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Reviewing Manufacturing Execution System in Industry 4.0: A Global Approach

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Abstract

INTRODUCTION: Manufacturing Execution Systems (MES) have evolved from basic production tracking tools into intelligent, AI-driven platforms integrated with IoT, cloud computing, and cyber-physical systems. In the context of Industry 4.0, MES play a key role in enabling real-time decision-making and operational efficiency. However, research in this field remains fragmented, with ongoing challenges related to interoperability, cybersecurity, and system integration.
OBJECTIVES: This study aims to map the MES research landscape within Industry 4.0 through a systematic literature review and bibliometric analysis. It identifies core research themes, technological trends, and persistent challenges, offering insights to guide future developments in MES.
METHODS: A Systematic Literature Review (SLR) was conducted using the Scopus database, applying specific search terms and strict inclusion/exclusion criteria. A total of 47 peer-reviewed articles (2010–2024) were analysed using VOSviewer to perform co-authorship, bibliographic coupling, and keyword co-occurrence mapping.
RESULTS: The analysis revealed three main research clusters: MES core technologies, MES integration with Industry 4.0, and comparisons with ERP and SCADA systems. Key trends include the integration of AI, digital twins, and blockchain. Barriers such as interoperability, cybersecurity risks, and adoption costs—especially for SMEs—remain prevalent.
CONCLUSION: MES research is advancing toward intelligent, scalable, and interconnected systems. Future work should prioritise standardisation, secure data exchange, and cost-effective models to support broader Industry 4.0 adoption. Cross-disciplinary collaboration will be essential to achieve sustainable and resilient MES implementations.

Keywords: Manufacturing Execution Systems (MES), Industry 4.0, IoT, AI, Cyber-Physical Systems, Smart Manufacturing

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1. Introduction

The Manufacturing Execution System (MES) is the link between top-level (enterprise) and shop floor operations. They enable the collection, processing, and sharing of production data to improve the performance of both manufacturing processes and products quality [1,2]. With the advent of Industry 4.0, MES have moved on from the classic functions, like planning, executing, tracking the entire manufacturing process, to incorporate features such as artificial intelligence, real-time big data analytics and self-adaptive manufacturing processes [3].

However, the state of art in MES research still presents fragmented perspectives because optimal trajectories of innovation, system compatibility, and practical obstacles to industrial deployment are interpreted differently [4,5]. To resolve these fragmentation problems in this paper, it is proposed a Systematic Literature Review (SLR) with bibliometric analysis. To undertake these dual processing steps, dispersing knowledge is synthesized, dominant research topics are culled out and coherent trajectory lines to further investigate the MES field are suggested [6,7].

This analysis is organised according to four guiding research questions: (Q1) What are the primary weaknesses of MES? (Q2) Why should adopt MES? (Q3) What are alternatives to MES at present? (Q4) How are MES different from other industrial systems? The bibliometric results indicated three main thematic clusters, namely: (1) Core MES Technologies, (2) Integration of MES in the Industry 4.0 scenario and (3) Comparison of MES with alternative systems.

Despite the emergence of new technologies leading to more advanced MES functionalities, the above identified challenges (high deployment costs, integration difficulties, and scalability) have not disappeared and continue to limit the wider adoption of MES in the industrial context [8,9]. The research stresses the increasing importance of smart MES solutions that utilize modular design principles, artificial intelligence (AI) and blockchain-enhanced security mechanisms to create more flexible and resilient manufacturing ecosystems [10].

With the arrival of Industry 4.0, MES are becoming useful tools which are not only used for passive data capturing but will be seen as the enabler of strategic intelligence to turn raw industrial data into structured actionable insights through industrial science based on scientific, evidence-based methods. enabling the collection and analysis of data in real time [11].

The use of sound analytical methods, especially those that have been proven to be reliable and high quality (through peer-reviewed sources, for example the Scopus), is a cornerstone for establishing a sound knowledge base which can support MES development in the evolution and its proper deployment in Industry 4.0 manufacturing strategies. As this area of research is relatively recent (the first publications were published in 2013) it was only found two Systematic Literature Reviews.

