IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 23 April 2023, accepted 14 May 2023, date of publication 17 May 2023, date of current version 31 May 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3277429

RESEARCH ARTICLE

Model-Based System Engineering of the Internet of Things: A Bibliometric Literature Analysis

EHSAN AHMAD
College of Computing and Informatics, Saudi Electronic University, Riyadh 11673, Saudi Arabia
e-mail: e.ahmad@seu.edu.sa

ABSTRACT Model-based System Engineering (MBSE) of the Internet of Things (IoT) literature is broad, and analysis of this literature enables the identification of themes and potential future study topics that will influence system development. This paper reports on bibliometric literature analysis of MBSE of IoT. It considers conference and journal publication trends in the state-of-the-art to identify emerging research themes from the standpoint of trans/multi-disciplinary scholarship and technology. We used Elsevier's Scopus database to find relevant publications from January 2018 to December 2022. Using publication citation ranking and other factors (*e.g.,* publication venues), we selected 110 articles and then analyzed them using BibExcel and VOSviewer software tools. With a modest decline in 2021, this analysis shows an overall increase in publications during the time period. A thematic analysis of the abstracts revealed a strong focus on the introduction of reference architectures and integration of MBSE with business and management methodologies like Agile and BPMN 2.0. Model-driven engineering and machine learning techniques are essential among the enablers for realization of complex heterogeneous IoT systems in the realm of Industry 4.0. We highlight these findings to better understand and meet the enduring challenge of scaling MBSE of IoT across diverse sectors like health, manufacturing, and transportation.

INDEX TERMS BibExcel, bibliometrics, Internet of Things, industry 4.0, model-based system engineering, model-driven engineering, thematic analysis, VOSviewer.

I. INTRODUCTION

An Internet of Things (IoT) is a network of internet-connected dynamically configurable *things* with the ability of data collection and exchange at any time and in any place [1]. The things connected in an IoT system may include everything ranging from a temperature sensor, camera, smart phone, home appliances, to a car, and so on. Applications of IoT systems are immense in various sectors of our daily life. For example, in ambient environment for intelligently controlling the heating and cooling [2], in health care for promoting wearable devices for collecting various vital signs [3], in "smart" homes/buildings wherein appliances talk to each other [4], [5], [6], in transportation for emergency path planning [7] and last-mile delivery [8], and most recently in industries for equipment health monitoring and predictive maintenance [9].

Diverse interaction among heterogeneous nodes (things), and requirement for clear understanding of the domain knowledge make the design and development of IoT systems complex, time-consuming, and challenging. Unlike other stand-alone systems, IoT systems are also required to be *open* to communicate and integrate with other systems in different domains (medical, aerospace, transportation, manufacturing etc.) to support context-awareness and dynamic adaptability that are some of the important properties of future generation systems.

Model-based System Engineering (MBSE) is a formalized approach of system development based on modeling [10], [11]. MBSE promotes definition, analysis, and transformation of models (into more concrete models) throughout the system development life cycle. MBSE approaches help to manage and reduce system complexity with abstraction in modeling, analyzability in development stages, and support for many viewpoints. Additionally, it assists development teams express design purpose, comprehend the effects

The associate editor coordinating the review of this manuscript and approving it for publication was Md. Arafatur Rahman.

of design changes, and evaluate a system design prior to construction. Different engineering domains have successfully used MBSE to develop complex systems; for example, for mission engineering [12], Cyber-physical Systems (CPS), [13], [14], System of Systems (SoS) [15], [16], digital twins [17], and IoT systems [18], [19]. The maturity of design and development methodologies of IoT systems has a considerable impact on the pervasive use of their applications.

A. MOTIVATION

IoT applications are essentially multidomain, large-scale systems made up of a variety of interconnected devices. Such complicated IoT systems are more challenging to design and construct than software-only systems because of connectivity, security, dynamic reconfiguration, and compatibility difficulties. Significant human effort is required to verify the correct design and construction of IoT systems. Industry and academia have explored different software and system engineering methodologies for IoT systems while keeping an eye on advancements in networking and hardware technology. MBSE has been a popular strategy for comprehending multidomain disciplines and complicated systems, such as IoT [20].

As a system engineering methodology, MBSE focuses on identifying and describing critical system properties through the use of models at various phases of the design and development process. In order to assure effective development and operational dependability of complex IoT systems, application of MBSE has been thoroughly investigated in recent years. There is a growing interest in developing analyzable architectural and design models as well as transferring these high-level verified models to low-level synthesis models for the successful implementation of IoT systems. The International Council on Systems Engineering (INCOSE) has also stated in its Vision 2035 that MBSE environments with multidisciplinary analysis capabilities are crucial for addressing new problems in complex system development [21]. Additionally, integrated model-based tools and methodologies are anticipated to become de facto industry standards by 2035. As a result, adoption of MBSE for IoT system design and development has been explored extensively in recent years. This rapid growth in the literature on MBSE of IoT system design and development demands an investigation of the trajectory and impacts of this scholarship.

Although many researchers and practitioners are familiar with the current state-of-the-art in MBSE of IoT, an analysis of the development and outcomes of this literature is required to cover the breadth and depth of the scholarship. A thorough examination of the publications will elucidate information regarding potential MBSE integration with other engineering and management methodologies, as well as current trends and future research directions that will support the use of cutting-edge tools and techniques to deal with failures and ensure the reliability of complex IoT systems [22], [23].

The author has worked on initiatives aimed at developing environments and tools for using MBSE for highly integrated complex systems [24], [25]. Researching the application of MBSE approaches for the design and development of IoT systems is thought to be highly beneficial and promising. It is reasonable to raise questions to evaluate various aspects of employing MBSE for the design and development of IoT systems, such as: *i)* What is the growth of MBSE-related publication and citation in IoT system development? *ii)* What are top venues of publications related to MBSE of IoT? *iii)* What modeling tools, methods, approaches, and languages are used most commonly for MBSE of IoT? and *iv)* What are the emerging research themes in the field?

To answer the aforementioned (and other related) questions, this paper presents the results of a bibliometric analysis performed on the literature investigating MBSE of IoT to evaluate the academic impact and characteristics of publications. This analysis focuses on examining the publication trends, identifying emerging themes and future research directions, and reflecting on major development and operational challenges. We used Elsevier's Scopus database to search for peer-reviewed journal and conference papers published between January 2018 – December 2022. A final set of 110 publications were analyzed using BibExcel [26] and VOSviewer [27] software tools. In addition to the standard features of the bibliometric analysis, we have also conducted a comprehensive analysis of the all 110 publications through manual reading of the abstracts and the evaluation methods supported in BibExcel. These analyses have resulted in identifying six key emerging themes and future research areas.

B. OUTLINE

Section II presents related work by summarizing the bibliometirc studies conducted on MBSE and IoT. Section III describes the research methodology used to perform this study. Section IV presents the results in terms of the publication characteristics, keywords analysis, and term co-occurrence network map. Section V contains comprehensive thematic analysis. The findings are discussed in Section VI. Section VII concludes this study.

II. RELATED WORK

Different systematic techniques have been used to analyze the literature on MBSE and IoT separately. For example, *systematic literature reviews* are conducted on the literature on classification and evaluation of MBSE tools for embedded systems [28], and to justify the use of MBSE approach across the engineering enterprise [29]. Studies like [30], and [31] are the examples of *systemic mapping* investigating model-based security engineering of Cyber-physical Systems (CPS), and MBSE as a key enabler of Industry 4.0, respectively.

Similarly, literature on IoT is also systematically reviewed from different perspectives [32], [33]. The investigations described in [34] and [35] are the exemplars of systematic mapping studies conducted on IoT publications. As far as

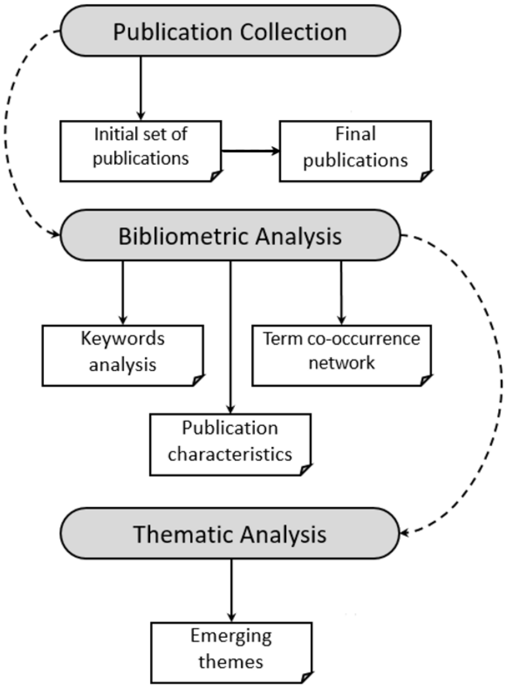

FIGURE 1. Research methodology.

we know, no systematic literature review or mapping of the literature specifically looking on MBSE of IoT has been published.

The papers that are more closely related to our work are the bibliometric analyses of the state-of-the-art on MBSE and IoT. Several studies have provided bibliometric analyses of the literature on MBSE, including [36], [37], and [38]. Similar to this, bibliometric analyses of the literature on the IoT have also been published [39], [40], [41]. Such earlier analyses either concentrated on MBSE or IoT individually. Our study, on the other hand, investigates the literature on the applicability and values of MBSE with focus on IoT systems. To the best of our knowledge, no such work has been published previously. Hence, there is need to investigate the constantly expanding body of knowledge of applying MBSE tools and techniques to cope with the challenges of designing and developing dependable IoT systems.

III. METHODOLOGY

Bibliometric analysis is a widely accepted quantitative tool for examining many facets of a certain study topic or concept in order to track advancements, assess impacts, and pinpoint new avenues for future research [42]. In this study, we applied bibliometric methods to analyze the literature on MBSE of IoT system design and development. Figure 1 illustrates the research methodology used to study the MBSE of IoT. The research methodology of this study is organized in three steps: *Publication Collection*, *Bebliometric Analysis*, and *Thematic Analysis*. Each of these steps is thoroughly explained in the rest of this section.

A. PUBLICATION COLLECTION

In the first step of this study, the bibliometric literature is extracted from the Elsevier Scopus database, which is considered as a largest database covering various research areas [43]. Many scholars have also used Scopus for bibliometric analysis across different research fields, for example studies reported in [36], [44], and [45].

In order to cover the wide range of literature on MBSE of IoT, we used the terms model-based system engineering and internet of things with possible variations to search the titles, abstracts, and keywords from articles published between January 2018 – December 2022. The exact search string automatically generated and used by Scopus is as follows:

```
(TITLE-ABS-KEY ( model AND based AND
system AND engineering ) OR
TITLE-ABS-KEY ( model-based AND
system AND engineering ) AND
TITLE-ABS-KEY ( iot ) OR
TITLE-ABS-KEY ( internet AND of AND
things ) ) AND
( LIMIT-TO ( PUBYEAR,  2023 ) OR
LIMIT-TO ( PUBYEAR,  2022 ) OR
LIMIT-TO ( PUBYEAR,  2021 ) OR
LIMIT-TO ( PUBYEAR,  2020 ) OR
LIMIT-TO ( PUBYEAR,  2019 ) OR
LIMIT-TO ( PUBYEAR,  2018 ) ) AND
(LIMIT-TO (LANGUAGE, ``English''))\\ AND
(  LIMIT-TO ( OA,  ``all'' ) OR
LIMIT-TO (OA, ``publisherfullgold'')\\OR
LIMIT-TO ( OA, ``publisherhybridgold'' ))
```

Our search was also restricted to peer-reviewed journal articles and conference papers written in English language. We then filtered the results for fully open-access and hybrid access (open and subscription-based) documents. This search process resulted in 340 publications. Information about the authors, title, abstract, publication year, number of citations, source title (journal or conference name), author keywords, and index keywords are downloaded for these publications. Considering that this study is focused on design and development of the IoT systems, we examined the titles and abstracts of the initial set of 340 publications to exclude those that solely addressed the application aspect of the IoT systems in various domains. The criteria applied for inclusion were:

- Publications pertaining to IoT and MBSE-related topics (*e.g.,* modeling language, transformation, validation, code generation, framework etc.,) are included.
- Only journal publication are included for extended version of conference publications published as journal articles.

