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Comparing Research Trends And Industrial Adoption Of Manufacturing Operations Management Solutions

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Abstract

For decades, the operations on the shop floor of manufacturing organizations have been supported by Manufacturing Execution Systems. In this paper, we investigate the trends of Manufacturing Operations Management in the research community and analyse the adoption in the industry. Our literature review identifies the following trends for Manufacturing Operations Management: distributed system architectures, cloud technology, and use of standards. We conducted a survey targeting Manufacturing Operations Management solution providers and adopters to explore the adoption of these trends. The survey results show that the use of standards is already addressed to some extent by the industry. Practitioners anticipate distributed system architectures for Manufacturing Operations Management solutions in the future. However, practitioners are still reluctant towards cloud-only technology and will continue to be so in the foreseeable future.

Keywords

Manufacturing Execution System; Manufacturing Operations Management; Cloud technology, Microservices; VDI 5600; IEC 62264

1. Introduction

Classical Manufacturing Execution Systems (MES) and their extension, Manufacturing Operations Management (MOM) systems, have long been used for managing shop floor operations, including tracking production orders, monitoring equipment, and managing inventory in manufacturing organizations [1]. The advent of Industry 4.0 promised many technological advancements from which MES/MOM systems could benefit [2].

This has sparked great interest among researchers to propose new concepts and develop new artefacts in the realm of MES/MOM. However, as a discipline in which design science is a major paradigm, these artefacts should also benefit practitioners [3]. For this purpose, it is essential to make the streams of MES/MOM research in terms of its prominent topics visible and to analyse their industry adoption. However, this has not been the focus of any study so far.

To address this issue, this paper seeks to identify the gaps between MES/MOM research and industrial adoption. Specifically, we aim to understand the current research trends in MES/MOM systems in the context of Industry 4.0 opportunities and how industry practitioners are adopting these trends. We do this by conducting a thorough literature review of the development of MES/MOM.

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We then derive hypotheses from our literature review, which are tested through a survey of industry practitioners. Our survey aims to understand the extent of the adoption of MES/MOM research trends in manufacturing organizations.

The remainder of the paper is organized to highlight our findings. We first review the historical development of MES systems to provide a foundation for understanding the current state of MES/MOM systems. Next, we present the results of our systematic literature review, which helps us to identify the latest research trends in MES/MOM systems. We then present the results of our industry survey, which provides a comprehensive understanding of the current adoption of MES/MOM systems in manufacturing organizations. We then discuss our study's limitations and conclude with our study's main points for practitioners and the future direction of MES/MOM system research.

2. Related Work

Reviewing the existing literature, it becomes clear that while many authors have addressed the future and state of MES/MOM in the context of Industry 4.0, there has been little work on the specific advances promised by Industry 4.0 and how practitioners adopt them in the field: [4] propose a taxonomy that addresses business and manufacturing factors and technology for characterizing MES, and discuss how MES can benefit from Industry 4.0. [5] analyse the trends that will determine the development of the next generation of MES and highlight the need for semantic metadata to support interoperability and modular development. [6] identify the importance of MES for Industry 4.0, but stress that how an enterprise utilizes MES features will determine whether it can achieve its Industry 4.0 goals. [2] argues that Industry 4.0 has created unique opportunities for defining target roadmaps for manufacturing operations and IT systems, but centralized and monolithic production monitoring and control applications will eventually give way to solutions capable of supporting a radically different vision of connected yet decentralized production and supply chain processes. Despite the valuable insights these authors offer, there has been no research on the specific advances that Industry 4.0 promises and how practitioners adopt them to our knowledge. Our work aims to address this gap in the literature by comparing research trends with the industrial adoption of MES/MOM.

3. Systematic literature review

We conducted a systematic literature review to identify the advances that Industry 4.0 concepts have brought to MES/MOM systems. According to [7], a systematic literature review (SLR) is a thorough, methodical, and repeatable technique used to identify, evaluate, and combine current research findings in a particular subject area. The SLR concentrates on a specific research field, for which the reviewers must evaluate the current research before beginning. The literature review is a secondary analysis of previously published research contributions. The SLR follows a six-phase methodological approach based on [7], which includes: (1) establishing a research hypothesis, (2) identifying relevant databases, (3) determining appropriate search terms for each database, (4) defining screening criteria for search results, (5) performing and documenting the literature review by reviewers, and (6) synthesizing the SLR results.