In the newest MES research field, the SLRs orientations and analytical frame vary. The first is a study by Cimino et al. (2019) of Politecnico di Milano [12]. It is based on the use of Digital Twin (DT) solutions in the manufacturing sector. This review article, in Journal of Manufacturing Systems (Elsevier, Q1, H-index 107), from 2015 to 2019 has accumulated 77 citations in Scopus, and 147 in all databases. The study (Review of Digital Twin Applications in Manufacturing) highlights the intersection between Digital Twins and MES, assessing how DT models are integrated and identifying critical gaps between theoretical designs and their practical implementation. The lack of standardised definitions, integration difficulties with MES platforms, and the limited functional scope of existing Digital Twins (DT) systems are underscored as major constraints. Consequently, the authors suggest future research directions that include the development of robust DT–MES integration frameworks, the application of AI for optimisation, and the enhancement of DT capabilities for real-time control and automation.

In contrast, the second review by Shojaeinasab et al. (2022) from the University of Victoria [4] undertakes a broader investigation into the evolution of MES within the Industry 4.0 paradigm. Also published in the Journal of Manufacturing Systems (Elsevier, Q1, H-index 107), this review covers a wider temporal scope, from 2012 to 202, and has received 97 Scopus citations, equalling the 147 total citations seen in the first review. The study (Intelligent Manufacturing Execution Systems: A Systematic Review) offers a detailed examination of the transformation of MES under Industry 4.0, proposing a classification of MES intelligence levels and presenting a conceptual framework for Intelligent MES systems. Key challenges identified in this body of work include the integration of artificial intelligence and Internet of Things (IoT) technologies, the absence of standardised system architectures, and the relatively slow rate of adoption by industry stakeholders. As a response, the authors advocate for the development of AI-enhanced MES models, the standardisation of intelligence classification within MES, and more effective strategies for real-time decision-making in smart manufacturing contexts.

Together, these reviews offer complementary insights: one through the lens of Digital Twin integration and the other through the evolution of MES intelligence. Accordingly, these reviews provide a valuable foundation for advancing MES research in alignment with the principles of Industry 4.0.

In the light of this theoretical and contextual review, Chapter 2 sheds light on the guidelines, while Chapter 3 explains the research method. Chapter 4 presents the main results, followed by the conclusion. The last section ends with the discussion of the key contributions and suggestions for future research.

2. Theoretical Framework

Owing to the accelerated pace of technological innovation, evolving industrial demands, and policy-driven initiatives aimed at advancing MES, academic interest in this field has expanded considerably. This section outlines the principal thematic areas that have emerged within the literature, alongside the conceptual frameworks that have informed the implementation and adoption of MES across various manufacturing contexts.

2.1. MES evolution

When MES solutions were first conceived, their original design purpose was to manage production control and provide immediate insight into manufacturing processes - so production would be more transparent. Legacy MES, the early generations of MES, were developed as monolithic systems and hardwired with low-level interfaces designed to be very vendor-centric with little or no ability to integrate with other enterprise-level systems.

However, over the years MES solutions expanded from their original roles, adding support for modular system structures, cloud-based infrastructure, and AI-driven analytics [13]. In Industry 4.0, the MES is not only a tool to collect basic data; instead, it becomes an intelligent system with autonomous decision capabilities. These new generation MES platforms are becoming more tightly coupled with innovations such as smart sensors, the Internet of Things (IoT) and cyber-physical systems (CPS) which facilitate a seamless connection of the physical to the digital layer of manufacturing processes [5,14].

2.2 Theoretical Perspectives in MES Research

Different theoretical frameworks have been used to explain the uptake and embedment of Manufacturing Execution Systems (MES) such as: (i) Technology Acceptance Model (TAM), (ii) Sociotechnical Systems Theory (SST), and (iii) Cyber-Physical Systems (CPS) Theory.

