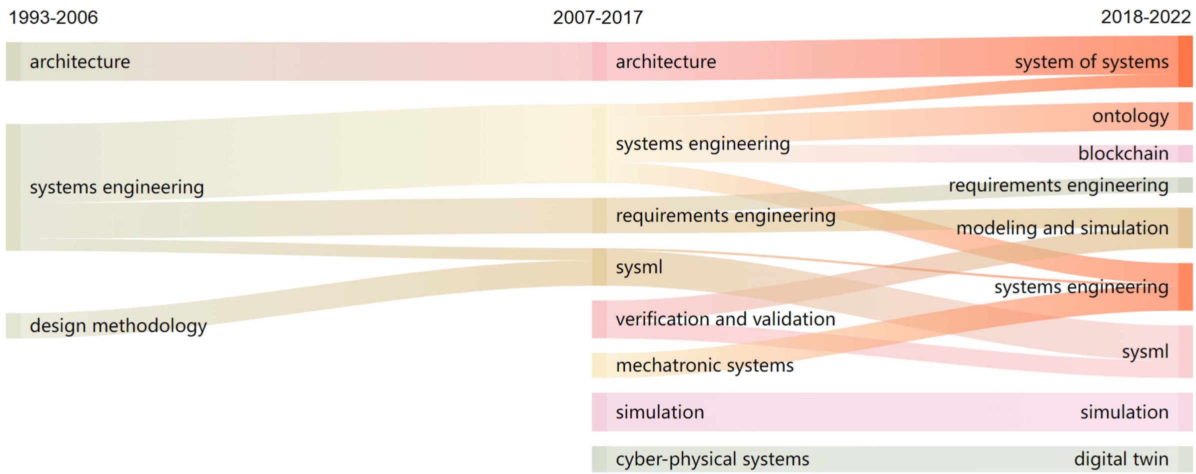

Fig. 11. Thematic evolution of MBSE.

The position of each topic is determined by centrality and density and thus distributed in different quadrants. Thematic evolution is a longitudinal thematic map analysis, dividing a period into different slices to study the tendencies of some topics to merge, or of a topic to spilt into several topics [122]. Time slices are divided according to the Fig. 1 in Section II.

The research topics in the first quadrant are the motor theme with high centrality and high density. These topics have been strongly developed and are greatly important within the field. Research on systems engineering topics is located in this quadrant. In Fig. 11, as a major cluster in the initial phase, systems engineering has evolved to research in languages, requirements engineering, modeling and simulation, SoS, ontology, blockchain, etc. Systems engineering itself also has always continued as a theme to this day. The evolution of digital technologies such as blockchain from systems engineering proves that systems engineering is the foundation and driving force of MBSE [106]. Therefore, the first future direction is to consolidate and extend the scientific foundation of systems engineering [123].

The second quadrant is the niche theme. The placement of topics in this quadrant is very specialized and peripheral [72], with low centrality and high density. Research on safety analysis topics is located in this quadrant. Safety analysis is a specific research domain and research on this topic is often combined with established security analysis methods such as FTA and FMEA [124]. Therefore, its own development is mature, but due to its specific application field, it has little connection with other topics. For safety analysis, it is normal for the cluster to be in the second quadrant. Some possible future direction for security analysis is to increase centrality, including increased research on cybersecurity analysis [125] and increased integration of safety analysis with modeling languages, which could even be a diagram of the system modeling language [126].

The third quadrant is the emerging or declining theme, representing low centrality and low density. Research on digitalization topics is located in this quadrant. Referring to Figs. 9 and 11, digitalization is made up of new technologies that have just emerged in recent years, which is a topic that is emerging rather than declining. In Fig. 11, the concepts related to digitalization have gone from being absent in the first and second stages to be able to occupy a certain weight in the third stage. It is clear that the researchers have made considerable efforts according to the bibliometric data. However, as can be seen in Fig. 10, there is still a large gap between this aspect of research and other topics. In fact, digital transformation has brought several benefits to MBSE. Therefore, the second future direction is to develop MBSE digital technologies, including digital twins, blockchain, AI and ML, IoT, etc. First, continued improvements in modeling and simulation (a topic in 2018–2022 in Fig. 11) techniques are the foundation of MBSE digital development. The system model needs to be well-integrated with the physical (mechanical and electrical engineering) models [127] to achieve an AST [128]. Data, software, information, and knowledge can be connected by digital thread technology for truly seamless interaction in the future [129]. Based on the above, the digital twin will support the physical product lifecycle activities [130]. Second, AI needs to be integrated with MBSE. Not only can AI and ML enhance the system model data analysis ability [131], but with machine learning, natural language processing, and other technologies, it provides modelers with modeling suggestions and even obtain solutions based on problem descriptions [105], [132].

The fourth quadrant is the basic theme, representing high centrality and low density. Research on SoSE and language topics is located in this quadrant. This category of topics, despite its importance for MBSE development, is still underdeveloped.

As the complexity, integration, and multidomain coupling of systems have increased, some of the concerns of researchers for systems have begun to shift to SoS [133]. As can be seen in Fig. 11, SoSE has evolved out of the study of systems engineering. Its strong correlation with systems engineering enhances the centrality of SoSE. Since most of the research on SoS is focused on critical infrastructure, such as smart grids, there is less research on modeling and simulation tools or languages for SoS architecture analysis [134], which in turn constrains the development of SoSE. This is because the integration of systems from different domains as SoS poses challenges for interoperability and compatibility between system models [135]. Thus, the development of SoSE also relies on advances in digitization technology and language to improve interoperability and compatibility issues [136].