The criteria applied for exclusion were:

- Publications that do not address IoT or MBSE in any way are excluded.
- Publications mainly focused on the application aspect of IoT in different sectors are also excluded.

Year	Publications
2018	42
2019	57
2020	68
2021	71
2022	102

Year	Publications
2018	19
2019	19
2020	32
2021	16
2022	24

FIGURE 2. Publication searching and selection strategy.

Figure 2 shows the search strategy and annual number of publications before and after applying the inclusion and exclusion criteria. A final set of 110 publications published in the past 05 years are considered for this study.

B. BIBLIOMETRIC ANALYSIS

In the second step of the study, for bibliometirc analysis, BibExcel software tool is used to examine the main characteristics of published papers, including publication type, year, keywords, and country of origin.

We analyzed frequency of author-specific and title keywords to explore how authors frame their work and identify the potential emerging research trends. As bibliometric analysis requires consistency in the statistical data, cleaning of the data set for consistency is performed in the author-specific and title keywords. All 1198 author-specific keywords, and 422 title keywords are reviewed for terminology uniformity. Several publications do not concur on whether to add "s" or "-" in the terms like 'twins', 'twin', and 'system of systems' etc. Such keyword were unified before visualizing data.

Along with the number of publications and citations, we have also analyzed several characteristics of publications like sources names, publication types, and countries of authors to assess the trends of publications. The data set is also cleaned up to ensure consistency in the names of the authors and the sources. The sources of conference papers were mostly defined by the year and session followed or preceded with "Proceedings of the" or "Proceedings - ". For example, the source title "SENSORNETS 2018 - Proceedings of the 7th International Conference on Sensor Networks" is different from the source title "IEEE SENSORNETS 2019". We deleted year and session of the conference and retained the main title of the sources in a unified format.

C. THEMATIC ANALYSIS

Finally, we conducted content analysis of the abstracts of 110 research publications to identify research themes. To investigate integration of knowledge in dynamic MBSE research with focus on IoT systems, VOSviewer is used to create a co-authorship network, and a network map of co-occurring terms extracted from the abstracts. We compiled and analyzed terms that co-occurred more than five times based on their relevance score and applying our intuition to exclude terms that were deemed be unsuitable (*e.g.,* synonyms, close related terms such as CPS and cyber-physical systems, MBSE, IoT).

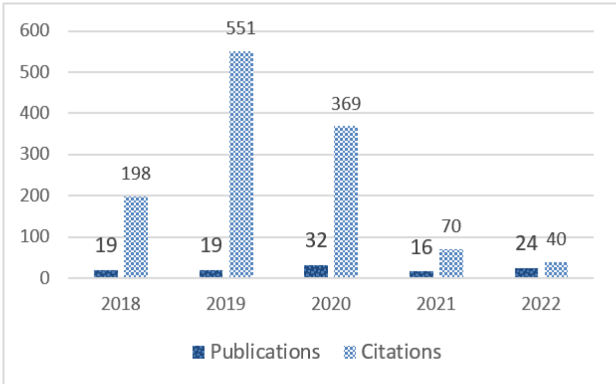

FIGURE 3. Cumulative trends in publications and citations in MBSE of IoT.

IV. RESULTS

This section presents results of bibliometric analysis of the literature on MBSE of IoT performed using BibExcel and VOSviewer software tools.

A. PUBLICATION CHARACTERISTICS

Below we specify the results related to the characteristics of publications.

1) TRENDS IN PUBLICATIONS AND CITATIONS

Figure 3 depicts the publication and citation trends from January 2018 to December 2022. We noted that while there were the same number of publications in 2018 and 2019, there were nearly three times as many citations in 2019. While the number of publications climbed in 2020 and 2022, the number of citations declined, and the number of publications decreased by 50% in 2021.

It is also observed that in the first 3 years, at least 5 studies were cited more than 15 times with couple of studies [17]

TABLE 1. Top ten conferences where literature on MBSE of IoT is published.

Conference/Proceedings series Name	Frequency
Lecture Notes in Computer Science (LNCS)	4
Procedia CIRP	3
Procedia Computer Science	3
IOP Conference Series: Materials Science and Engineering	2
IFAC-PapersOnLine	2
Procedia Manufacturing	2
Proceedings of the ACM Symposium on Applied Computing	2
Proceedings of the International Conference on Software Engineering	2
Proceedings of the ACM/IEEE International Conference on Model Driven Engineering Languages and Systems	1
Proceedings of the IEEE International Conference on Software Architecture	1

and [46] cited by 271 and 104, respectively. The most citations in the last two years are 14, while zero citations are found in nearly two-thirds of articles from 2022 which may be due to the short publication time. The average citation is 13.97 per paper in the past five years. 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.

2) SOURCES ANALYSIS

To determine the trends in publications, we examined the number of publications and citations, journal names, publication types, and author countries. Out of 110 publications in our sample, 63% are from peer-reviewed journal articles while 47% are from conference proceedings. The names of the top 10 conferences/proceedings series where research on MBSE of IoT was published are listed and ranked based on their frequency in Table 1.

Lecture Notes in Computer Science(LNCS) conference series had highest number of publications, followed by *Procedia CIRP* and *Procedia Computer Science* with equal number of publications. The proceedings of numerous relevant conferences are published in these conference series. The LNCS series, which is published by Springer, covers multiple conferences in different areas of computer science. The International Conference on Information Systems Security, International Semantic Web Conference, International Workshop on the Security of Industrial Control Systems and Cyber-Physical Systems, and NASA Formal Methods Symposium are the primary sources for the frequency of publishing for LNCS in Table 1. Proceedings from conferences held under The International Academy for Production Engineering, France, are published by Procedia CIRP. Conference proceedings from all areas of computer science research are published by Procedia Computer Science. Procedia CIRP, Procedia Computer Science, Procedia Manufacturing are published by ScienceDirect.

The names of the top 10 journals where research was published are listed and ranked based on their frequency in Table 2. Current and five year Impact Factor (IF) is shown along with access type and frequency of publications. "N/A" indicates that the IF is not available on journal website.

Among all these journals, *Applied Sciences* had the highest number of publications, followed by *IEEE Access*. With equal number of publications *IEEE Internet of Things Journal*, and *Systems* are at the third position. Eight out of these ten journals are fully open access while *IEEE Internet of Things Journal* and *Software and Systems Modeling* have subscription-based and hybrid access (open and subscription-based), respectively.

It is observed that, despite their rankings, these conferences and journals are not necessarily accurate representations of the variety of venues where research papers are published. This highlights the cross-disciplinary aspect of the topic even further. It is intriguing that no conference offers a dedicated section for research on MBSE of IoT. The conference *Proceedings of the ACM/IEEE International Conference on Model Driven Engineering Languages and Systems* is at 7^{th} rank with only one publication.

3) RESEARCH TEAM ANALYSIS

The main research teams and their interactions were examined using the co-authorship analysis in VOSviewer software tool. To clarify the full range of collaboration among authors, we choose all 443 authors with all 110 publications to visualization network between research teams. The clustering algorithm used by VOSviewer assigns the same color to nodes that are closely associated to a cluster. Additionally, we imposed the requirement that a cluster must contain three authors or more. Figure 4 depicts the co-authorship network with modularity normalization method. Authors are represented as nodes with the node size representing the number of publications. Research teams formed clusters shown in different colors and location of the cluster is arbitrary with no significant meaning. Six major research teams (at the edge of network) for the MBSE of IoT field are identified. It is important to note that very few teams are connected by cross-team collaboration. Most of the teams had more than five members, which is more than the number of some teams in the majority.

B. KEYWORDS ANALYSIS

To understand how the authors frame their work and to discover new research trends, we analyzed the author-specific and title keywords. Author-specific and title keywords were gathered from 110 research articles and then ranked according to how frequently they appeared. 1198 author-specific and 422 title keywords were retrieved using BibExcel.

Since our field of study (MBSE of IoT) involves the fusion of two research domains, We observed that the keywords can be broadly categorized into two groups: keywords related to the domain and keywords connected to engineering methodologies/practices. Keywords representing the IoT systems (*e.g.,* "Internet of Things", "IoT", "Industrial Internet of things", "IIoT"), and its application domain (*e.g.,* "Industry 4.0", "cyber-phsical systems", "smart manufacturing",

TABLE 2. Top ten journals where literature on MBSE of IoT is published.

Journal Name	Access	Frequency	IF(5 years)	IF(2021)
Applied Sciences	Open	8	2.921	2.838
IEEE Access	Open	7	N/A	3.476
IEEE Internet of Things Journal	Subscription-based	4	11.043	10.238
Systems	Open	4	2.410	2.895
Software and Systems Modeling	Hybrid	3	2.423	2.211
Sensors	Open	3	4.050	3.847
Journal of Sensors	Open	2	N/A	2.336
International Journal of Production Research	Open	2	7.837	9.018
Journal of Big Data	Open	2	N/A	10.835
International Journal of Advanced Computer Science and Applications	Open	2	N/A	N/A

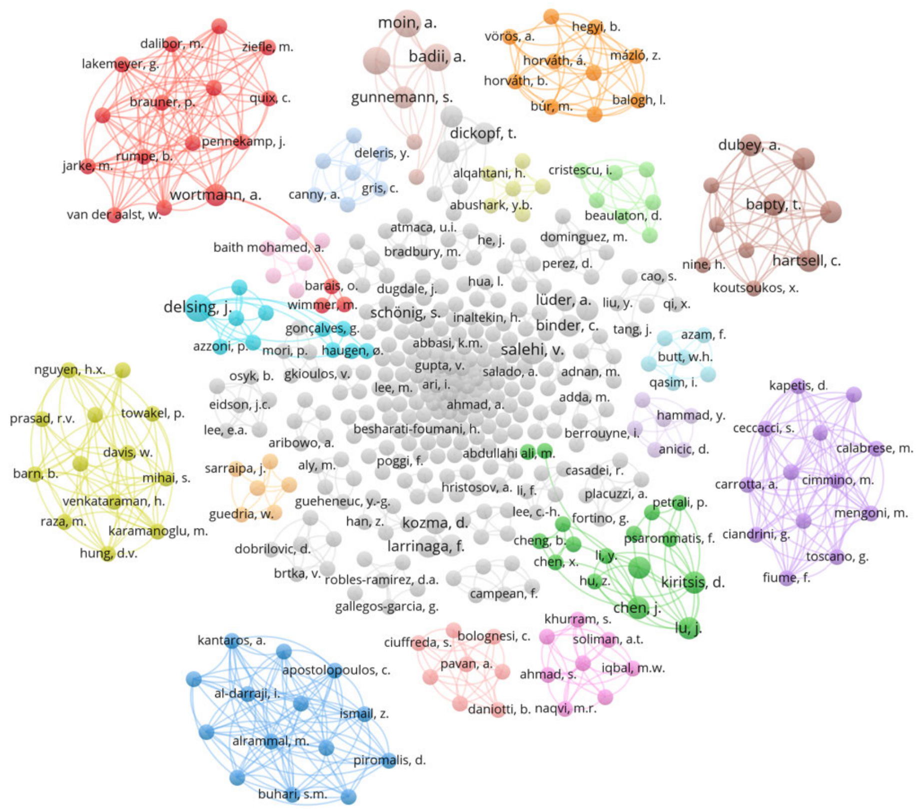

FIGURE 4. Authors collaboration network.

"digital twin") were removed as they were dominating in the list of author-specific keywords. Similarly keywords such as "MBSE", "modeling", "Model-based system engineering" are also not considered.

Table 3 shows the top-ranked keywords. The keywords related to engineering of the computational aspect of IoT systems (software) are ranked highest in author-specific keywords, followed by technology-related keywords. It is important to note that we have distinguished between "model-driven engineering" and "model-based system engineering" because the former refers to a software-centric approach while the latter refers to a systems engineering technique. "Machine learning" at the top of the author-specific keywords indicates the extensive use of such techniques both at the development and application level. Studies like [47] and [48] are the examplars. Although, terms like "uml", "domain-specific modeling", "meta-modeling" are not in top ten keywords but also indicate the dominance of software-centric techniques in IoT system development. The keywords related to "simulation" also occasionally existed, but they weren't particularly common.

For title keywords on the other hand, system engineering-related keywords are ranked the highest, followed by the software-centric keywords. Overall, there seems to be a relative dominance of software-related keywords in the table, which indicates relatively high exploration of software development in IoT systems. It also shows the software-intensiveness of such systems.