The TAM model suggests that perceived usefulness and perceived ease of use are the major determinants of its acceptance to industrial environments [15, 16]. This claim is supported by empirical evidence as well where the usability of MES platforms [17, 18] as well as their capability to respond fast to rapidly changing manufacturing conditions significantly determine the users' intention to use such systems.

Sociotechnical Systems Theory focuses on the technical infrastructure, e.g., MES software, sensor networks and automation technology and how this interacts with the social, e.g., operators, decision-makers and the larger organisational and management infrastructure [19]. Consistent with that view, [20, 21, 22] propose that MES should be designed based on human factors engineering principles, to ensure that the system is efficient and ease to use.

Finally, CPS theory yields a more modern perspective, especially in the Industry 4.0, in which MES are increasingly becoming integrated cyber-physical systems. These are systems that combine Big Data analytics, edge computing and IoT capabilities to deliver smarter and proactive manufacturing environments [23, 24, 25].

2.3 MES vs. Alternative Systems

Among others, one of the most active in the discussion topics is the comparison of MES with industrial platforms (in particular against ERPs, SCADAs, and PLMs). MES and their role in real-time production control MES play a critical role as the creator of a new type of coupling, close to the ERP, which enables two previously separated but, pure process-control system shall be bridged - the ERP system for the management of the enterprises at the business level and SCADA systems for the closed-loop control of the plant at the operational level [26, 27].

This integrative role has been the focus of many studies, which all underline the powerful influence MES exert in supporting data exchange and transmission from the business to the shop-floor level in manufacturing. In this perspective, ERP systems focus on the company-wide resource planning and management, across all processes belonging to the organization, and SCADA systems perform only data collection and real-time process monitoring.

In contrast, MES are dedicated to fulfilling the tasks of running and monitoring production processes, providing the interface between the strategic goals and the operational activities. Nevertheless, while indispensable having the role of lab to the field bridging, MES is not free from issues. One of the main challenges in this respect is the homogenisation of heterogeneous systems, especially when considering multi-vendor solutions. Interoperability is, hence, a predominant issue and frequently limits the efficiency, scalability, and consistency of connected industrial domains [28, 29, 30, 31].

2.4 MES in the Context of Industry 4.0

The progress of Industry 4.0 also remarkably affects the future trend of MES research, and the research of MES has gradually changed to smart manufacturing, process automation with IoT and intelligent decision-making with AI. This change is possible using IoT-sensors and cloud computing solutions, enabling the collection and analysis of data in an ongoing and real-time fashion. It enables the visibility enhancement as well as responsiveness in operations for the better production flow [10].

Moreover, the implementation of AI-related and predictive analytics components is reconstructing MES, even allowing manufactures not only to forecast an equipment failure and take dynamic scheduling actions, even play a zero-tolerance game for a real-time disturbance enroute to a precise and better production plan [32].

On the other hand, cyber security and the blockchain technology are emerging as the important points of the next-generation MES development. This is where new generation technologies such as blockchain, in its variant, go some way to address some of those age-old issues that has often concerned enterprise about who it could share data with safely even with centralized data manipulation systems, how it could assuredly do so with regards to integrity and trust with respect to decentralized manufacturing systems. Relying on the decentralised ledger techniques, the trust is trying to enhance security and trace the production data away from the systemic risk posed by the transparency of the operations that the network is connected to [33, 34].

For that, an AI in the form of a lightweight reasoning mechanism was included as an indispensable component in the MES architecture revealed in this context. Applications can range multiple functional fields such as real time monitoring, predictive maintenance and agile schedule. MES packages are grafted with all sorts of AI technologies. These include Modern machine learning algorithms such as Multilayer Perceptrons, Decision Trees, Random Forests, or Optimisation Algorithms like Genetic Algorithm, Particle Swarm Optimisation etc. which are more powerful techniques for outlier detection and are also being increasingly employed straight in order to verify the process robustness and as soon as possible detect with higher confidence the existence of a fault. Taken together, these AI-led capabilities see MES as a prominent enabler of the Industry 4.0 vision, paving the way for smarter manufacturing systems that may be even more flexible, agile and intelligent.