Language is undoubtedly an important part of current modeling and simulation [90]. Almost all MBSE activities are inseparable from language support, hence the high centrality of language topics [137]. In fact, in conjunction with the MBSE development timeline in the Fig. 1, the various languages of MBSE have each evolved over a long period. However, the study of this cluster is still underdeveloped. From the algorithmic rules of the thematic map, the connection of the keywords within the topic determines the degree of development of the topic. The language cluster includes a variety of different languages within it, including SysML, UML, and Modelica. The various languages have different application areas [138], which leads to the connections within this cluster not being close enough. To improve the density parameter of the language cluster, the integration of the languages should be enhanced. In Fig. 11, SysML is the most important modeling language, and research on SysML still holds great weight even now. SysML v2's request for proposal (RFP) was released in December 2017 and aims to achieve higher precision, expressiveness, and usability [139]. SysML v2 is no longer just a graphical modeling language, but a language with multiple forms such as text, graphs, and tables based on formal semantics [140]. In addition, SysML v2 has been designed with a standard API for accessing models. Similar to SysML v2, KARMA is a formal semantic modeling language based on GOPPRRE [141]. The emergence of these two languages reflects the third future direction of modeling languages from graphical to semantic modeling. Because of these changes, it is sufficient to provide the basis for model integration and interoperability that is of interest to both the digitization topic and SoSE [142], thus driving MBSE to a new stage.

V. Discussions

A. Results

First, according to the research-team analysis, MBSE is widely implemented worldwide and has gradually formed several noteworthy teams, which range from collaborative to independent teams. All teams possess several publications and have been cited multiple times. Second, we found a few high-quality sources in the MBSE field with a large number of publications and citations. In addition, as indicated in Table III, the most influential publications focus on digital twins and the practice or guidance of MBSE. Third, MBSE research is divided into six major categories, including systems engineering, languages, CPS, digitization, safety analysis, and SoSs engineering. Fourth, future research priorities will be mutually reinforcing. To better adapt to the development of technology and seize opportunities, we must consider the following focal points. Research in the basic science of systems engineering is to be emphasized, as this is the driving force of MBSE. The development of MBSE is to be integrated with the latest digital technologies, especially in the domains of digital twins, AI, etc. Another focus is on the evolution of next-generation modeling languages, and semantic modeling may be an important pathway to solving current model integration problems [143].

For the three research questions raised in Section II, the results obtained in this article also give answers. The *RQs* are answered in detail as follows.

RQ1:Is the upgrade of the modeling language relevant for MBSE at this stage? What is the direction of the upgrade?

Modeling languages still occupy the current phase of research in Fig. 11, represented by SysML. The future direction of the language is to build semantic modeling-related capabilities.

RQ2:Are new concepts such as digital engineering, digital twin, and artificial intelligence becoming separate research areas for MBSE, and how are they related to the future development of MBSE?

Figs. 8–11 all indicate that these new concepts already exist as independent research clusters. Moreover, Fig. 11 also shows that the new concepts represented by digital twin and blockchain have become hot topics of research at this stage. Combined with the keyword connections in Fig. 8, these new concepts of digitization are related to the modeling and simulation of MBSE [144]. It plays a significant role in the construction of system models, and authoritative truth Sources [145].

RQ3: Are the application areas of MBSE still in aerospace?

In Table V, we can see that MBSE applications have begun to expand, involving complex systems such as electric vehicles and smart grids.

To summarize, in the maturity curve in the introduction, MBSE is in the slope-of-enlightenment period owing to the influx of new technologies. Researchers must leverage digital transformation and focus on systems engineering, digitalization, and languages research so that they can stably apply MBSE in the near future.

B. Limitations

First, the visualized network tends to lose certain information; therefore, the context of the nodes cannot be directly inferred from the network. For example, when we constructed the source citation network, we could view the identity of the citers, but we could not ascertain the reason. Thus, the networks are a supplement to the analysis, for which the details can be viewed in a table in this study, or the publications of interest may be downloaded according to the figure.

Second, we can only adjust the resolution and accuracy of clustering by modifying some of the parameters provided by the bibliometric tool. Therefore, although we ensured that, influenced by the stability of the algorithm and the freedom of the tool [146], the overall topic clustering is accurate, a few keywords may be inaccurately categorized.

VI. Conclusion

MBSE has developed rapidly in recent times, but it has not been comprehensively reviewed by researchers for a thorough understanding of the latest MBSE techniques. Consequently, we presented a bibliometric analysis of the MBSE publications from to 1993–2022. Scopus and the Wiley online Library were used as the two digital libraries to collect MBSE publications. We used VOSViewer and BibliometriX to analyze the research team, source, current practice, and future directions related to MBSE.

At least 49 MBSE research teams have been formed within the research communities of universities that collaborate with industries. MBSE publications have also begun to take shape, forming professional MBSE sources, such as *systems engineering*. MBSE technology is transitioning into the second generation, which has revealed several future directions simultaneously. We suggest researchers be updated with their technologies in the latest research fields, such as digital twins and AI, to guard against the threat of slow or uneven technological innovation.

To this end, recalling the maturity curve in Section II, MBSE is in the slope-of-enlightenment period and is entering the most widespread application stage. Researchers must continue exploring MBSE applications and prepare for the explosion of the next generation of novel MBSE techniques in fields such as digitalization and semantic modeling.