TABLE 3. Keyword ranking.

Rank	Author-Specified Keyword	Title Keywords
1	Machine learning	Framework
2	Model-driven engineering	Architecture
3	Modeling languages	Approach
4	Edge computing	Applications
5	Software engineering	Model-driven
6	Software design	Learning
7	System of systems	Control
8	Safety engineering	Requirements
9	Life cycle	Development
10	Decision making	Management

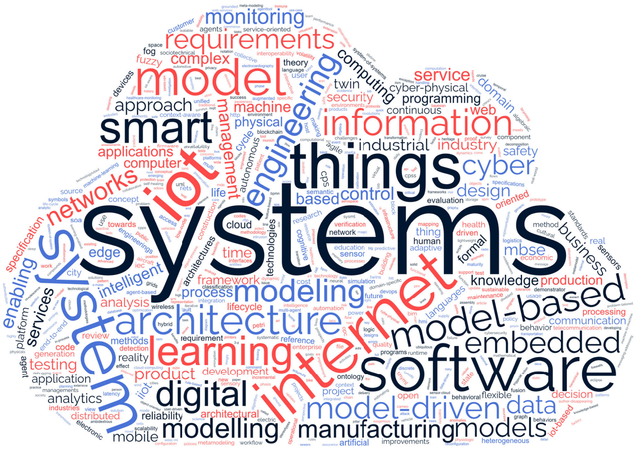

FIGURE 5. Author-specific and title keyword cloud.

It is important to note that, despite appearing in the top ten, management-related keywords like ''decision making'' and ''Management'' were ranked poorly in both categories.

Figure 5 depicts the word cloud created using all author-specific and title keyword extracted using BibExcel software tool. It shows different-sized keywords. The more often a term appears in the data set, the bigger and bolder it is displayed in the cloud. It can be observed that the prominent terms (except the terms ''systems'', ''iot'', and ''things'') like ''architecture'', ''model-driven'', ''learning'', ''machine'' in the word cloud are aligned with Table 3 and the thematic analysis presented in Section V.

C. TERM CO-OCCURRENCE NETWORK

We used VOSviewer for analyzing term co-occurrence in the abstracts of 110 publications. Starting from the entire texts of the abstracts, including 3172 terms, all words fewer than five occurrences were excluded. Only 134 terms met the threshold. Using the relevance score in VOSviewer, only the terms within highest 60% of the relevance scores were selected, reducing the number of the eligible terms to 80 for analysis. The terms were then manually screened to remove the terms that are more general and uninformative such as researcher, proposal, and article. Terms directly representing MBSE or IoT such as ''mbse'', ''iot application'', ''iiot'' are also removed while the terms ''cyber physical systems'' and ''systems engineering'' are kept based on their number of occurrence and relevance score. At the end, 48 terms are captured in the network map.

Figure 6 shows the relevant unique terms and their co-occurrence network helping us to understand the knowledge components and their structure. Visual analysis can not only present the unbiased view of all the keywords but also guides in identifying research directions by highlighting the terms and connections between them. Terms that are missing in the network map or weakly represented indicate potential research gaps. In this visualization the size of the node depicts the number of abstracts where the term was mentioned while the thickness of the lines between the nodes shows the level of direct association (number of abstracts in which the two terms co-occur). The total link strength attribute indicates the total strength of the links of a given node with other linked nodes. The distance between two nodes in this network indicates the relatedness of the nodes.

VOSviewer also arranges nodes into clusters represented in different colors. Each node can be in only one cluster which is collection of closely related nodes. As shown in Figure 6, the terms are arranged into five clusters to express their link in the literature. The blue cluster with nine terms centers on ''goal'' with 31 links and total link strength of 49. This clusters includes other terms such as ''agent'', ''organization'', ''stakeholder'', ''practitioner'', ''innovation'', and ''software engineering''. The theme of this cluster is characterized as goal definition.

The theme of green cluster is about the software and sensor cloud. It centers on ''sensor'' with 36 links and total link strength of 72. The green cluster includes eleven terms such as ''cloud'', ''software'', ''paradigm'', ''layer'', ''device'', and ''quality''.

The red cluster with twelve terms centers on ''language'' with 38 links and total link strength of 80. The theme of this cluster is characterized to be on the effective use of modeling languages and technologies. It includes terms such as ''model driven engineering'', ''time'', ''machine learning'', ''technique'', and ''heterogeneity''.

The theme of yellow cluster is about the quality attribute of IoT systems. It centers on ''cyber physical system'' with 43 links and total link strength of 104. The yellow cluster includes eight terms such as ''security'', ''availability'', ''performance'', ''scalability'', ''interaction'', and ''maintenance''.

The purple cluster with eight terms centers on ''systems engineering'' with 42 links and total link strength of 122. The theme of this cluster is characterized to be on software and system engineering including terms such as ''complex system'', ''software development'', ''simulation'', and ''product''.

It is important to note that the red and green clusters are connected to one another more closely than other clusters. Most of the terms in these two clusters are also linked with terms in other clusters. It is also interesting to note that although terms ''simulation'' and ''operation'' are in purple

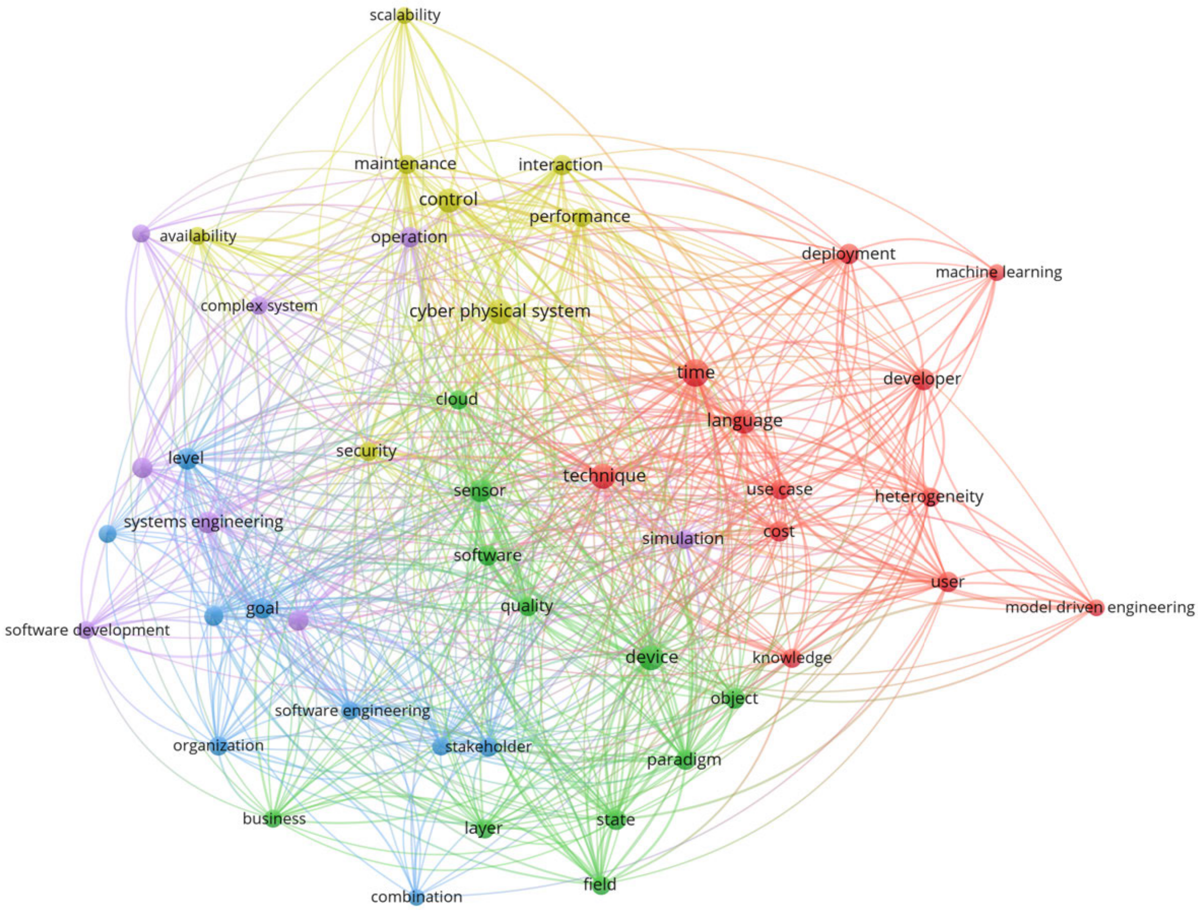

FIGURE 6. Network of terms from publication abstracts created using VOSviewer.

cluster but they are placed closer to the red and yellow clusters, respectively. This suggests an integrated research investigation of these areas. On the other hand, ''scalability'' lies at the edge of the map with no connections to ''model driven engineering''. This suggests that research on scalability of IoT systems is not well integrated with modeling methodologies and practices.

V. THEMATIC ANALYSIS

Keyword and term analyses helped us in setting the foundation for the identification of key themes in the literature on MBSE of IoT. We manually read through the abstracts of 110 publications selected based on the criteria explained in Section III-A. Abstracts are generally considered as stand-alone summaries of a research study highlighting the research foci, methods, and key findings. The rest of this section reports the results of this analysis with explanation of the key themes.

A. INTEGRATION WITH BUSINESS AND MANAGEMENT METHODOLOGIES

As shown in Figure 7, the dominant theme in the literature of MBSE of IoT relates to the integration of business and management methodologies and techniques used at different levels of system development life cycle. Several studies under this theme are focused on incorporating software engineering and management paradigms [49], operation capabilities and constraints modeling and verification [50], and contemplating business process modelling and improvement with physical devices for informed decision making [51], [52].

In [53], a systematic literature review is reported for highlighting the integration and interoperability challenges related to the engineering of IoT systems. A closed-loop engineering approach, based on a combination of MBSE and product development, is proposed to support multiple lifecycle phases and usage context [54].

Munich Agile MBSE Concept (MAGIC) adopted agile into MBSE for requirement traceability, better communication among stakeholders, achieving design automation, and iterative and incremental development [55]. For conceptual modeling of IoT systems, issues with stereotype aspects of Object-Process Methodology (OPM) ISO 19450 are studied [56]. Naqvi et al. investigated the use of Protégé to design test strategies for IoT systems using an ontological reasoning approach [57] while MATTER is introduced for model-based generation of executable test scripts for IoT systems [58]. For the purpose of effect evaluation in IoT-enabled interactive UI design, a discrete mathematical model is created using discrete Hopfield neural network and seven evaluation indicators are analyzed [59]. Product-based System of Systems (SoS) engineering methodology is proposed by usage data into the early phases of MBSE to ensure sustainability in system operation [60]. Imran and Kantola proposed use of sociotechnical system theory and competence-based view for IoT system implementation in relation with Industry 4.0 for improving user interaction and acceptability [61].

Based on Protelis and EdgeCloudSim, a model-based toolchain is susggested for deployment performance estimation and simulation-based evaluation [62]. To enhance IoT system operation capabilities and constraint definition, certain modeling and verification approaches are also integrated with MBSE. For example, context-awareness has been investigated in a number of research on MBSE. An ontology-based approach is used to offer run-time models for physical devices (*e.g.,* sensors and actuators) [63], while in [64], context pre-modeling is investigated through numerical measure transformation and normalization for context selection, correlation, and evaluation. To enhance operational security, a distributed firmware update architecture based on blockchain technology is introduced in coordination with Software Updates for Internet of Things (SUIT) [65]. Context-Oriented Behavioral Programming (COBP) is proposed by connecting behavioral and context (represented through data) models with update and select queries for context-ware behavior specification of complex robotics and IoT systems [66]. In an analytical framework, IoT nodes are represented as dynamical systems to study the best design options to provide low latency for IoT applications [67].

Merging of MBSE with business processes is also investigated as a way to integrate MBSE with product development processes for complexity management. Business Process Model Notation (BPMN) 2.0 is extended to facilitate modeling of IoT-aware business processes [68], and for security requirement modeling [69]. Kozma et al. presented a framework based on BPMN for enterprise level modeling and color colored Petri nets at production level [70]. Models are then implemented and executed on platform built upon Service-Oriented Architecture (SOA).