3. Methodology

This research follows a systematic literature review (SLR) methodology, integrating bibliometric analysis to obtain key investigation comprehensions. The methodology was considered following the recommendations proposed by [6, 7].

3.1 Data Collection and Selection Sample

To guarantee the incorporation of high quality, as well as relevant to the topic studies, a stringent methodological technique was followed for this SLR. The Scopus repository was chosen as the main information resource/facility to identify academic literature, because of its extensive multidisciplinary coverage, wide coverage of numerous peer-reviewed journals within engineering, industrial management and business. Compared with other scientific databases, e.g., IEEE Xplore and Web of Science, the free and open-to-public access platform like Scopus provide a better coverage, especially when dealing with cross-disciplinary research areas such as MES. What's more, Scopus' strong citation coverage allows for deep quantitative bibliometric analysis and for a more robust analytical depth and trustworthiness.

However, the use of a single database could cause a selection bias. In order to address this shortcoming, the review adopted a series of stringent inclusion and exclusion criteria to only include studies that had proper empirical or theoretical grounding. Search criteria used specific keywords to include the extent of MES in the 4th Industrial Revolution, "Manufacturing Execution System" AND "Industry 4.0", "MES AND ERP AND SCADA" and "MES limitations OR MES advantages". These words were searched for in titles, abstracts and keywords to ensure the maximum number of related publications were retrieved.

The first query retrieved 178 documents. To further limit the range, records were kept that were categorized under certain subject categories: Engineering; Business, Management and Accounting; Economics, Econometrics and Finance and Environmental Sciences. This filter resulted in 125 documents. The search was further refined by including only peer-reviewed articles and reviews (excluding conference proceedings and other grey literature). The application of this type of document filter resulted in 56 records.

Language also served as a gatekeeping criterion, only English articles were screened, which eventually resulted in final pool of 47. A check for filters on publication type, contributing to science, and publication date was used as a final screen step. Only journal articles published from 2010 up to 2024 were included with a minim focus on the MES technologies, challenges in their implementation and integration aspects for the industry 4.0 environment. After the application of all inclusion and exclusion criteria, the final sample included 45 original studies and 2 RS.

This systematic and transparent approach was designed to provide assurance regarding the dependability of the literature review as well as the replicability of the insights that emerged from the set of selected publications.

3.2 Bibliometric Analysis Using VOSviewer

VOSviewer [35], a well-established software tool for visualizing scientific landscapes, was used for bibliometric mapping. This process includes steps such as the identification and analysis of co-authorship network, bibliographic coupling and keyword co-occurrence, with the purpose of identifying the major trends in research on MES. Through co-authorship mapping, the super contributors to MES research, as well as the collaborative relationships that bind them in scientific terms, were uncovered (Figure 1).

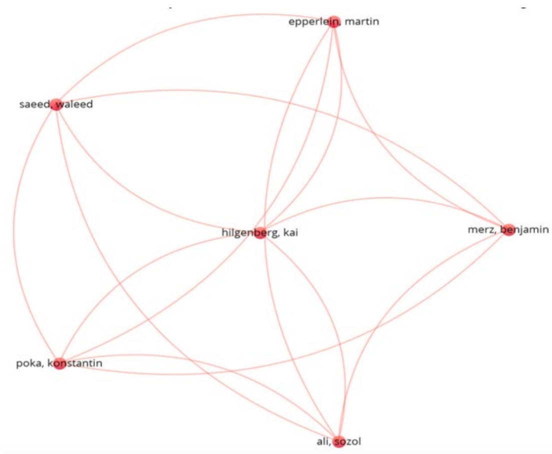

Figure 1. Co-authorship analysis (own elaboration)

Subsequently, a bibliographic coupling analysis was performed to find the clusters of publications that are related because they share references and similar themes. This method allowed us to identify groups of correlated studies that corresponded to the intellectual structure of the MES research field (Figure 2).