Acknowledgment

The authors would like to thank the IoF Systems Engineering Working Group [147] for supporting the data analysis.

References

[1] J. Heihoff-Schwede, L. Kaiser, and R. Dumitrescu, "An MBSE-based approach for the analysis of requirements towards engineering it architectures," in *Proc. Int. Symp. Syst. Eng.*, 2019, pp. 1–8.

[2] W. A. Wayne, "Model-based systems engineering," Boca Raton: CRC Press,1993.

[3] N. J. Shallcross, G. S. Parnell, E. A. Pohl, and E. A. Specking, "Informing program management decisions using quantitative set-based design," *IEEE Trans. Eng. Manag.*, pp. 1–16, 2021.

[4] F. Elakramine, R. Jaradat, N. U. I. Hossain, M. Banghart, C. Kerr, and S. El Amrani, "Applying systems modeling language in an aviation maintenance system," *IEEE Trans. Eng. Manag.*, no. 99, pp. 1–13, Jul. 2021.

[5] L. E. Hart, "Introduction to model-based system engineering (MBSE) and SysML," in *Delaware Valley INCOSE Chapter Meeting*, vol. 30, New Jersey, NJ, USA: Ramblewood Country Club Mount Laurel, 2015.

[6] L. Bornmann and R. Mutz, "Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references," *J. Assoc. Inf. Sci. Technol.*, vol. 66, no. 11, pp. 2215–2222, 2015.

[7] P. Layus and P. Kah, "Bibliometric study of welding scientific publications by Big Data analysis," *Int. J. Mech. Eng. Appl.*, vol. 3, no. 5, pp. 94–102, 2015.

[8] J. C. Donohue, "A bibliometric analysis of certain information science literature," *J. Amer. Soc. Inf. Sci.*, vol. 23, no. 5, pp. 313–317, 1972.

[9] T. Saracevic and L. J. Perk, "Ascertaining activities in a subject area through bibliometric analysis application to library literature," *J. Amer. Soc. Inf. Sci.*, vol. 24, no. 2, pp. 120–134, 1973.

[10] J. Huang, L.-X. Mao, H.-C. Liu, and M.-S. Song, "Quality function deployment improvement: A bibliometric analysis and literature review," *Qual. Quantity*, vol. 56, pp. 1–20, 2021.

[11] D. Yu, W. Wang, W. Zhang, and S. Zhang, "A bibliometric analysis of research on multiple criteria decision making," *Curr. Sci.*, vol. 114, no. 4, pp. 747–758, 2018.

[12] F. J. Martínez-López, J. M. Merigó, L. Valenzuela-Fernández, and C. Nicolás, "Fifty years of the european journal of marketing: A bibliometric analysis," *Eur. J. Marketing*, vol. 52, no. 1/2, pp. 439–468, 2018.

[13] H. Chen, R. H. Chiang, and V. C. Storey, "Business intelligence and analytics: From big data to big impact," *MIS Quart.*, vol. 36, pp. 1165–1188, 2012.

[14] J. Y. Park and Z. Nagy, "Comprehensive analysis of the relationship between thermal comfort and building control research-a data-driven literature review," *Renewable Sustain. Energy Rev.*, vol. 82, pp. 2664–2679, 2018.

[15] M. Palmblad and N. J. van Eck, "Bibliometric analyses reveal patterns of collaboration between ASMS members," *J. Amer. Soc. Mass Spectrometry*, vol. 29, no. 3, pp. 447–454, 2018.

[16] N. Telis, B. V. Lehmann, M. W. Feldman, and J. K. Pritchard, "A bibliometric history of the journal genetics," *Genetics*, vol. 204, no. 4, pp. 1337–1342, 2016.

[17] C. Figueroa-Domecq, A. Pritchard, M. Segovia-Pérez, N. Morgan, and T. Villacé-Molinero, "Tourism gender research: A critical accounting," *Ann. Tourism Res.*, vol. 52, pp. 87–103, 2015.

[18] P. Roques, "MBSE with the arcadia method and the capella tool," in *Proc. 8th Eur. Congr. Embedded Real Time Softw. Syst.*, 2016, pp. 1–11.

[19] C. Haskins, "4.6. 1 a historical perspective of MBSE with a view to the future," in *Proc. Incose Int. Symp.*, 2011, pp. 493–509.

[20] A. Linden and J. Fenn, "Understanding gartner's hype cycles," *Strategic Anal. Rep. N R-20-1971*, Gartner, Inc, vol. 88, 2003, pp. 1–12.

[21] M. Chami and J.-M. Bruel, "A survey on MBSE adoption challenges," in *Proc. INCOSE EMEA Sector Syst. Eng. Conf.*, 2018, pp. 1–16.

[22] D. W. Oliver, "Descriptions of systems engineering methodologies and comparison of information representations," in *Proc. INCOSE Int. Symp.*, 1993, pp. 97–104.

[23] D. Dori, "Analysis and representation of computer vision systems by the object-process methodology," in *Proc. Mach. Vis. Appl.*, 1994, pp. 200–209.

[24] R. Breu et al., "Towards a formalization of the unified modeling language," in *Proc. Eur. Conf. Object-Oriented Program.*, 1997, pp. 344–366.

[25] M. Hause et al., "The SysML modelling language," in *Proc. 15th Eur. Syst. Eng. Conf.*, vol. 9, 2006, pp. 1–12.