B. COMBINING SYSTEM ENGINEERING APPROACHES

System engineering has evolved into a interdisciplinary approach for developing complex systems. Under this paradigm, several methodologies are used at various stages of system development, from requirement elicitation to design synthesis and system validation. System engineering and MBSE combined have been the subject of several research.

Zeigler et al. investigated combining Modeling and Simulation (M&S) and MBSE to cope with engineering challenges of complex highly integrated systems [71]. Private and governmental infrastructure are both upgraded with IoT devices and sensors for management and monitoring. In [72], an SoS

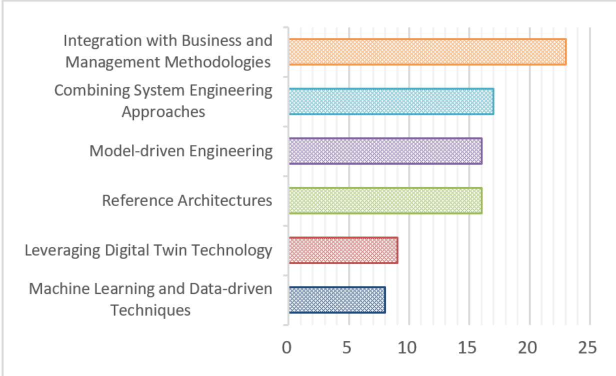

FIGURE 7. Number of publications focused on the six identified themes.

modeling approach, based on complex adaptive system theory, is proposed for emergent national infrastructure system based on interdependencies between energy, transport, and water. For the verification of IoT-based smart city applications, a model-based run-time monitoring approach based on message sequence charts is suggested [73]. Complex-event processing patterns are used to represent these systems' dynamic behavior. In line with this, Lefticaru et al. investigate the use of formal verification and model-based testing techniques together [74].

In order to support heterogeneity and volatility for simulation-base system validation, a flexible and adaptable agent-based approach is proposed [75]. This approach uses cost- and time-efficient stochastic processes to characterize events in an IoT environment. When developing wireless sensor networks for the IoT, MBSE is used in conjunction with the RFLP (Requirements engineering, Functional design, Logical design, Physical design) principle of the V-model [76].

With a formalized approach, DevOps has also been investigated through the software and systems process engineering metamodel (SPEM) [77]. In regard to IoT, Big Data, and AI, Besharati-Foumani et al. in [78], addressed the difficulties in establishing next-generation social manufacturing systems. The needs for cross-domain interaction and interoperability are met by a feature-based modeling method. The Assurance-based Learning-enabled CPS (ALC) Toolchain offers a workflow modeling language to automate the creation of complex systems by merging disparate modeling languages [79].

Numerous researches have thoroughly examined system engineering's entire life cycle. In [80], SoSLM (System of Systems Life cycle Management) is reported as an approach for comprehensive system life cycle management that is based on process engineering approaches and ITSM (Information Technology Service Management). The Arrowhead framework is used to implement the suggested SoSLM. In a framework that enables the use of discrete and continuous time modeling and simulation methodologies for IoT systems, the ideas of aspect-oriented modeling, contract-based modeling, agent-based modeling, and services-oriented modeling are merged [81]. Another topic of investigation is the formal specification of multitask hybrid systems as observational transition systems (OTS) [82].

Approaches to requirement engineering that take into account various system engineering viewpoints are also investigated. In order to produce personalized products, a technique is built to translate client input into technical specifications, and the Kano model is utilized to investigate the relationship between the deployment of quality functions and customer satisfaction [83]. In a study on trade-off analysis at an early stage in the development, Gupta et al. [84] offered a requirement engineering level risk estimation and management model based on multiple criteria using fuzzy logic. Collaborative visual thinking is also encouraged for systems specification and design to lessen the cognitive load involved [85].

C. MODEL-DRIVEN ENGINEERING

Model-Driven Engineering (MDE) is a software development paradigm in which models are regarded as first-class artifacts. In contrast to MBSE, MDE is a *software-centric* approach where the engineering/development process is driven by modeling and the creation of working software is based on model definition and transformation. Numerous studies examined the creation and use of Domain-Specific Languages (DSL), the core of MDE, in relation with MBSE of IoT.

An MDE framework is presented for IoT-based assembly systems for controlling product variety and volume [86]. For IoT-based smart and safe CPSs, the research demonstrator MoDeS3 combines model-driven development, formal verification, and safety engineering [87]. C*yprIoT* is presented to model and control network-based IoT applications using MDE techniques [88]. It is realized as a plugin that integrates a networking language, rule-based policy language, and code generator. In [89], the TRILATERAL framework was introduced by Iglesias et al. It uses a DSL to enable users to graphically construct the IEC 61850 information model of the industrial CPS. For controlling, TRILATERAL supports a number of communication protocols, including HTTP-REST, WS-SOAP, and CoAP. O-MaSE is a model-driven development framework for layer-based multi agent systems CPS to reduce coupling and facilitate abstraction [90], [91].

The *AutoIoT* framework makes it easy to model necessary functionality in a straightforward JSON file in order to encourage application developers to use MDE [92]. The development of server-side IoT apps follows, using automatic model-to-model and model-to-text transformations. To generate run-time models for architectural creation and successful operation of self-adopting systems, a rule-based history-aware model-driven technique is suggested [93]. In [94], to address the issues of rising complexity, a comprehensive methodology is offered together with a DSL for architectural specification and a development process. An adaptive sensor-cloud approach is suggested to improve the reliability through a run-time model approach [95].

In a few studies, the use of MDE for the design and development of IoT systems in the healthcare industry is also covered. Using Modeling Scenarios of Internet of Things (MoSIoT), healthcare professionals can simulate and model IoT healthcare-monitoring system scenarios created for various illnesses and disabilities [96]. For the purpose of validating, MoSIoT is used in a real-world situation involving a patient with Alzheimer's illness. The variability of hardware and software systems makes it difficult to design mobile apps for IoT-based health monitoring. To increase the efficiency of software developers, *HealMA*, designed as an Eclipse plugin, is introduced with a DSL with appropriate validation criteria, a graphical modeling editor, and a set of model-to-code transformation [97].

The field of intelligent IoT systems also explores the integration of Machine Learning (ML) with MDE. Based on ThingML, ML-Quadrat is suggested as a comprehensive method for developing model-driven software for intelligent systems that use ML [98]. In [99], for TinyML systems with substantial resource constraints, ML and MDE integrated model refinement from platform-independent to platform-specific models is also studied.

Additionally, using MDE enables reasoning on the model prior to producing actual deployment artifacts. Instead of digging into the back-end technologies (such as blockchain) for alternate investigation, developers can concentrate on the business models [100]. This is particularly true in case of complex heterogeneous environments like Industry 4.0. In an extensive analysis of 408 articles on the use of modeling in Industry 4.0, Wortmann et al. also suggest integrated modeling of systems engineering with CPS and knowledge engineering [101].

D. REFERENCE ARCHITECTURES

A *reference architecture* identifies the typical outline of a system in a particular domain. It includes generic elements, their relationship, common principles, and architectural guidelines to set core foundation for architecture development. Creation and use of reference architecture in MBSE ecosystems for IoT domain is discussed in many of the reviewed abstracts [102]. Shaaban et al. proposed a cloud-based reference model (CloudWoT) for knowledge-based IoT based on a combination of edge computing, semantic web, and could computing [103]. To encourage the development of an open IoT ecosystem, a framework based on MBSE and system architecture design is suggested [104]. It tries to address the challenges associated with interoperability, flexibility, and features of policy and regulation. For dynamic role allocation, advanced IoT systems require better usage control methods. Architectural enhancements are introduced to improve the resilience, scalability, and run-time efficiency of the existing models [105].

IoT is also used in space, creating the Internet of Space Things (IoST), allowing a larger reliance on satellite-to-satellite communication and interactions with a wider range of the ground segment. To explain high-level system components, their relationships, and the cyber security threat landscape of space systems, a reference architecture for the new space environment is presented [106]. Component behavior, interface, and information and control flow is specified through rigorous architecture refinements. In [107], End-to-End IoT system reliability modeling and prediction are provided using an IoT network-based layered architecture based on Reliability Block Diagram (RBD). Early reliability prediction can assist engineers in developing efficient maintenance procedures during the design and operational phases. A demonstration of an instantiated architecture for situation-aware logistics is reported to provide insights in the field of enterprise computing [108].

Reference Architecture Model Industry 4.0 (RAMI 4.0) is a complete modeling technique that combines architectural concepts with domain-specific details from MBSE in order to enable the mutual engineering of present and future industrial systems [94]. Regarding numerous value-added services for various levels of digital manufacturing platforms utilizing IIoT, the Industrial Internet Integrated Reference Model (I3RM) is also presented [109]. After comparing three engineering approaches, Brando et al. proposed a reference architecture for sharing resources in an IoT network [110]. In these techniques, a revised IoT architecture based on the Sensor-as-a-Service concept is used with embedded multi-agent systems (MAS) for information exchange. A service-oriented architectural paradigm based on Eclipse Arrowhead framework is presented for modern systems engineering [111]. In [112], to enable designers to incorporate a bio-inspired anomaly-based host intrusion detection system (A-HIDS) in Edge devices, an IoT design approach based on the IEC 61499 standard is put forward. For the abstraction of collective behavior for multi-dimensional features of IoT interactions, a modeling approach based on process algebra *dTP-Calculus* and lattice *n:2-Lattice* is proposed [113].

A few studies also examine requirement mapping from an architectural perspective. An initial version of *IotReq* is for requirement management is presented in [114]. IotReq exploits UML with service-oriented paradigm for domain modeling and elicitation and specification of IoT system requirements. For modeling security needs during the analysis phase of a plan-driven development methodology using the MBSE approach, the SysML extension IoTsecM is recommended [115].

E. LEVERAGING DIGITAL TWIN TECHNOLOGY

A digital twin is a virtual data-driven representation of a real-world entity created for real-time monitoring and controling. In order to carry out in-depth research and analysis on the modeling of complex systems, the study of digital twins is given considerable attention [116]. It has also been researched in relation to MBSE in IoT systems. Madni et al. in [17], have suggested using digital twin technology into the MBSE approach .

Dynamic knowledge bases and digital twins are used to create intelligent manufacturing that has strong learning and cognitive capabilities [117]. To enable the investigation of the key influencing elements in Industry 4.0, a digital twin model linked with multi-agent architecture and the MPFQ-model (Material, Production Process, Product Function/Future, Product Quality) is adopted [118].

To improve the engineering process for CPS, TwinOps links the digital twin with MBSE and DevOps practices [119]. In TwinOps, models are first-class objects that are created and managed from the early phases of development to the monitoring of a system when it is in operation after development. A Cognitive Twin (CT) facilitates the co-simulation of the complex heterogeneous IoT systems based on the ontology model and FMI 2.0 for cognitive ability and standardized interconnection, respectively [120]. The complexity of co-simulation is reduced through the unification of ontology modelling and the architecture of CT. For analysis-specific co-existence of dynamical models (continuous-time and discrete-event) for digital twins, a modeling strategy is offered to enhance mutual consistency and interaction [121].

In [122], Brauner et al. devised a research road map based on a detailed analysis of the challenges in the integration of digital twins and IoT system engineering. The concept of *Digital Shadows* is introduced on the basis of effective human interfaces and availability of manufacturing data for interconnected infrastructure.

F. MACHINE LEARNING AND DATA-DRIVEN TECHNIQUES

Numerous studies have documented the manipulation of data-driven and machine learning (ML) approaches in IoT applications. ML methods are looked into for model development, visualization, analysis, and reuse in relation to MBSE. The studies focusing on using ML or data-driven methodologies in different aspects of MBSE of IoT are discussed under this theme.

Hartmann et al. in [123], reported applying ML into domain modeling. To make it easier to combine together learned behaviors, the system is designed to be composed of independently computable and reusable parts. In [124], an anomaly detection engine is created using a variety of time series models to help with predictive maintenance in IoT networks' convergence and software engineering aspects.

In [48], a reference architecture based on several architecture implementations for the design of big data systems with ML techniques in edge computing environments is presented. The reference architecture contributed to lower maintenance and development expenses. To determine the emotional state of users, a study of the process modeling for developing predictive models is provided [125]. These models are then applied to the simulation of complex systems to forecast user emotions based on physiological conditions for the creation of user-accepted systems. To help with the use of RAMI 4.0 in IIoT, a thorough architecture description of the information layer is provided [126]. It enables the use of MBSE for utilizing readily available industrial data for system development and is supported by the Zachman framework.