Table 1: Search Strategy

Search Fields	Main Terms	Context Terms
Title	Manufacturing Execution System	Design
Abstract Keywords	Manufacturing Operations Management	Architecture

The hypothesis that guided our literature review is that there are topics and topics enabled by Industry 4.0 - as envisioned by the previously mentioned work in section 2 - and that they have been implemented in the design and architecture of MES/MOM. Due to the computer-science nature of the hypothesis, we chose the most relevant databases in this field. In contrast to [6], who specifically excluded papers focusing on MES/MOM design and architecture, we were especially interested in these papers as they relate to our hypothesis and thus used them as shown in table 1.

The screening process, including all filtering at each stage, is visualized in figure 1. We filtered out any work that only refers to the general Industry 4.0 work in which MES/MOM was only a part of a broader Industry 4.0 architecture concept. We also excluded all work in which MES/MOM was only seen as an enabler for a specific function (e.g., MES enabling predictive maintenance) that was described in further detail in the paper. For the remaining papers, we identified the key research topic.

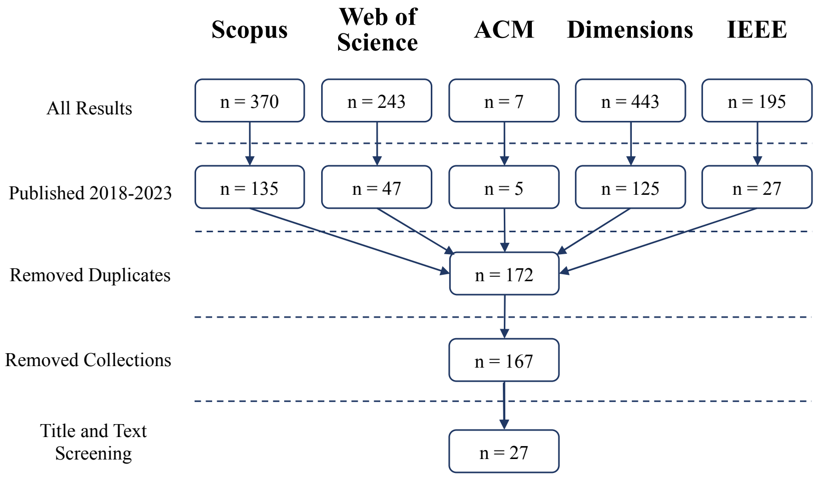

Fig. 1 Number of papers at each stage of the screening process

The result of this process can be found in table 2. Not all papers had a guiding topic identifiable for the MES/MOM design and/or architecture. In total, four topics were identified. The topic "collaboration" could only be identified in one of the papers and thus was not further considered for the study, as it can be argued that this topic has not yet gained momentum in the research community and thus is unlikely to be relevant in the practitioner's community.

The transfer of the remaining three topics in the practitioner's community, "Use of Standards", "Cloud Technology", and "Collaboration" were investigated in an industry survey.

Table 2: Topics identified in the review

Topic	Description	Paper
Use of Standards	Use of Standards, specifically for ISA95/IEC62264 for designing the functionality of the MES/MOM solution.	[8], [9], [10], [11]
Distributed Architecture	Design of the MES/MOM solution as non-monolithic system. This can be either app-based, microservices or agents.	[8], [9], [10], [12], [13], [14], [15]. [16], [11], [17]
Cloud technology	MES/MOM solution hosted in the cloud as in contrast to systems that are hosted on premise, enabling SaaS payment.	[18], [19], [9], [20], [16], [17], [21]
Collaboration	Support of "order-design-production-delivery" value chain in personalized products	[18]

4. Industry survey

For conducting the industry survey, we formulated a hypothesis for each identified topic. We formulated accordingly associated questions that aimed at testing these questions more specifically, as shown in table 3. As with every survey design, there is a trade-off between the richness of the information that can be gained from the questions and the time required from the responders to complete the questionnaire. As we included these questions in a larger survey (with over 19 questions in total), we prioritized simplicity for the responder over information richness. For this reason, we do not base our questions on Likert-type scales. Instead, we use ordinal scales to identify the standard relevance (H1) level and modularity of an MES/MOM solution (H2) across different time horizons.