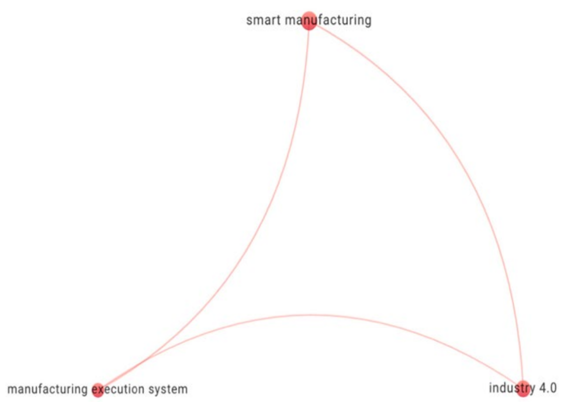

Figure 2. Co-occurrence analysis (own elaboration)

A keyword co-occurrence analysis was also conducted to investigate dominant and emerging themes in the MES literature (Figure 3). This study gave an early impetus on the development path and explained how MES is now increasingly on jointing with leading Industry 4.0 technologies.

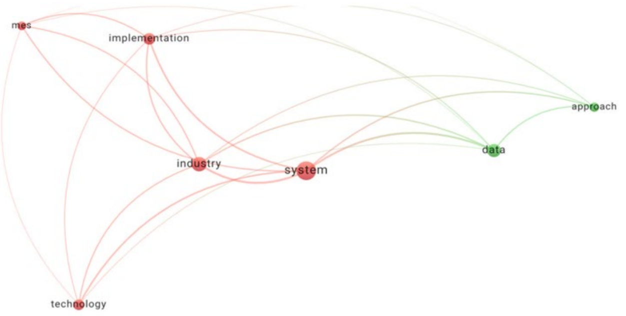

Figure 3. Keyword occurrence analysis (own elaboration)

Following this, a bibliographic coupling analysis was undertaken to identify clusters of publications connected through shared references and thematic similarities. This approach enabled the recognition of groups of interrelated studies, reflecting the intellectual structure of the MES research domain. In parallel, a keyword co-occurrence analysis was carried out to explore the prevailing and emerging topics within the MES literature. This analysis offered valuable insights into evolving research directions and clarified how MES is increasingly interlinked with core Industry 4.0 technologies.

4 Results and Discussion

4.1 Co-authorship Analysis

The generated visualization (Figure 1) produced a single research cluster of six authors, suggesting that the research domain of MES is driven by a core set of prominent authors.
The analysis showed a sparse network structure is due to either specialization in this field, centralized collaboration in big institutions, or generally little cross-disciplinary integration. Extending the data set and scaling up the temporal coverage of the upcoming investigations may help to capture larger patterns of collaboration and to provide a deeper knowledge of the changing dynamics of co-authorship in this area.

Geographically, three regional research clusters were observed in the analysis. Firstly, research groups are mainly involved in MES standardization and regulations, especially with reference to ISO 22400 and compliance-based approaches [36, 37, 38]. These results are in line with [29, 39] which raise that European academics have a strong focus on formalised production control to catalyse sustainable manufacturing. Second, North American research networks have a keen interest in AI-driven MES, where integration of ML-based predictive analytics in production system is researched [5]. These observations reflect that of [40] which point to the performance improvements that an AI-driven MES contribute to the industrial automation space. Third, most Asian research groups concentrate on IoT-enabled MES solutions, especially with scalability and cost-effective deployment [13]. According to [26], this emphasis is due to the regional need of flexible and cost-effective manufacturing systems.