Ren et al. introduced the Semantic Low-Code Engineering for ML Applications (SeLoC-ML) framework in order to assist non-experts in rapid development of ML applications in the IIoT by utilizing semantic web technologies [127]. SeLoC-ML helps to cope with the compatibility challenges in integrating heterogenious non-standardized models.

Some studies are not exactly categorized under the themes mentioned above. For instance, [128] and [129] concentrated on educational strategies for boosting the skills needed for Industry 4.0. The use of IoT for monitoring the working environment and estimating the cost of high-rise buildings is the emphasis of [130] and [131], respectively. A conceptual paradigm for integrating human behavior, under the umbrella of the Internet of Behaviors (IoB), in the development process is reported in [132].

VI. DISCUSSION

In this section, we discuss the major results from the bibliometric analysis regarding trends in the publications, the current state of integration across disciplines and methods, and impact on IoT application use-cases in different domain and key technologies.

This bibliometric analysis has provided some insights regarding research trends in the literature on MBSE of IoT system design and development. The average citation is 13.97 per paper in the past five years. It has been noted that the majority of IoT literature focuses on investigating its applicability in various industries, including healthcare, smart cities, manufacturing, etc. This tendency is particularly obvious in 2021, where only 16 out of a total of 71 papers are found to be related to design and development, with the remaining 55 being (directly or indirectly) related to the application side. The overall trend has a respectable growth rate in the other four years notwithstanding this decline.

According to country-wise research contribution analysis, as depicted in Figure 8, MBSE of IoT is being researched in numerous nations across all continents. Germany, the United Kingdom, and the USA are the top three nations in terms of paper distribution, with 19, 12, and 11 papers, respectively. For research collaboration on MBSE of IoT, Saudi Arabia and France share the top position with 14 links (collaborating countries), followed by the United Kingdom with 11 links. Ten of the forty-eight countries in total (including Finland, Indonesia, Israel, and others) with no collaboration are not displayed in Figure 8.

The integration of different business and system engineering methodologies, model-driven engineering, reference architectures, digital twins, and machine learning strategies are the six main themes that have been the focus of research on MBSE of IoT systems. It is important to note that various research have looked into the domain-specific design and development methodologies for IoT systems. Application use-cases are in industry 4.0 and smart manufacturing, cloud-based systems, and healthcare domains discussed in several publications.

The transformation of industrial manufacturing into ''intelligent manufacturing'' and realization of Industry 4.0 through IIoT is one of the most investigated application domains. IoT, together with Cloud computing and CPS, is one of the key enabling technologies for the implementation of Industry 4.0. The application of IIoT and MBSE was examined from a variety of perspectives in publications relating to intelligent manufacturing and Industry 4.0. Automation of various jobs during the development and operation phases of assembly systems are studied [86] along with digital twin based and data-driven strategies for intelligent monitoring and regulating strategies [94], [117]. Reference architectures based on Industrial Internet Integrated Reference Model (I3RM) [109] and strategies based on SERVUS (also referenced in ISO 19119 Annex D) [49] are used to cope with challenges of requirements and design mapping among diverse teams working on IIoT service platforms. MBSE is also combined with BPMN and serice-oriented models workflow management in a ''smart factory'' [70], [90] and Workplace monitoring is investigated by using wireless sensor technologies and the message queuing telemetry transport (MQTT) protocol [130]. Predictive maintenance is also studied with data-driven approaches based on machine learning to assure machine availability and reduce downtime [47].

Although there is a sizable body of research on IoT application in the healthcare sector, only a small number of papers have specifically addressed the use of combination of MBSE and IoT in healthcare. In our data set of 110 papers, we only discovered two studies that address this issue. The first one offered Modeling Scenarios of Internet of Things (MoSIoT) to model and simulate healthcare monitoring system scenarios for people with varied disabilities and diseases [96]. The second one suggested the HealMA framework, which is an Eclipse plugin equipped with a DSL, graphical modeling editor, and code generation to speed up the development of IoT-based Android health monitoring mobile applications [97]. Some of the reasons for this limited investigation are training the essential parties, creating the requisite tool chain, and presenting documents with assurance cases to regulating authorities. We believe that as MBSE has shown success in the manufacturing sector for Industry 4.0, its application for IoT-based solutions for the healthcare sector also needs to be further investigated.

A. LIMITATIONS OF THE STUDY

There are some limitations of this study. First, We have included the most recent research studies published during the past five years, from January 2018 to December 2022. Therefore, this paper does not include the research studies published before 2018.

Second, we used Scopus, which is among the largest and most widely used research databases. Other databases can also be used.

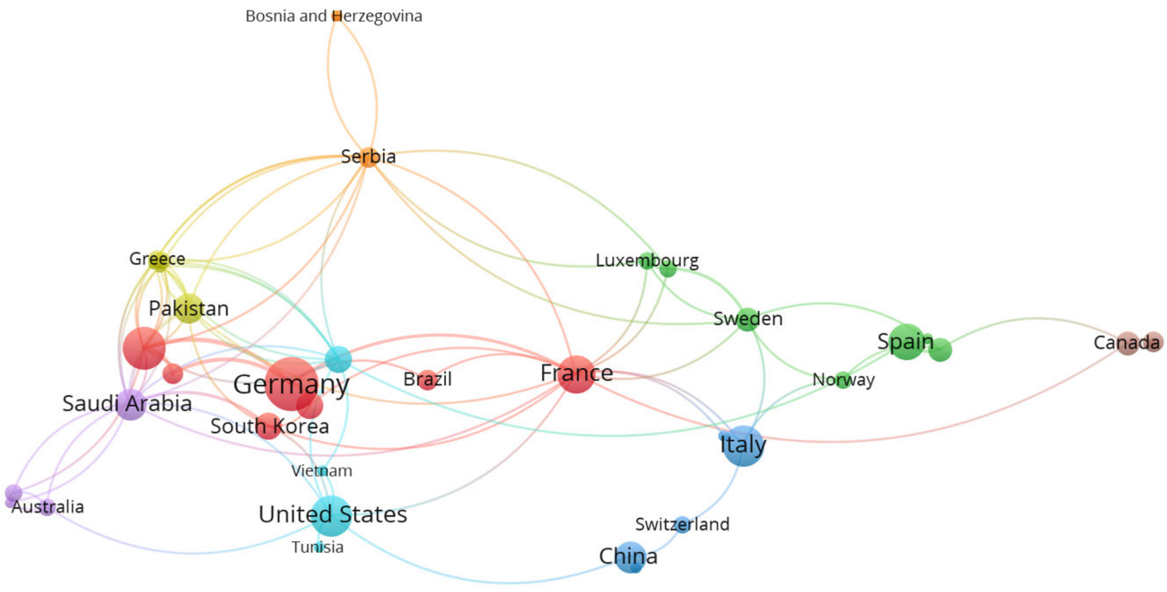

FIGURE 8. Country-wise research contribution and collaboration.

Third, the scope of our bibliometric analysis is restricted to model-based system engineering, a subfield of system engineering. Thus, more systems engineering sub-domains should be explored in future research.

VII. CONCLUSION AND FUTURE WORK

This paper reports on a bibliometric analysis of the literature on MBSE of IoT performed on 110 research papers published between January 2018 and December 2022. Overall, a growing trend is observed in number of publications on this topic. The analysis of author-specific and title keywords revealed an interplay between computational aspects and the use of engineering methodologies/practices covering perspectives such as modeling, technology, and management. Five clusters, based on selected 48 co-occurring terms, are identified in the VOSviewer network map. They are goal definition, software and sensor cloud, effective use of modeling technologies, quality attribute of IoT systems, and software and system engineering. The thematic analysis of the selected papers revealed an increase in the introduction of new reference architectures, and integration of MBSE with business and management methodologies such as Agile, OPM, and BPMN 2.0.

The fundamental goals of employing MBSE for the creation of IoT systems still revolve around combining system engineering approaches and applying model-driven engineering techniques, especially in light of complete system engineering using machine learning and data-driven methodologies. For a thorough understanding, development, and applicability of MBSE of IoT, it is recommended to undertake systematic literature studies using other research databases and methodologies. This will assist in setting the foundation for effective system development of such complex and multidisciplinary field of IoT that can satisfy the needs of multiple stakeholders.

ACKNOWLEDGMENT

The author would like to thank Hessam S. Sarjoughian from the Arizona Center for Integrative Modeling and Simulation (ACIMS), Arizona State University, for his feedback on an earlier version of this article.

REFERENCES

[1] R. Minerva, A. Biru, and D. Rotondi, "Towards a definition of the Internet of Things (IoT)," in *Proc. IEEE Internet Things Telecom Italia*, May 2015, pp. 1–86.

[2] Y. Zhao, P. V. Genovese, and Z. Li, "Intelligent thermal comfort controlling system for buildings based on IoT and AI," *Future Internet*, vol. 12, no. 2, p. 30, Feb. 2020. [Online]. Available: https://www.mdpi.com/1999-5903/12/2/30

[3] N. Surantha, P. Atmaja, David, and M. Wicaksono, "A review of wearable Internet-of-Things device for healthcare," *Proc. Comput. Sci.*, vol. 179, pp. 936–943, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877050921001149

[4] K. M. Al-Obaidi, M. Hossain, N. A. M. Alduais, H. S. Al-Duais, H. Omrany, and A. Ghaffarianhoseini, "A review of using IoT for energy efficient buildings and cities: A built environment perspective," *Energies*, vol. 15, no. 16, p. 5991, Aug. 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/16/5991

[5] S. Constantinou, A. Konstantinidis, P. K. Chrysanthis, and D. Zeinalipour-Yazti, "Green planning of IoT home automation workflows in smart buildings," *ACM Trans. Internet Things*, vol. 3, no. 4, pp. 1–30, Sep. 2022, doi: 10.1145/3549549.

[6] W. Yaïci, K. Krishnamurthy, E. Entchev, and M. Longo, "Recent advances in Internet of Things (IoT) infrastructures for building energy systems: A review," *Sensors*, vol. 21, no. 6, p. 2152, Mar. 2021.

[7] L. Chen and J. Chung, "Mobility-aware and congestion-relieved dedicated path planning for group-based emergency guiding based on Internet of Things technologies," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 9, pp. 2453–2466, Sep. 2017.

[8] K. Chen, M. Xie, Y. Chen, T. Chu, and Y. Lin, "DroneTalk: An Internet-of-Things-based drone system for last-mile drone delivery," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 9, pp. 15204–15217, Sep. 2022.

[9] J. Passlick, S. Dreyer, D. Olivotti, L. Grützner, D. Eilers, and M. H. Breitner, "Predictive maintenance as an Internet of Things enabled business model: A taxonomy," *Electron. Markets*, vol. 31, no. 1, pp. 67–87, Mar. 2021, doi: 10.1007/s12525-020-00440-5.

[10] International Council on Systems Engineering (INCOSE), "Systems engineering vision 2020," Proc. Int. Council Syst. Eng. (INCOSE), San Diego, CA, USA, Tech. Rep. INCOSE-TP-2004-004-02 Version 2.03, Sep. 2007.

[11] A. W. Wymore, *Model-Based Systems Engineering*. Boca Raton, FL, USA: CRC Press, 1993.

[12] P. Beery and E. Paulo, "Application of model-based systems engineering concepts to support mission engineering," *Systems*, vol. 7, no. 3, p. 44, Sep. 2019. [Online]. Available: https://www.mdpi.com/2079-8954/7/3/44

[13] C. Neureiter and C. Binder, "A domain-specific, model based systems engineering approach for cyber-physical systems," *Systems*, vol. 10, no. 2, p. 42, Mar. 2022. [Online]. Available: https://www.mdpi.com/2079-8954/10/2/42

[14] E. Ahmad, B. R. Larson, S. C. Barrett, N. Zhan, and Y. Dong, "Hybrid annex: An AADL extension for continuous behavior and cyber-physical interaction modeling," in *Proc. ACM SIGAda Annu. Conf. High Integrity Lang. Technol.* New York, NY, USA: Association for Computing Machinery, Oct. 2014, pp. 29–38, doi: 10.1145/2663171.2663178.