[26] D. Harel and E. Gery, "Executable object modeling with statecharts," in *Proc. IEEE 18th Int. Conf. Softw. Eng.*, 1996, pp. 246–257.

[27] NoMagic, "Press release," [Online]. Available: https://www.magicdraw.com/files/PressRelMagicDraw60.html

[28] SPARX, "About us," [Online]. Available: https://sparxsystems.com/about.html

[29] Wikipedia, "Capella (engineering)," [Online]. Available: https://en.wikipedia.org/wiki/Capella_(engineering)

[30] S. Kelly, K. Lyytinen, and M. Rossi, "Metaedit a fully configurable multiuser and multi-tool case and came environment," in *Proc. Int. Conf. Adv. Inf. Syst. Eng.*, 1996, pp. 1–21.

[31] INCOSE Technical Operations, "Systems Engineering Vision 2020 version 2.03.," Int. Council Syst. Eng., Seattle, WA, USA, Tech. Rep. TP-2004-004-02, 2007.

[32] International Council on Systems Engineering (INCOSE), "Systems Engineering Vision 2025," Jul. 2014.

[33] Open Services for Lifecycle Collaboration, "OSLC Primer," *Primer-Learning the Concepts of OSLC*, p. 30, 2008.

[34] P. Zimmerman, "Dod digital engineering strategy," in *Proc. 20th Annu. NDIA Syst. Eng. Conf. DoD Digit. Eng. strategy*, Springfield, VA, 2017, pp. 1–17.

[35] E. Negri, L. Fumagalli, and M. Macchi, "A review of the roles of digital twin in CPS-based production systems," *Procedia Manuf.*, vol. 11, pp. 939–948, 2017.

[36] S. Wolny, A. Mazak, C. Carpella, V. Geist, and M. Wimmer, "Thirteen years of SysML: A systematic mapping study," *Softw. Syst. Model.*, vol. 19, no. 1, pp. 111–169, 2020.

[37] OMG, "Sysml v2_omg sysml," [Online]. Available: https://www.omgsysml.org/SysML-2.htm

[38] D. Dori et al., "OPCloud: An OPM integrated conceptual-executable modeling environment for industry 4.0," *Syst. Eng. 4th Ind. Revolution*, 2019, ch. 11, pp. 243–271.

[39] J. Hatakeyama, D. Seal, D. Farr, and S. Haase, "Systems engineering 'v' in a model-based engineering environment: Is it still relevant ?," in *Proc. Amer. Inst. Aeronaut. Astronaut. SPACE Astronaut. Forum Expo.*, 2018, paper no. 5326.

[40] D. Fulghum and G. Warwick, "Industry works to boost security as cyberattacks escalate," in *Proc. Aviation Week Space Technol. Aviation Week Netw.*, 2009, vol. 170, no. 17, p. 17.

[41] T. McDermott, D. DeLaurentis, P. Beling, M. Blackburn, and M. Bone, "AI4SE and SE4AI: A research roadmap," *Insight*, vol. 23, no. 1, pp. 8–14, 2020.

[42] J. Lu, G. Wang, J. Ma, D. Kiritsis, H. Zhang, and M. Törngren, "General modeling language to support model-based systems engineering formalisms (part 1)," in *Proc. INCOSE Int. Symp.*, 2020, pp. 323–338.

[43] ZKhoneycomb, "Metagraph," [Online]. Available: http://www.zkhoneycomb.com/

[44] J. Lu, J. Ma, X. Zheng, G. Wang, H. Li, and D. Kiritsis, "Design ontology supporting model-based systems engineering formalisms," *IEEE Syst. J.*, pp. 1–12, 2021.

[45] A. F. Choudhri, A. Siddiqui, N. R. Khan, and H. L. Cohen, "Understanding bibliometric parameters and analysis," *Radiographics*, vol. 35, no. 3, pp. 736–746, 2015.

[46] J. A. Wallin, "Bibliometric methods: Pitfalls and possibilities," *Basic Clin. Pharmacol. Toxicol.*, vol. 97, no. 5, pp. 261–275, 2005.

[47] J. O. Agushaka, "Automatic clustering algorithms: A systematic review and bibliometric analysis of relevant literature," *Neural Comput. Appl.*, vol. 33, pp. 6247–6306, 2021.

[48] A. Anfossi, A. Ciolfi, F. Costa, G. Parisi, and S. Benedetto, "Large-scale assessment of research outputs through a weighted combination of bibliometric indicators," *Scientometrics*, vol. 107, no. 2, pp. 671–683, 2016.

[49] Y. Zhang, M. Wu, Z. Hu, R. Ward, X. Zhang, and A. Porter, "Profiling and predicting the problem-solving patterns in China's research systems: A methodology of intelligent bibliometrics and empirical insights," *Quantitative Sci. Stud.*, vol. 2, no. 1, pp. 409–432, 2021.

[50] M. Wu, D. C. Kozanoglu, C. Min, and Y. Zhang, "Unraveling the capabilities that enable digital transformation: A data-driven methodology and the case of artificial intelligence," *Adv. Eng. Informat.*, vol. 50, 2021, Art. no. 101368.

[51] C. Mejia, M. Wu, Y. Zhang, and Y. Kajikawa, "Exploring topics in bibliometric research through citation networks and semantic analysis," *Front. Res. Metrics Analytics*, vol. 6, 2021, Art. no. 742311.