In addition to the observed regional segmentation, the co-authorship network reveals a tightly interconnected structure within the identified six-author cluster. The density of links, with multiple reciprocal collaborations among members, suggests sustained and possibly long-term research partnerships. Certain authors, notably *Hilgenberg, Kai*, appear to occupy a central position, acting as pivotal connectors between sub-pairs of collaborators and facilitating the internal cohesion of the group. This configuration resembles a near-complete graph, where most members are directly linked to one another, indicating strong intra-cluster collaboration. However, the absence of visible connections to other author clusters underscores the insular nature of this network, which, while fostering stability and depth of cooperation within the group, may limit exposure to diverse perspectives and innovative

In sum, the results presented in this paper indicate that MES research continues to be fragmented on a regional basis and there is little cross-border collaboration. This is consistent with findings of [28, 36], where the authors emphasize the advantages of promoting higher international collaboration towards the further development of MES standardisation and the worldwide spread of enabling technologies.

4.2 Bibliographic Coupling Analysis

There were 107 unique terms (Keyword co-occurrence analysis) in the MES research dataset. However, there were only three employer-related keywords (Figure 2) that appeared in four or more studies, which may imply that repetition is limited and widely spread. This distribution corresponds to the absence of a single common term in the MES research community that prevail one over the others, maybe because of the interdisciplinary character of the MES discipline and the diversity of its research perspectives.

In addition, the genesis of a sole topical cluster has also served to corroborate the argument that MES research has not progressed towards a mature academic discipline sufficiently. It may suggest that there is significant thematic overlap between the studies, despite the use of different terminology. This recent on-going thematic convergence could be further investigated in future research and the selection of keywords could be further refined to increase the transparency and the conceptual clarity of MES-related studies.

Meanwhile, based on its bibliographic coupling analysis results, three main research themes of the literature were presented in the literature. The first theme is implementation cases studies that offer empirical evidence with respect to the use of MES in practice, particularly in domains such as the automotive and pharmaceutical manufacturing industry [33]. Consistent with this the work in [26] suggests that "for MES solutions deployed in a heavily-regulated industry, compliance mechanisms must be put in place to guarantee successful adoption".

Second theme, the literature has compared MES with ERP and SCADA systems, and the relative strengths and weaknesses of each system for real-time decision making and for improving operational performance [23]. As [28] pointed out, even if ERP systems could be designed to manage high-frequency production data, MES still need special integration interface to well fulfil their specialised operations.

The third emerging theme is related to research directions for AI and blockchain. Researchers are also more recently exploring how blockchain can be used to secure the exchange of production data [33] and how AI can support autonomous decision-making in manufacturing environments. All the above advances in AI are backed by the results from [32], that shows that AI enhanced MES solutions have significant predictive analytics capabilities that can prevent production stoppage in advance, as well as the response time of the system can be improved.

4.3 Evolution of MES Research and Challenges

A remarkable direction towards that trend in MES has been discussed in the recent surveys [4,41] that indicate an emerging attention not on the trends of smart manufacturing, digital twin, real-time monitoring, and cyber security (Figure 3). These are transitioning MES to decoupled scalability architectures also for cloud and edge computing capacities. Hybrid cloud structures have been perceived as vital to guarantee operational freedom and effective data exchange [13, 42]. These bibliometrics results further support the evolution of MES role from traditional control for shop-floor data to smart process optimisation and the real-time analytics, which are the fundamentals of related to the Industry 4.0 and Fourth industrial revolution [32, 40].

Nevertheless, there are some obstacles that prevent the widespread application and use of MES technologies. Prominent among these are issues pertaining to data interoperability, threats to cybersecurity landscape, and constraints of budgetary resources. The undesirable, usually proprietary-dependent intersections of these systems are a major obstacle to integration generally.

However, the use of standard communication protocol is a promising way to enable the interfacing of heterogenous systems [43] and an appropriate protocol can be applied, e.g. OPC UA [23, 44, 45] or MQTT [36]. In addition, more requirements for data security and data audit are emerging because of data breaches via cyber-attacks and to driving a need for a MES architecture utilizing a blockchain to maintain the security and traceability of FACTORY2 data [44]. And then when you start bringing in the financial barriers, particularly for small and medium-sized enterprises, it makes it even harder. MES delivery through subscription-based means serves as flexible and low-cost solutions, when being challenged by such circumstances [8, 45].