[15] P. Acheson, C. Dagli, and N. Kilicay-Ergin, "Model based systems engineering for system of systems using agent-based modeling," *Proc. Comput. Sci.*, vol. 16, pp. 11–19, 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877050913000033

[16] E. M. Ahmad and H. Sarjoughian, "A behavior annex for AADL using the DEVS formalism," in *Proc. Spring Simul. Conf. (SpringSim)* San Diego, CA, USA: Society for Computer Simulation International, Apr. 2019, pp. 1–12.

[17] A. Madni, C. Madni, and S. Lucero, "Leveraging digital twin technology in model-based systems engineering," *Systems*, vol. 7, no. 1, p. 7, Jan. 2019. [Online]. Available: http://www.mdpi.com/2079-8954/7/1/7

[18] T. Dickopf, S. Forte, C. Apostolov, and J. C. Göbel, "Closed-loop systems engineering—Supporting smart system design adaption by integrating MBSE and IoT," in *Complex Systems Design & Management*, D. Krob, L. Li, J. Yao, H. Zhang, and X. Zhang, Eds. Cham, Switzerland: Springer, 2021, pp. 203–214.

[19] N. Navarro, L. Horvath, and A. Salado, "Design of an IoT system for the palletized distribution supply chain with model-based systems engineering tools," *Systems*, vol. 10, no. 1, p. 4, Dec. 2021. [Online]. Available: https://www.mdpi.com/2079-8954/10/1/4

[20] A. L. Ramos, J. V. Ferreira, and J. Barcelo, "Model-based systems engineering: An emerging approach for modern systems," *IEEE Trans. Syst., Man, Cybern., C Appl. Rev.*, vol. 42, no. 1, pp. 101–111, Jan. 2012.

[21] *Systems Engineering Vision 2035*, International Council on Systems Engineering (INCOSE), San Diego, CA, USA, Sep. 2021.

[22] M. Melo and G. Aquino, "The pathology of failures in IoT systems," in *Computational Science and Its Applications–ICCSA*, O. Gervasi, B. Murgante, S. Misra, C. Garau, I. Blečić, D. Taniar, B. O. Apduhan, A. M. A. C. Rocha, E. Tarantino, and C. M. Torre, Eds. Cham, Switzerland: Springer, 2021, pp. 437–452.

[23] L. Xing, "Cascading failures in Internet of Things: Review and perspectives on reliability and resilience," *IEEE Internet Things J.*, vol. 8, no. 1, pp. 44–64, Jan. 2021.

[24] E. Ahmad, Y. Dong, B. Larson, J. Lü, T. Tang, and N. Zhan, "Behavior modeling and verification of movement authority scenario of Chinese train control system using AADL," *Sci. China Inf. Sci.*, vol. 58, no. 11, pp. 1–20, Nov. 2015, doi: 10.1007/s11432-015-5346-2.

[25] E. Ahmad and H. S. Sarjoughian, "An environment for developing simulatable AADL-DEVS models," *Simul. Model. Pract. Theory*, vol. 123, Feb. 2023, Art. no. 102690. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1569190X22001599

[26] O. Persson, R. Danell, and J. W. Schneider, "How to use Bibexcel for various types of bibliometric analysis," in *Celebrating Scholarly Communication Studies: A Festschrift for Olle Persson at his 60th Birthday*, 2009, pp. 9–24.

[27] A. Perianes-Rodriguez, L. Waltman, and N. J. van Eck, "Constructing bibliometric networks: A comparison between full and fractional counting," *J. Informetrics*, vol. 10, no. 4, pp. 1178–1195, Nov. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1751157716302036

[28] 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, Aug. 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S016412121500103X

[29] E. R. Carroll and R. J. Malins. *Systematic Literature Review: How is Model-Based Systems Engineering Justified?* Accessed: Apr. 5, 2023. [Online]. Available: https://www.osti.gov/biblio/1561164

[30] 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, Mar. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950584916303214

[31] A. Wortmann, B. Combemale, and O. Barais, "A systematic mapping study on modeling for industry 4.0," in *Proc. ACM/IEEE 20th Int. Conf. Model Driven Eng. Lang. Syst. (MODELS)*, Sep. 2017, pp. 281–291.

[32] M. S. Farooq, S. Riaz, A. Abid, T. Umer, and Y. B. Zikria, "Role of IoT technology in agriculture: A systematic literature review," *Electronics*, vol. 9, no. 2, p. 319, Feb. 2020. [Online]. Available: https://www.mdpi.com/2079-9292/9/2/319

[33] R. Ahmad and I. Alsmadi, "Machine learning approaches to IoT security: A systematic literature review," *Internet Things*, vol. 14, Jun. 2021, Art. no. 100365. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542660521000093

[34] F. Sadoughi, A. Behmanesh, and N. Sayfouri, "Internet of Things in medicine: A systematic mapping study," *J. Biomed. Informat.*, vol. 103, Mar. 2020, Art. no. 103383. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1532046420300101

[35] H. Muccini and M. T. Moghaddam, "IoT architectural styles," in *Software Architecture*, C. E. Cuesta, D. Garlan, and J. Pérez, Eds. Cham, Switzerland: Springer, 2018, pp. 68–85.

[36] Z. Li, J. Lu, G. Wang, L. Feng, D. G. Broo, and D. Kiritsis, "A bibliometric analysis on model-based systems engineering," in *Proc. IEEE Int. Symp. Syst. Eng. (ISSE)*, Oct. 2021, pp. 1–8.

[37] Z. Li, G. Wang, J. Lu, D. G. Broo, D. Kiritsis, and Y. Yan, "Bibliometric analysis of model-based systems engineering: Past, current, and future," *IEEE Trans. Eng. Manag.*, early access, Jul. 13, 2022, doi: 10.1109/TEM.2022.3186637.

[38] M. Dong, J. Lu, G. Wang, X. Zheng, and D. Kiritsis, "Model-based systems engineering papers analysis based on word cloud visualization," in *Proc. IEEE Int. Syst. Conf. (SysCon)*, Apr. 2022, pp. 1–7.

[39] K. Szum, "IoT-based smart cities: A bibliometric analysis and literature review," *Eng. Manage. Prod. Services*, vol. 13, no. 2, pp. 115–136, Jun. 2021, doi: 10.2478/emj-2021-0017.

[40] Y. Bouzembrak, M. Klüche, A. Gavai, and H. J. P. Marvin, "Internet of Things in food safety: Literature review and a bibliometric analysis," *Trends Food Sci. Technol.*, vol. 94, pp. 54–64, Dec. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0924224419303048

[41] W. Choi, J. Kim, S. Lee, and E. Park, "Smart home and Internet of Things: A bibliometric study," *J. Cleaner Prod.*, vol. 301, Jun. 2021, Art. no. 126908. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652621011276

[42] O. Ellegaard and J. A. Wallin, "The bibliometric analysis of scholarly production: How great is the impact?" *Scientometrics*, vol. 105, no. 3, pp. 1809–1831, Dec. 2015, doi: 10.1007/s11192-015-1645-z.

[43] M. Schotten, M. El Aisati, W. Meester, S. Steiginga, and C. Ross, *A Brief History Of Scopus: The World'S Largest Abstract and Citation Database of Scientific Literature*. Boca Raton, FL, USA: CRC Press, Jan. 2017, pp. 31–58.

[44] W. Choi, J. Kim, S. Lee, and E. Park, "Smart home and Internet of Things: A bibliometric study," *J. Cleaner Prod.*, vol. 301, Jun. 2021, Art. no. 126908. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652621011276

[45] A. Rejeb, S. Simske, K. Rejeb, H. Treiblmaier, and S. Zailani, "Internet of Things research in supply chain management and logistics: A bibliometric analysis," *Internet Things*, vol. 12, Dec. 2020, Art. no. 100318. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2542660520301499

[46] L. U. Khan, I. Yaqoob, M. Imran, Z. Han, and C. S. Hong, "6G wireless systems: A vision, architectural elements, and future directions," *IEEE Access*, vol. 8, pp. 147029–147044, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9163104/

[47] M. Calabrese, M. Cimmino, F. Fiume, M. Manfrin, L. Romeo, S. Ceccacci, M. Paolanti, G. Toscano, G. Ciandrini, A. Carrotta, M. Mengoni, E. Frontoni, and D. Kapetis, ''SOPHIA: An event-based IoT and machine learning architecture for predictive maintenance in industry 4.0,'' *Information*, vol. 11, no. 4, p. 202, Apr. 2020. [Online]. Available: https://www.mdpi.com/2078-2489/11/4/202

[48] P. Pääkkönen and D. Pakkala, ''Extending reference architecture of big data systems towards machine learning in edge computing environments,'' *J. Big Data*, vol. 7, no. 1, p. 25, Dec. 2020. [Online]. Available: https://journalofbigdata.springeropen.com/articles/10.1186/s40537-020-00303-y

[49] T. Usländer and T. Batz, ''Agile service engineering in the industrial Internet of Things,'' *Future Internet*, vol. 10, no. 10, p. 100, Oct. 2018. [Online]. Available: http://www.mdpi.com/1999-5903/10/10/100

[50] D. Beaulaton, N. Ben Said, I. Cristescu, R. Fleurquin, A. Legay, J. Quilbeuf, and S. Sadou, ''A language for analyzing security of IoT systems,'' in *Proc. 13th Annu. Conf. Syst. Syst. Eng. (SoSE)*, Jun. 2018, pp. 37–44. [Online]. Available: https://ieeexplore.ieee.org/document/8428704/

[51] S. Schönig, L. Ackermann, and S. Jablonski, ''Internet of Things meets BPM: A conceptual integration framework,'' in *Proc. 8th Int. Conf. Simul. Model. Methodologies, Technol. Appl.*, 2018, pp. 307–314. [Online]. Available: http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0006824803070314

[52] C. Stoiber and S. Schönig, ''Patterns for IoT-based business process improvements: Developing a metamodel,'' in *Proc. 24th Int. Conf. Enterprise Inf. Syst.*, 2022, pp. 655–666. [Online]. Available: https://www.scitepress.org/DigitalLibrary/Link.aspxdoi=10.5220/0011059300003179

[53] M. Aly, F. Khomh, Y. Guéhéneuc, H. Washizaki, and S. Yacout, ''Is fragmentation a threat to the success of the Internet of Things?'' *IEEE Internet Things J.*, vol. 6, no. 1, pp. 472–487, Feb. 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8424819/

[54] D. Thomas, A. Hristo, M. Patrick, J. C. Göbel, and F. Sven, ''A holistic system lifecycle engineering approach–closing the loop between system architecture and digital twins,'' *Proc. CIRP*, vol. 84, pp. 538–544, Jan. 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2212827119309047

[55] V. Salehi and S. Wang, ''Munich agile MBSE concept (MAGIC),'' in *Proc. Design Society, Int. Conf. Eng. Design*, vol. 1, no. 1, pp. 3701–3710, Jul. 2019. [Online]. Available: https://www.cambridge.org/core/product/identifier/S2220434219003779/type/journal_aricle

[56] H. Kohen and D. Dori, ''Improving conceptual modeling with object-process methodology stereotypes,'' *Appl. Sci.*, vol. 11, no. 5, p. 2301, Mar. 2021. [Online]. Available: https://www.mdpi.com/2076-3417/11/5/2301

[57] M. Raza Naqvi, M. Waseem Iqbal, M. Usman Ashraf, S. Ahmad, A. T. Soliman, S. Khurram, M. Shafiq, and J.-G. Choi, ''Ontology driven testing strategies for IoT applications,'' *Comput., Mater. Continua*, vol. 70, no. 3, pp. 5855–5869, 2022. [Online]. Available: https://www.techscience.com/cmc/v70n3/44937

[58] D. Olianas, M. Leotta, and F. Ricca, ''MATTER: A tool for generating end-to-end IoT test scripts,'' *Softw. Quality J.*, vol. 30, no. 2, pp. 389–423, Jun. 2022. [Online]. Available: https://link.springer.com/10.1007/s11219-021-09565-y

[59] H. Sun and K. Kim, ''Evaluation of IoT-enabled interactive UI design effect based on the discrete mathematical model,'' *Mobile Inf. Syst.*, vol. 2022, pp. 1–7, Oct. 2022. [Online]. Available: https://www.hindawi.com/journals/misy/2022/2139754/

[60] S. Forte, T. Dickopf, S. Weber, and J. C. Göbel, ''Towards sustainable systems reconfiguration by an IoT-driven system of systems engineering lifecycle approach,'' *Proc. CIRP*, vol. 105, pp. 654–659, Jan. 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S221282712200110X