[52] Y. Zhang, A. L. Porter, S. Cunningham, D. Chiavetta, and N. Newman, “Parallel or intersecting lines? intelligent bibliometrics for investigating the involvement of data science in policy analysis,” *IEEE Trans. Eng. Manag.*, vol. 68, no. 5, pp. 1259–1271, Oct. 2020.

[53] M. Rashid, M. W. Anwar, and A. M. Khan, “Toward the tools selection in model based system engineering for embedded systems’a systematic literature review,” *J. Syst. Softw.*, vol. 106, pp. 150–163, 2015.

[54] J. Linnosmaa, J. Valkonen, P. Karpati, A. Hauge, F. Sechi, and B. A. Gran, “Towards model-based specification and safety assurance of nuclear i $\&$; c systems? applicability of SysML and aadl,” *Nucl. Sci. Eng.*, pp. 276–289, 2021.

[55] W. Torres, M. van den Brand, and A. Serebrenik, “Model management tools for models of different domains: A systematic literature review,” in *Proc. IEEE Int. Syst. Conf.*, 2019, pp. 1–8.

[56] C. E. Dridi, Z. Benzadri, and F. Belala, “System of systems modelling: Recent work review and a path forward,” in *Proc. Int. Conf. Adv. Aspects Softw. Eng.*, 2020, pp. 1–8.

[57] J. Lu, Y. Wen, Q. Liu, D. Gürdür, and M. Törngren, “MBSE applicability analysis in chinese industry,” in *Proc. INCOSE Int. Symp.*, 2018, pp. 1037–1051.

[58] M. M. Schmidt, T. C. Zimmermann, and R. Stark, “Systematic literature review of system models for technical system development,” *Appl. Sci.*, vol. 11, no. 7, 2021, Art. no. 3014.

[59] K. Henderson and A. Salado, “Value and benefits of model-based systems engineering (MBSE): Evidence from the literature,” *Syst. Eng.*, vol. 24, no. 1, pp. 51–66, 2021.

[60] B. Cameron and D. M. Adsit, “Model-based systems engineering uptake in engineering practice,” *IEEE Trans. Eng. Manag.*, vol. 67, no. 1, pp. 152–162, Feb. 2018.

[61] A. Akundi and O. Mondragon, “Model based systems engineering’a text mining based structured comprehensive overview,” *Syst. Eng.*, vol. 25, pp. 51–67, 2021.

[62] Z. Li, J. Lu, G. Wang, L. Feng, D. Gürdür, and D. Kiritsis, “A bibliometric analysis on model-based systems engineering,” in *Proc. INCOSE Int. Symp.*, 2021, pp. 1–8.

[63] P. Mongeon and A. Paul-Hus, “The journal coverage of web of science and scopus: A comparative analysis,” *Scientometrics*, vol. 106, no. 1, pp. 213–228, 2016.

[64] L.-X. Hou, R. Liu, H.-C. Liu, and S. Jiang, “Two decades on human reliability analysis: A bibliometric analysis and literature review,” *Ann. Nucl. Energy*, vol. 151, 2021, Art. no. 107969.

[65] Scopus, “Scopus preview,” [Online]. Available: https://www.scopus.com

[66] Wiley, “Wiley online library - scientific research articles, journals, books, and reference works,” [Online]. Available: https://onlinelibrary.wiley.com/

[67] A. D. Cohen, A. S. Jagra, B. Yang, B. Fernandez, S. Banerjee, and Y. Wang, “Detecting task functional MRI activation using the multiband multiecho (MBME) echo-planar imaging (EPI) sequence,” *J. Magn. Reson. Imag.*, vol. 53, no. 5, pp. 1366–1374, 2021.

[68] F. Xu, Y. J. Fang, Z. Wu, and J. Q. Liang, “A method based on multiscale base-scale entropy and random forests for roller bearings faults diagnosis,” *J. Vibroengineering*, vol. 20, no. 1, pp. 175–188, 2018.

[69] J. Lu and J. Andrian, “Using pixel array method to optimize battery remaining useful life model,” in *Proc. IEEE Veh. Power Propulsion Conf.*, 2018, pp. 1–4.

[70] N. J. Van Eck and L. Waltman, “Software survey: Vosviewer, a computer program for bibliometric mapping,” *Scientometrics*, vol. 84, no. 2, pp. 523–538, 2010.

[71] M. Aria and C. Cuccurullo, “Bibliometrix: An r-tool for comprehensive science mapping analysis,” *J. Informetrics*, vol. 11, no. 4, pp. 959–975, 2017.

[72] M. J. Cobo, A. G. López-Herrera, E. Herrera-Viedma, and F. Herrera, “An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the fuzzy sets theory field,” *J. Informetrics*, vol. 5, no. 1, pp. 146–166, 2011.

[73] T. Bauernhansl, M. Ten Hompel, and B. Vogel-Heuser, “*Industrie 4.0 in Produktion*,” Automatisierung und logistik: Anwendung technologien migration, Wiesbaden: Springer, 2014.

[74] S. Ili, A. Albers, and S. Miller, “Open innovation in the automotive industry,” *R&d Manage.*, vol. 40, no. 3, pp. 246–255, 2010.

[75] F. Tao, H. Zhang, A. Liu, and A. Y. Nee, “Digital twin in industry: State-of-the-art,” *IEEE Trans. Ind. Informat.*, vol. 15, no. 4, pp. 2405–2415, Apr. 2018.