Communication and organisation apart from technical and financial aspects, MES implementation is increasingly related to human and organization concerns. And then there's employee resistance to change, not to mention different stages of digital literacy. Solutions In order to address these problems it is recommended to implement a trainee program in parallel to the implementation of the shared MES-human interfaces to support the employees to become familiar to the system [8, 46]. Finally, it is evident from the results of bibliometric analysis that the MES research is heading towards intelligent and autonomous manufacturing ecosystems employing artificial intelligence.

However, for the evolution to be fully mature, acquisition of future work is still required to standardisation, AI-based cybersecurity models, economically sustainable ways for the adoption of such models, particularly in the resource limited industrial setting. [35, 47]. AI, which is introduced into the architecture of MES, has developed rapidly in the smart manufacturing, and its applications are mainly concentrated on the following three aspects. For example, scheduler optimization uses machine learning algorithms such as Decision Trees, Reinforcement Learning to optimize production schedules on the fly to minimize downtime considering demand trends, and available resources. Second, AI-based anomaly detection such as Isolation Forest and One-Class SVM for equipment behavior detection enhances the real-time monitoring to minimize unplanned downtime. Thirdly, the defect monitoring system inspects the product defects based on computer vision and deep learning methods on MES level and the better quality of products is ensured by less material waste reduction.

Such advancements guided by AI have been indicating that MES increasingly transcends the conventional scope of monitoring and control, and serves as an enabler for more efficiency, resilience, and automation in future manufacturing operations.

5. Conclusion

As far as we know, this study is shedding light on MES from a different perspective and will be a value resource for the industrial managers, software vendors, and the policy makers. It lays the groundwork for application of MES in a scalable and economic way in an Industry 4.0 environment. This bibliometric study suggests that MES has been transformed from conventional systems for shop-floor data management to intelligent systems supported by AI, cloud computing, IoT, CPS, and blockchain. These have tremendously increased the level of automation of processes, efficiency and decision-making in real time. But there are several remaining barriers with interoperability, cybersecurity and costs being the chief among them.

Existing problems with the integration of MES, ERP and SCADA system still delay the seamless data transmission between these systems, as depicted in [48]. The increased dependence on cloud architecture further increases concerns over data security, thus underlining the need for blockchain-based security protocols [49]. To address the scalability issue and also to support advanced analytics, the scalable MES solutions designed based on open, standard networking technologies, which are OPC UA and MQTT, can be an interesting starting point for further development [50].

The study situates the MES research within the larger body of STS theory and TAM models literature. Using bibliometric techniques (e.g., co-authorships analysis, keyword co-occurrence, and bibliographic coupling) and with the help of VOSviewer software (Van Eck & Waltman, 2010), this article attempts to rely on a mixed methods approach by combining qualitative with quantitative patterns and mapping. This method allows a more granular examination of the evolution and structure of MES research. However, the current investigation is not without limitations. Our exclusive search on the Scopus database might have led to excluding relevant articles indexed at other repositories (e.g. IEEE Xplore, WoS, Google Scholar). Additionally, the study lacks qualitative content analysis, which leads to limitations in depth interpretations regarding the theoretical position of the MES research paradigm [6]. It also restricts the review to English-language publications, and here presents an opportunity for future case-based and qualitative research to build further on insights from different linguistic and industry domains. Expanding the qualitative analysis in future work, for instance, by examining in-depth case studies, sector-specific challenges, or successful implementation narratives, could enrich understanding and strengthen the practical applicability of findings.

Several suggestions for further study are derived from its findings. These range from developing predictive analytics AI-enabled MES, to the management of security threats in the cloud-based MES architecture, to drive the development of “green” MES for green manufacturing and build low-price MES to meet the requirement of the SME. Nonetheless, while MES scales into realising an AI-supported networked system, several open issues including interoperability, security, cost-efficiency and sustainability, must be addressed.

The collaboration and multi-interdisciplinary approach and engagement among researchers, industry and policy makers is needed to overcome these challenges in the journey to reach the vision of a smart manufacturing and to realize scalable, trustable, and effective MES operations.

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