[61] F. Imran and J. Kantola, ''Review of industry 4.0 in the light of sociotechnical system theory and competence-based view: A future research agenda for the evolute approach,'' in *Advances in Human Factors, Business Management and Society* (Advances in Intelligent Systems and Computing), vol. 783, J. I. Kantola, S. Nazir, and T. Barath, Eds. Cham, Switzerland: Springer, pp. 118–128. [Online]. Available: https://link.springer.com/10.1007/978-3-319-94709-9_12

[62] R. Casadei, G. Fortino, D. Pianini, A. Placuzzi, C. Savaglio, and M. Viroli, ''A methodology and simulation-based toolchain for estimating deployment performance of smart collective services at the edge,'' *IEEE Internet Things J.*, vol. 9, no. 20, pp. 20136–20148, Oct. 2022. [Online]. Available: https://ieeexplore.ieee.org/document/9768117/

[63] E. Giallonardo, F. Poggi, D. Rossi, and E. Zimeo, ''Context-aware reactive systems based on runtime semantic models (S),'' in *Proc. 31st Int. Conf. Softw. Eng. Knowl. Eng.*, 2019, pp. 301–306. [Online]. Available: http://ksiresearchorg.ipage.com/seke/seke19paper/seke19paper_169.pdf

[64] I. H. Sarker, H. Alqahtani, F. Alsolami, A. I. Khan, Y. B. Abushark, and M. K. Siddiqui, ''Context pre-modeling: An empirical analysis for classification based user-centric context-aware predictive modeling,'' *J. Big Data*, vol. 7, no. 1, p. 51, Dec. 2020. [Online]. Available: https://journalofbigdata.springeropen.com/articles/10.1186/s40537-020-00328-3

[65] S. Choi and J. Lee, ''Blockchain-based distributed firmware update architecture for IoT devices,'' *IEEE Access*, vol. 8, pp. 37518–37525, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9007435/

[66] A. Elyasaf, ''Context-oriented behavioral programming,'' *Inf. Softw. Technol.*, vol. 133, May 2021, Art. no. 106504. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S095058492030094X

[67] H. Inaltekin, M. Gorlatova, and M. Chiang, ''Virtualized control over fog: Interplay between reliability and latency,'' *IEEE Internet Things J.*, vol. 5, no. 6, pp. 5030–5045, Dec. 2018. [Online]. Available: https://ieeexplore.ieee.org/document/8533367/

[68] Y. Cheng, S. Zhao, B. Cheng, X. Chen, and J. Chen, ''Modeling and deploying IoT-aware business process applications in sensor networks,'' *Sensors*, vol. 19, no. 1, p. 111, Dec. 2018. [Online]. Available: http://www.mdpi.com/1424-8220/19/1/111

[69] S. Zareen, A. Akram, and S. Ahmad Khan, ''Security requirements engineering framework with BPMN 2.0.2 extension model for development of information systems,'' *Appl. Sci.*, vol. 10, no. 14, p. 4981, Jul. 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/14/4981

[70] D. Kozma, P. Varga, and F. Larrinaga, ''Dynamic multilevel workflow management concept for industrial IoT systems,'' *IEEE Trans. Autom. Sci. Eng.*, vol. 18, no. 3, pp. 1354–1366, Jul. 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9131867/

[71] B. Zeigler, S. Mittal, and M. Traore, ''MBSE with/out simulation: State of the art and way forward,'' *Systems*, vol. 6, no. 4, p. 40, Nov. 2018. [Online]. Available: http://www.mdpi.com/2079-8954/6/4/40

[72] E. J. Oughton, W. Usher, P. Tyler, and J. W. Hall, ''Infrastructure as a complex adaptive system,'' *Complexity*, vol. 2018, pp. 1–11, Nov. 2018. [Online]. Available: https://www.hindawi.com/journals/complexity/2018/3427826/

[73] K. Incki and I. Ari, ''Model-based runtime monitoring of smart city systems,'' *Proc. Comput. Sci.*, vol. 134, pp. 75–82, Jan. 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1877050918311098

[74] R. Lefticaru, S. Konur, U. Yildirim, A. Uddin, F. Campean, and M. Gheorghe, ''Towards an integrated approach to verification and model-based testing in system engineering,'' in *Proc. IEEE Int. Conf. Internet Things (iThings) IEEE Green Comput. Commun. (GreenCom) IEEE Cyber, Phys. Social Comput. (CPSCom) IEEE Smart Data (SmartData)*, Jun. 2017, pp. 131–138.

[75] M. Pérez-Hernández, B. Alturki, and S. Reiff-Marganiec, ''FABIoT: A flexible agent-based simulation model for IoT environments,'' in *Proc. IEEE Int. Conf. Internet Things (iThings) IEEE Green Comput. Commun. (GreenCom) IEEE Cyber, Phys. Social Comput. (CPSCom) IEEE Smart Data (SmartData)*, Jul. 2018, pp. 66–73.

[76] J. Taha, V. Salehi, and F. Abraham, ''Development of a low powered wireless IoT sensor network based on MBSE,'' in *Proc. IEEE Int. Syst. Eng. Symp. (ISSE)*, Oct. 2018, pp. 1–8. https://ieeexplore.ieee.org/document/8544420/

[77] M. A. López-Peña, J. Díaz, J. E. Pérez, and H. Humanes, ''DevOps for IoT systems: Fast and continuous monitoring feedback of system availability,'' *IEEE Internet Things J.*, vol. 7, no. 10, pp. 10695–10707, Oct. 2020. [Online]. Available: https://ieeexplore.ieee.org/document/9151987/

[78] H. Besharati-Foumani, M. Lohtander, and J. Varis, ''Fundamentals and new achievements in feature-based modeling, a review,'' *Proc. Manuf.*, vol. 51, pp. 998–1004, 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2351978920319971

[79] C. Hartsell, N. Mahadevan, H. Nine, T. Bapty, A. Dubey, and G. Karsai, ''Workflow automation for cyber physical system development processes,'' in *Proc. IEEE Workshop Design Autom. CPS IoT (DESTION)*, Apr. 2020, pp. 1–9. [Online]. Available: https://ieeexplore.ieee.org/document/9140663/

[80] D. Kozma, P. Varga, and F. Larrinaga, ''System of systems lifecycle management—A new concept based on process engineering methodologies,'' *Appl. Sci.*, vol. 11, no. 8, p. 3386, Apr. 2021. [Online]. Available: https://www.mdpi.com/2076-3417/11/8/3386

[81] K. M. Abbasi, T. A. Khan, and I. U. Haq, "Modeling-framework for model-based software engineering of complex Internet of Things systems," *Math. Biosciences Eng.*, vol. 18, no. 6, pp. 9312–9335, 2021. [Online]. Available: http://www.aimspress.com/article/doi/10.3934/mbe.2021458
[82] M. Nakamura, K. Sakakibara, Y. Okura, and K. Ogata, "Formal verification of multitask hybrid systems by the OTS/CafeOBJ method," *Int. J. Softw. Eng. Knowl. Eng.*, vol. 31, no. 11, pp. 1541–1559, Dec. 2021. [Online]. Available: https://www.worldscientific.com/doi/abs/10.1142/S0218194021400118
[83] C.-H. Lee, C.-H. Chen, C. Lin, F. Li, and X. Zhao, "Developing a quick response product configuration system under industry 4.0 based on customer requirement modelling and optimization method," *Appl. Sci.*, vol. 9, no. 23, p. 5004, Nov. 2019. [Online]. Available: https://www.mdpi.com/2076-3417/9/23/5004
[84] C. Gupta and V. Gupta, "Are these requirements risky: A proposal of an IoT-based requirements risk estimation framework," *Mathematics*, vol. 10, no. 8, p. 1210, Apr. 2022. [Online]. Available: https://www.mdpi.com/2227-7390/10/8/1210
[85] A. Ivo, S. Ribeiro, and F. Mattiello-Francisco, "EMBED-SoSE: Drawing a cyber-physical system of systems," in *Proc. 17th Int. Conf. Eval. Novel Approaches Softw. Eng.*, 2022, pp. 485–493. [Online]. Available: https://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0011082600003176
[86] K. Thramboulidis, I. Kontou, and D. C. Vachtsevanou, "Towards an IoT-based framework for evolvable assembly systems," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 182–187, 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S240589631831379X
[87] A. Vörös, M. Búr, I. Ráth, Horváth, Z. Micskei, L. Balogh, B. Hegyi, B. Horváth, Z. Mázló, and D. Varró, "MoDeS$_3$: Model-based demonstrator for smart and safe cyber-physical systems," in *NASA Formal Methods* (Lecture Notes in Computer Science), vol. 10811, A. Dutle, C. Muñoz, and A. Narkawicz, Eds. Cham, Switzerland: Springer, pp. 460–467. [Online]. Available: http://link.springer.com/10.1007/978-3-319-77935-5_31
[88] I. Berrouyne, M. Adda, J.-M. Mottu, J.-C. Royer, and M. Tisi, "CyprIoT: Framework for modelling and controlling network-based IoT applications," in *Proc. 34th ACM/SIGAPP Symp. Appl. Comput.*, Apr. 2019, pp. 832–841. [Online]. Available: https://dl.acm.org/doi/10.1145/3297280.3297362
[89] A. Iglesias, M. Iglesias-Urkia, B. López-Davalillo, S. Charramendieta, and A. Urbieta, "TRILATERAL: Software product line based multidomain IoT artifact generation for industrial CPS," in *Proc. 7th Int. Conf. Model-Driven Eng. Softw. Develop.*, 2019, pp. 64–73. [Online]. Available: http://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0007343500640073
[90] I. Qasim, M. W. Anwar, F. Azam, H. Tufail, W. H. Butt, and M. N. Zafar, "A model-driven mobile HMI framework (MMHF) for industrial control systems," *IEEE Access*, vol. 8, pp. 10827–10846, 2020. [Online]. Available: https://ieeexplore.ieee.org/document/8954725/
[91] I. Batchkova and T. Ivanova, "Model-driven development of agent-based cyber-physical systems," *IFAC-PapersOnLine*, vol. 52, no. 25, pp. 258–263, 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2405896319324012
[92] T. Nepomuceno, T. Carneiro, P. H. Maia, M. Adnan, T. Nepomuceno, and A. Martin, "AutoIoT: A framework based on user-driven MDE for generating IoT applications," in *Proc. 35th Annu. ACM Symp. Appl. Comput.*, Mar. 2020, pp. 719–728. [Online]. Available: https://dl.acm.org/doi/10.1145/3341105.3373873
[93] L. Sakizloglou, S. Ghahremani, T. Brand, M. Barkowsky, and H. Giese, "Towards highly scalable runtime models with history," in *Proc. IEEE/ACM 15th Int. Symp. Softw. Eng. Adapt. Self-Managing Syst.*, Jun. 2020, pp. 188–194. [Online]. Available: https://dl.acm.org/doi/10.1145/3387939.3388614
[94] C. Binder, C. Neureiter, and A. Lüder, "Towards a domain-specific approach enabling tool-supported model-based systems engineering of complex industrial internet-of-things applications," *Systems*, vol. 9, no. 2, p. 21, 2021. [Online]. Available: https://www.mdpi.com/2079-8954/9/2/21
[95] I. M. Murwantara, H. Tjahyadi, P. Yugopuspito, A. Aribowo, and I. A. Lazarusli, "Towards adaptive sensor-cloud for Internet of Things," *TELKOMNIKA (Telecommunication Comput. Electron. Control)*, vol. 16, no. 6, p. 2771, Dec. 2018. [Online]. Available: http://telkomnika.uad.ac.id/index.php/TELKOMNIKA/article/view/11557
[96] S. Meliá, S. Nasabeh, S. Luján-Mora, and C. Cachero, "MoSIoT: Modeling and simulating IoT healthcare-monitoring systems for people with disabilities," *Int. J. Environ. Res. Public Health*, vol. 18, no. 12, p. 6357, Jun. 2021. [Online]. Available: https://www.mdpi.com/1660-4601/18/12/6357
[97] M. Mehrabi, B. Zamani, and A. Hamou-Lhadj, "HealMA: A model-driven framework for automatic generation of IoT-based Android health monitoring applications," *Automated Softw. Eng.*, vol. 29, no. 2, p. 56, Nov. 2022. [Online]. Available: https://link.springer.com/10.1007/s10515-022-00363-9
[98] A. Moin, M. Challenger, A. Badii, and S. Günnemann, "A model-driven approach to machine learning and software modeling for the IoT: Generating full source code for smart Internet of Things (IoT) services and cyber-physical systems (CPS)," *Softw. Syst. Model.*, vol. 21, no. 3, pp. 987–1014, Jun. 2022. [Online]. Available: https://link.springer.com/10.1007/s10270-021-00967-x
[99] A. Moin, M. Challenger, A. Badii, and S. Günnemann, "Supporting AI engineering on the IoT edge through model-driven TinyML," in *Proc. IEEE 46th Annu. Comput., Softw., Appl. Conf. (COMPSAC)*, Jun. 2022, pp. 884–893. [Online]. Available: https://ieeexplore.ieee.org/document/9842593/
[100] A. Barisic, E. Zhu, and F. Mallet, "Model-driven approach for the design of multi-chain smart contracts," in *Proc. 3rd Conf. Blockchain Res. Appl. Innov. Netw. Services (BRAINS)*, Sep. 2021, pp. 37–38. [Online]. Available: https://ieeexplore.ieee.org/document/9569809/
[101] A. Wortmann, O. Barais, B. Combemale, and M. Wimmer, "Modeling languages in industry 4.0: An extended systematic mapping study," *Softw. Syst. Model.*, vol. 19, no. 1, pp. 67–94, Jan. 2020. [Online]. Available: http://link.springer.com/10.1007/s10270-019-00757-6
[102] A. Alreshidi and A. Ahmad, "Architecting software for the Internet of Thing based systems," *Future Internet*, vol. 11, no. 7, p. 153, Jul. 2019. [Online]. Available: https://www.mdpi.com/1999-5903/11/7/153
[103] A. M. Shaaban, C. Schmittner, T. Gruber, A. B. Mohamed, G. Quirchmayr, and E. Schikuta, "CloudWoT—A reference model for knowledge-based IoT solutions," in *Proc. 20th Int. Conf. Inf. Integr. Web-Based Appl. Services*, Nov. 2018, pp. 272–281. [Online]. Available: https://dl.acm.org/doi/10.1145/3282373.3282400
[104] M. Zdravković, J. Zdravkovic, A. Aubry, N. Moalla, W. Guedria, and J. Sarraipa, "Domain framework for implementation of open IoT ecosystems," *Int. J. Prod. Res.*, vol. 56, no. 7, pp. 2552–2569, Apr. 2018. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00207543.2017.1385870
[105] V. Gkioulos, A. Rizos, C. Michailidou, P. Mori, and A. Saracino, "Enhancing usage control for performance: An architecture for systems of systems," in *Computer Security* (Lecture Notes in Computer Science), vol. 11387, S. K. Katsikas, F. Cuppens, N. Cuppens, C. Lambrinoudakis, A. Antón, S. Gritzalis, J. Mylopoulos, and C. Kalloniatis, Eds. Cham, Switzerland: Springer, pp. 69–84. [Online]. Available: http://link.springer.com/10.1007/978-3-030-12786-2_5
[106] M. Bradbury, C. Maple, H. Yuan, U. I. Atmaca, and S. Cannizzaro, "Identifying attack surfaces in the evolving space industry using reference architectures," in *Proc. IEEE Aerosp. Conf.*, Mar. 2020, pp. 1–20. [Online]. Available: https://ieeexplore.ieee.org/document/9172785/
[107] K. Azghiou, M. El Mouhib, M.-A. Koulali, and A. Benali, "An end-to-end reliability framework of the Internet of Things," *Sensors*, vol. 20, no. 9, p. 2439, Apr. 2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/9/2439
[108] J. P. S. Piest, R. H. Bemthuis, and G. Charismadiptya, "Demonstrating the architecture for situation-aware logistics using smart returnable assets," in *Proc. IEEE 24th Int. Enterprise Distrib. Object Comput. Workshop (EDOCW)*, Oct. 2020, pp. 86–90. [Online]. Available: https://ieeexplore.ieee.org/document/9233229/
[109] F. Fraile, R. Sanchis, R. Poler, and A. Ortiz, "Reference models for digital manufacturing platforms," *Appl. Sci.*, vol. 9, no. 20, p. 4433, Oct. 2019. [Online]. Available: https://www.mdpi.com/2076-3417/9/20/4433
[110] F. C. Brandão, M. A. T. Lima, C. E. Pantoja, J. Zahn, and J. Viterbo, "Engineering approaches for programming agent-based IoT objects using the resource management architecture," *Sensors*, vol. 21, no. 23, p. 8110, Dec. 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/23/8110