[76] S. Boschert and R. Rosen, “Digital twin the simulation aspect,” in *Mechatronic Futures*, 2016, pp. 59–74.

[77] A. Kossiakoff, W. N. Sweet, S. J. Seymour, and S. M. Biemer, *Systems Engineering: Principles and Practice*. vol. 83, New York, NY, USA: Wiley, 2011.

[78] M. L. Tuballa and M. L. Abundo, “A review of the development of smart grid technologies,” *Renewable Sustain. Energy Rev.*, vol. 59, pp. 710–725, 2016.

[79] C. Keating et al., “System of systems engineering,” *Eng. Manage. J.*, vol. 15, no. 3, pp. 36–45, 2003.

[80] S. Friedenthal, A. Moore, and R. Steiner, *A Practical Guide to SysML: The Systems Modeling Language, version 1.3*. Morgan Kaufmann, 2012.

[81] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, “Characterising the digital twin: A systematic literature review,” *Corporate Insolvency Resolution Process J. Manuf. Sci. Technol.*, vol. 29, pp. 36–52, 2020.

[82] A. M. Madni, C. C. Madni, and S. D. Lucero, “Leveraging digital twin technology in model-based systems engineering,” *Systems*, vol. 7, no. 1, p. 7, Jan. 2019, doi: 10.3390/systems7010007.

[83] G. Dileep, “A survey on smart grid technologies and applications,” *Renewable Energy*, vol. 146, pp. 2589–2625, 2020.

[84] A. L. Ramos, J. V. Ferreira, and J. Barceló, “Model-based systems engineering: An emerging approach for modern systems,” *IEEE Trans. Syst., Man, Cybern., Part C.*, vol. 42, no. 1, pp. 101–111, Jan. 2011.

[85] D. Kaslow, B. Ayres, P. T. Cahill, and L. Hart, “A model-based systems engineering approach for technical measurement with application to a cubesat,” in *Proc. IEEE Aerosp. Conf.*, 2018, pp. 1–10.

[86] A. M. Madni, M. Nance, M. Richey, W. Hubbard, and L. Hanneman, “Toward an experiential design language: Augmenting model-based systems engineering with technical storytelling in virtual worlds,” *Procedia Comput. Sci.*, vol. 28, pp. 848–856, 2014.

[87] Y. Bernard, “Requirements management within a full model-based engineering approach,” *Syst. Eng.*, vol. 15, no. 2, pp. 119–139, 2012.

[88] D. Dori, I. Reinhartz-Berger, and A. Sturm, “Developing complex systems with object-process methodology using OPCAT,” in *Proc. Int. Conf. Conceptual Model.*, 2003, pp. 570–572.

[89] Y. Van Tendeloo and H. Vangheluwe, “Discrete event system specification modeling and simulation,” in *Proc. Winter Simul. Conf.*, 2018, pp. 162–176.

[90] K. A. Reilley, S. Edwards, R. Peak, and D. Mavris, “Methodologies for modeling and simulation in model-based systems engineering tools,” in *Proc. Amer. Inst. Aeronaut. Astronaut.*, 2016, pp. 1–14.

[91] J. Guo, G. Wang, J. Lu, J. Ma, and M. Törngren, “General modeling language supporting model transformations of MBSE (part 2),” in *Proc. INCOSE Int. Symp.*, 2020, pp. 1460–1473.

[92] A. Alshareef, D. Kim, C. Seo, and B. P. Zeigler, “Activity diagrams between devs-based modeling and simulation and FUML-based model execution,” in *Proc. Summer Simul. Conf.*, 2020, pp. 1–12.

[93] D. Kaslow, B. Ayres, P. T. Cahill, L. Hart, and R. Yntema, “A model-based systems engineering (MBSE) approach for defining the behaviors of cubesats,” in *Proc. IEEE Aerosp. Conf.*, 2017, pp. 1–14.

[94] S. M. Dibaji, M. Pirani, D. B. Flamholz, A. M. Annaswamy, K. H. Johansson, and A. Chakrabortty, “A systems and control perspective of CPS security,” *Annu. Rev. Control*, vol. 47, pp. 394–411, 2019.

[95] R. Plateaux, O. Penas, J.-Y. Choley, F. Mhenni, M. Hammadi, and F. Louni, “Evolution from mechatronics to cyber physical systems: An educational point of view,” in *Proc. 11th France- Jpn. 9th Europe-Asia Congr. Mechatronics (MECATRONICS)/17th Int. Conf. Res. Educ. Mechatronics*, 2016, pp. 360–366.

[96] C. Tschirner, L. Bretz, R. Dumitrescu, and J. Gausemeier, “Applying model-based systems engineering for product engineering management concepts for industrial application,” in *Proc. IEEE Int. Symp. Syst. Eng.*, 2015, pp. 42–49.

[97] L. van Ruijven, “Ontology for systems engineering as a base for MBSE,” in *Proc. INCOSE Int. Symp.*, 2015, pp. 250–265.

[98] D. Ernadote, “An ontology mindset for system engineering,” in *Proc. IEEE Int. Symp. Syst. Eng.*, 2015, pp. 454–460.

[99] D. Ernadote, “Ontology-based pattern for system engineering,” in *Proc. ACM/IEEE 20th Int. Conf. Model Driven Eng. Lang. Syst.*, 2017, pp. 248–258.

[100] P. H. Nguyen, S. Ali, and T. Yue, “Model-based security engineering for cyber-physical systems: A systematic mapping study,” *Inf. Softw. Technol.*, vol. 83, pp. 116–135, 2017.

[101] C. K. Keerthi, M. Jabbar, and B. Seetharamulu, “Cyber physical systems (CPS): Security issues, challenges and solutions,” in *Proc. IEEE Int. Conf. Comput. Intell. Comput. Res.*, 2017, pp. 1–4.

[102] V. Salehi, "Integration of blockchain technologie in case of systems engineering and software engineering in an industrial context," in *Proc. Des. Soc.*, 2021, vol. 1, pp. 1887–1896.
[103] V. Parida, "Digitalization," in *Addressing Societal Challenges*, Luleå Univ. Technol., 2018 pp. 23–38.
[104] M. Bone, M. Blackburn, B. Kruse, J. Dzielski, T. Hagedorn, and I. Grosse, "Toward an interoperability and integration framework to enable digital thread," *Systems*, vol. 6, no. 4, 2018, Art. no. 46.
[105] M. Chami, C. Zoghbi, and J.-M. Bruel, "A first step towards AI for MBSE: Generating a part of sysml models from text using AI," in *Proc. INCOSE Artif. Intell. Syst.: Conf.*, 2019, pp. 123–136.
[106] A. M. Madni and M. Sievers, "Model-based systems engineering: Motivation, current status, and research opportunities," *Syst. Eng.*, vol. 21, no. 3, pp. 172–190, 2018.
[107] R. Cloutier, B. Sauser, M. Bone, and A. Taylor, "Transitioning systems thinking to model-based systems engineering: Systemigrams to SysML models," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 45, no. 4, pp. 662–674, Apr. 2014.
[108] M. Russell, "Using MBSE to enhance system design decision making," *Procedia Comput. Sci.*, vol. 8, pp. 188–193, 2012.
[109] F. Mhenni, N. Nguyen, and J.-Y. Choley, "SafeSysE: A safety analysis integration in systems engineering approach," *IEEE Syst. J.*, vol. 12, no. 1, pp. 161–172, Mar. 2016.
[110] M. Izygon, H. Wagner, S. Okon, L. Wang, M. Sargusingh, and J. Evans, "Facilitating r&m in spaceflight systems with MBSE," in *Proc. Annu. Rel. Maintainability Symp.*, 2016, pp. 1–6.
[111] F. Asplund, J. McDermid, R. Oates, and J. Roberts, "Rapid integration of CPS security and safety," *IEEE Embedded Syst. Lett.*, vol. 11, no. 4, pp. 111–114, Dec. 2018.
[112] R. E. Giachetti, "Evaluation of the dodaf meta-model's support of systems engineering," *Procedia Comput. Sci.*, vol. 61, pp. 254–260, 2015.
[113] D. Joannou, R. Kalawsky, S. Saravi, M. Rivas Casado, G. Fu, and F. Meng, "A model-based engineering methodology and architecture for resilience in systems-of-systems: A case of water supply resilience to flooding," *Water*, vol. 11, no. 3, 2019, Art. no. 496.
[114] H. Abdi and D. Valentin, "Multiple correspondence analysis," *Encyclopedia Meas. Statist.*, vol. 2, no. 4, pp. 651–657, 2007.
[115] J.-H. Huang, X.-Y. Duan, F.-F. He, G.-J. Wang, and X.-Y. Hu, "A historical review and bibliometric analysis of research on weak measurement research over the past decades based on biblioshiny," pp. 1–19, 2021, *arXiv:2108.11375*.
[116] S. C. Spangelo et al., "Applying model based systems engineering (MBSE) to a standard cubesat," in *Proc. IEEE Aerosp. Conf.*, 2012, pp. 1–20.
[117] B. Kirpes, P. Danner, R. Basmadjian, H. D. Meer, and C. Becker, "E-mobility systems architecture: A model-based framework for managing complexity and interoperability," *Energy Informat.*, vol. 2, no. 1, pp. 1–31, 2019.
[118] P. Pearce and M. Hause, "Iso-15288, oosem and model-based submarine design," in *Proc. Syst. Eng. Test Eval./ 6th Asia Pacific Conf. Syst. Eng.*, 2012.
[119] D. Jianyu and H. Zhang, "Model-based systemic hazard analysis approach for connected and autonomous vehicles and case study application in automatic emergency braking system," *SAE Int. J. Connected Automated Veh.*, vol. 4, no. 12-04-01-0003, p. 12, 2021.
[120] M. Locatelli, E. Seghezzi, L. Pellegrini, L. C. Tagliabue, and G. M. Di Giuda, "Exploring natural language processing in construction and integration with building information modeling: A scientometric analysis," *Buildings*, vol. 11, no. 12, 2021, Art. no. 583.
[121] D. Armenta-Medina, T. A. Ramirez-delReal, D. Villanueva-Vásquez, and C. Mejia-Aguirre, "Trends on advanced information and communication technologies for improving agricultural productivities: A bibliometric analysis," *Agronomy*, vol. 10, no. 12, 2020, Art. no. 1989.
[122] X. Chen, Y. Lun, J. Yan, T. Hao, and H. Weng, "Discovering thematic change and evolution of utilizing social media for healthcare research," *Brihanmumbai Municipal Corporation Med. Informat. Decis. Mak.*, vol. 19, no. 2, pp. 39–53, 2019.
[123] D. Hybertson, "4.5. 2 next generation systems engineering: Expansion, foundation, unification," in *Proc. INCOSE Int. Symp.*, 2011, pp. 464–477.