[111] J. Delsing, G. Kulcsár, and Ø. Haugen, "SysML modeling of service-oriented system-of-systems," *Innov. Syst. Softw. Eng.*, pp. 1–17, May 2022. [Online]. Available: https://link.springer.com/article/10.1007/s11334-022-00455-5
[112] R. Pinto, G. Gonçalves, J. Delsing, and E. Tovar, "Enabling data-driven anomaly detection by design in cyber-physical production systems," *Cybersecurity*, vol. 5, no. 1, p. 9, Dec. 2022. [Online]. Available: https://cybersecurity.springeropen.com/articles/10.1186/s42400-022-00114-z
[113] J. Song, D. Karagiannis, and M. Lee, "Modeling method to abstract collective behavior of smart IoT systems in CPS," *Sensors*, vol. 22, no. 13, p. 5057, Jul. 2022. [Online]. Available: https://www.mdpi.com/1424-8220/22/13/5057
[114] G. Reggio, "A UML-based proposal for IoT system requirements specification," in *Proc. IEEE/ACM 10th Int. Workshop Model. Softw. Eng. (MiSE)*, May 2018, pp. 9–16. [Online]. Available: http://dl.acm.org/citation.cfm?doid=3193954.3193956
[115] P. J. Escamilla-Ambrosio, D. A. Robles-Ramírez, T. Tryfonas, A. Rodríguez-Mota, G. Gallegos-García, and M. Salinas-Rosales, "IoTsecM: A UML/SysML extension for Internet of Things security modeling," *IEEE Access*, vol. 9, pp. 154112–154135, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9605568/
[116] S. Mihai, M. Yaqoob, D. V. Hung, W. Davis, P. Towakel, M. Raza, M. Karamanoglu, B. Barn, D. Shetve, R. V. Prasad, H. Venkataraman, R. Trestian, and H. X. Nguyen, "Digital twins: A survey on enabling technologies, challenges, trends and future prospects," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 2255–2291, 4th Quart., 2022. [Online]. Available: https://ieeexplore.ieee.org/document/9899718/
[117] C. Zhang, G. Zhou, J. He, Z. Li, and W. Cheng, "A data- and knowledge-driven framework for digital twin manufacturing cell," *Proc. CIRP*, vol. 83, pp. 345–350, 2019. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2212827119306985
[118] X. Zheng, F. Psarommatis, P. Petrali, C. Turrin, J. Lu, and D. Kiritsis, "A quality-oriented digital twin modelling method for manufacturing processes based on a multi-agent architecture," *Proc. Manuf.*, vol. 51, pp. 309–315, 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2351978920318990
[119] J. Hugues, A. Hristosov, J. J. Hudak, and J. Yankel, "TwinOps–DevOps meets model-based engineering and digital twins for the engineering of CPS," in *Proc. 23rd ACM/IEEE Int. Conf. Model Driven Eng. Lang. Syst., Companion Proc.*, Oct. 2020, pp. 1–5. [Online]. Available: https://dl.acm.org/doi/10.1145/3417990.3421446
[120] Y. Li, J. Chen, Z. Hu, H. Zhang, J. Lu, and D. Kiritsis, "Co-simulation of complex engineered systems enabled by a cognitive twin architecture," *Int. J. Prod. Res.*, vol. 60, no. 24, pp. 7588–7609, Dec. 2022. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00207543.2021.1971318
[121] C. Cimino, G. Ferretti, and A. Leva, "The role of dynamics in digital twins and its problem-tailored representation," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 10556–10561, 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2405896320335692
[122] P. Brauner, M. Dalibor, M. Jarke, I. Kunze, I. Koren, G. Lakemeyer, M. Liebenberg, J. Michael, J. Pennekamp, C. Quix, B. Rumpe, W. van der Aalst, K. Wehrle, A. Wortmann, and M. Ziefle, "A computer science perspective on digital transformation in production," *ACM Trans. Internet Things*, vol. 3, no. 2, pp. 1–32, 2022. [Online]. Available: https://dl.acm.org/doi/10.1145/3502265
[123] T. Hartmann, A. Moawad, F. Fouquet, and Y. Le Traon, "The next evolution of MDE: A seamless integration of machine learning into domain modeling," *Softw. Syst. Model.*, vol. 18, no. 2, pp. 1285–1304, Apr. 2019. [Online]. Available: http://link.springer.com/10.1007/s10270-017-0600-2
[124] N. Mohamudally and M. Peermamode-Mohaboob, "Building an anomaly detection engine (ADE) for IoT smart applications," *Proc. Comput. Sci.*, vol. 134, pp. 10–17, 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1877050918311013
[125] K. Fodor and Z. Balogh, "Process modelling and creating predictive models of sensory networks using fuzzy Petri nets," *Proc. Comput. Sci.*, vol. 185, pp. 28–36, 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1877050921010826
[126] C. Binder, C. Neureiter, and A. Lüder, "Towards a domain-specific information architecture enabling the investigation and optimization of flexible production systems by utilizing artificial intelligence," *Int. J. Adv. Manuf. Technol.*, vol. 123, nos. 1–2, pp. 49–81, Nov. 2022. [Online]. Available: https://link.springer.com/10.1007/s00170-022-10141-2
[127] H. Ren, K. Dorofeev, D. Anicic, Y. Hammad, R. Eckl, and T. A. Runkler, "SeLoC-ML: Semantic low-code engineering for machine learning applications in industrial IoT," in *The Semantic Web—ISWC* (Lecture Notes in Computer Science), vol. 13489, U. Sattler, A. Hogan, M. Keet, V. Presutti, J. P. A. Almeida, H. Takeda, P. Monnin, G. Pirrò, and C. d'Amato, Eds. Cham, Switzerland: Springer, 2022, pp. 845–862. [Online]. Available: https://link.springer.com/10.1007/978-3-031-19433-7_48
[128] J. J. Fuertes, M. Á. Prada, J. R. Rodríguez-Ossorio, R. González-Herbón, D. Pérez, and M. Domínguez, "Environment for education on industry 4.0," *IEEE Access*, vol. 9, pp. 144395–144405, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9576059/
[129] S. Kar, A. K. Kar, and M. P. Gupta, "Industrial Internet of Things and emerging digital technologies–modeling professionals' learning behavior," *IEEE Access*, vol. 9, pp. 30017–30034, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9354166/
[130] D. Dobrilovic, V. Brtka, Z. Stojanov, G. Jotanovic, D. Perakovic, and G. Jausevac, "A model for working environment monitoring in smart manufacturing," *Appl. Sci.*, vol. 11, no. 6, p. 2850, Mar. 2021. [Online]. Available: https://www.mdpi.com/2076-3417/11/6/2850
[131] L. Chen, H. Zhang, and F. Wang, "Intelligent evaluation method of engineering cost feasibility model based on Internet of Things," *J. Sensors*, vol. 2022, pp. 1–8, Oct. 2022. [Online]. Available: https://www.hindawi.com/journals/js/2022/3420723/
[132] M. T. Moghaddam, H. Muccini, J. Dugdale, and M. B. Kjagaard, "Designing Internet of Behaviors systems," in *Proc. IEEE 19th Int. Conf. Softw. Archit. (ICSA)*, Mar. 2022, pp. 124–134. [Online]. Available: https://ieeexplore.ieee.org/document/9779704/

EHSAN AHMAD received the Ph.D. degree in computer science and information technology. He was an Assistant Professor with the Department of Computer Science, Air University, Pakistan, and a Research Fellow with the State Key Laboratory of Computer Science, Institute of Software, Chinese Academy of Sciences, China. He is currently an Assistant Professor with the College of Computing and Informatics, Saudi Electronic University, Saudi Arabia. His research interests include (but not limited to) the model-based engineering of software-intensive systems, the Internet of Things, and the adoption of e-learning methodologies and tools.