[124] J.-Y. Choley, F. Mhenni, N. Nguyen, and A. Baklouti, "Topology-based safety analysis for safety critical CPS," *Procedia Comput. Sci.*, vol. 95, pp. 32–39, 2016.
[125] J. M. Borky and T. H. Bradley, "Protecting information with cybersecurity," in *Effective Model-Based Syst. Eng.*, 2019, pp. 345–404.
[126] G. Biggs, T. Juknevicius, A. Armonas, and K. Post, "Integrating safety and reliability analysis into MBSE: Overview of the new proposed OMG standard," in *Proc. INCOSE Int. Symp.*, 2018, pp. 1322–1336.
[127] D. DeLaurentis, "Sebok part 8: Emerging knowledge," [Online]. Available: https://www.sebokwiki.org/wiki/Emerging_Knowledge
[128] B. Kruse and M. Blackburn, "Collaborating with OpenMBEE as an authoritative source of truth environment," *Procedia Comput. Sci.*, vol. 153, pp. 277–284, 2019.
[129] J. V. Zweber, R. M. Kolonay, P. Kobryn, and E. J. Tuegel, "Digital thread and twin for systems engineering: Requirements to design," in *Proc. 55th AIAA Aerosp. Sci. Meeting*, 2017, paper no. 0875.
[130] J. Liu, J. Liu, C. Zhuang, Z. Liu, and T. Miao, "Construction method of shop-floor digital twin based on MBSE," *J. Manuf. Syst.*, vol. 60, pp. 93–118, 2021.
[131] M. Arantes, R. Bonnard, A. P. Mattei, and P. de Saqui-Sannes, "General architecture for data analysis in industry 4.0 using SysML and model based system engineering," in *Proc. Annu. IEEE Int. Syst. Conf.*, 2018, pp. 1–6.
[132] R. Saini, "Artificial intelligence empowered domain modelling bot," in *Proc. 23 rd ACM/IEEE Int. Conf. Model Driven Eng. Lang. Syst., Companion Proc.*, 2020, pp. 1–6.
[133] C. Fu, J. Liu, L. Zhang, Y. Mao, and J. Jin, "Knowledge graph based system model configuration design," in *Proc. J. Physics: Conf. Ser.*, 2021, Paper no. 012108.
[134] D. Joannou and R. Kalawsky, "A novel 'resilience viewpoint' to aid in engineering resilience in systems of systems (SOS)," in *Proc. INCOSE Int. Symp.*, 2018, pp. 835–849.
[135] C. Neureiter, C. Binder, B. Brankovic, and G. Lastro, "Extending the concept of domain specific systems engineering to system-of-systems," in *Proc. IEEE 15th Int. Conf. Syst. Syst. Eng.*, 2020, pp. 000391–000396.
[136] L. Zhang, "Specification and design of cyber physical systems based on system of systems engineering approach," in *Proc. 17th Int. Symp. Distrib. Comput. Appl. Bus. Eng. Sci.*, 2018, pp. 300–303.
[137] Y. Zhang, Z. Liu, Q. Han, and W. Zhang, "Development of system life cycle processes standardization and future evolution analysis," in *Proc. 8th Int. Conf. Dependable Syst. Their Appl.*, 2021, pp. 240–246.
[138] J. D'Ambrosio and G. Soremekun, "Systems engineering challenges and MBSE opportunities for automotive system design," in *Proc. IEEE Int. Conf. Systems, Man, Cybern.*, 2017, pp. 2075–2080.
[139] S. Friedenthal, "Requirements for the next generation systems modeling language (SysML v2)," *Insight*, vol. 21, no. 1, pp. 21–25, 2018.
[140] I. Gomes and B. Regalia, "Connected engineering for a connected world Feat. Mars 2020, Jupyter, SysML v2 and OpenMBEE," 2020. [Online]. Available: https://trs.jpl.nasa.gov/bitstream/handle/2014/53447/CL%2320-6147.pdf?sequence=1
[141] J. Ma, G. Wang, J. Lu, S. Zhu, J. Chen, and Y. Yan, "Semantic modeling approach supporting process modeling and analysis in aircraft development," *Appl. Sci.*, vol. 12, no. 6, 2022, Art. no. 3067.
[142] M. Bajaj, S. Friedenthal, and E. Seidewitz, "Systems modeling language (SysML v2) support for digital engineering," *INSIGHT*, vol. 25, no. 1, pp. 19–24, 2022.
[143] J. Lu, Z. Yang, X. Zheng, J. Wang, and D. Kiritsis, "Exploring the concept of cognitive digital twins from model-based systems engineering perspective," to be published, doi: 10.21203/rs.3.rs-1431416/v1.
[144] Z. Bing, L. Xin, and W. Xinxin, "From digital twin to digital engineering modeling and simulation entering a new era," *J. System Simul.*, vol. 31, no. 3, pp. 369–376, 2019, .
[145] K.-B. Yue et al., "Applying blockchain technology on model-based systems engineering," in *Proc. Amer. Inst. Aeronaut. Astronaut. Scitech 2021 Forum*, 2021, paper no. 0093.
[146] R. Vogel and W. H. Güttel, "The dynamic capability view in strategic management: A bibliometric review," *Int. J. Manage. Rev.*, vol. 15, no. 4, pp. 426–446, 2013.
[147] IOF, "Systems engieering wg," [Online]. Available: https://www.industrialontologies.org/systems-engineering-wg