Regarding the operation mode of MOM solutions (H3), we use a categorical scale (public cloud vs. hybrid cloud/edge) across the same time horizons we use for H2. For H1, we consider the MES/MOM standards VDI5600, IEC 62264, NAMUR, and MESA, which have been mentioned in the relevant literature of our systematic review. We measure the relevance levels on a scale from standard unknown, over standard irrelevant, planned to use the standard to standard already in use. In order to ensure a common understanding of the granularity measure of the MES/MOM solution, we worked with pictograms in the questionnaire showing a monolithic package at the one end, over a smaller monolithic package supplemented by smaller independent services, to only independent software services.

As we want to study how the industry adopts the topics identified in our literature review, we use three time horizons for H2 and H3: today, the future up to three years, and the future between three and five years. We did not use this time frame for H1 as the time horizon is included in the scale, and we wanted to limit the extent of the questions in the overall questionnaire. The questionnaire was distributed among manufacturing organization contacts from our research institute in Germany, Austria, and Switzerland. We also advertised at the institute's LinkedIn presence. The survey was open from the 31st of October to the 21st of December 2022. In total, 100 participants answered the questionnaire.

Table 3: Hypotheses and survey questions

#	Hypothesis	Survey Questions	Response Options
H1	Standards MES/MOM have no relevance in practice.	Q1: Do you consider one of the following standards your MES/MOM solution? Q1a: IEC62264 Q1b: VDI5600 Q1c: MESA Q1d: NAMUR	R1: Use of the standard R2: Planned use of the standard R3: Standard not relevant R4: Standard unknown
H2	Monolithic architectures are still prevalent for MES/MOM systems.	Q2: Which of the following architecture is the best representation of your MES/MOM in the following time frame? Q2a: Today Q2b: 3 years in the future Q2c: 3 to 5 years in the future	R1: Monolith R2: Monolith supplemented with services/applications R3: Independent Single services/applications R4: No solution
H3	Manufacturing organizations are reluctant to use cloud only technology for	Q3: How shall your MES/MOM solution be operated in the following time frame? Q3a: Today	R1: Public Cloud (national) R2: Public Cloud (international) R3: Edge supplemented with Public Cloud (national)

their MES/MOM solution.		Q3b: 3 years in the future Q3c: 3 to 5 years in the future	R4: Edge supplemented with Public Cloud (international)

5. Analysis and results

We performed statistical tests on the survey responses to address the hypotheses above. Each question required specific statistical tests according to the scale and variable structure. For each test, we used α=5% ($p<0.05$) level to reject the null hypothesis.

5.1 H1 – Standard relevance

For H1, we could reject the null hypothesis that the responses for the various standards have the same distributions. We then conducted pairwise comparisons between the responses for the different standards. In these tests, we could only identify that there are differences between VDI5600 and NAMUR, and VDI5600 and MESA standards, as indicated in table 4. To assess how relevant the standards are, we first conducted a chi-square test to ensure that there are statistically significant differences between each response level. We then analysed the frequency distribution table (see table 7 in the appendix). Except for the VDI5600, over 50% of the survey participants did not know each standard. Looking at the actual usage of the standard, the VDI5600 is also leading the frequency count with 17 mentions, followed by the IEC 62264 with 16. However, considering the planned standard usage, the VDI5600 is again greater than IEC 62264, with 13 over six mentions. As a consequence of the statistical tests and the response frequencies, we conclude that MES/MOM standards play a role for practitioners, and thus, we reject H1.

Table 4: H1 Statistical tests and results

Test	Variables	Test statistic	P-value	H_0 Decision
Kruskal-Wallis H test	All H1 variables	12.48	0.0059	Reject
Mann-Whitney U test	IEC 62264 vs VDI 5600	1789.5	0.1860	Accept
	IEC 62264 vs NAMUR	2373.0	0.0786	Accept
	IEC 62264 vs MESA	2214.5	0.3729	Accept
	VDI5600 vs NAMUR	2724.5	0.0005	Reject
	VDI5600 vs MESA	2510.5	0.0172	Reject
	NAMUR vs MESA	1883.5	0.3660	Accept
Chi-square test	VDI5600	10.875	0.0124	Reject
	IEC 62264	37.625	<0.00001	Reject
	NAMUR	58.875	<0.00001	Reject
	MESA	44.375	<0.00001	Reject

5.2 H2 – Prevalence of monolithic architectures

To investigate the development of the adoption of distributed architectures, we first tested the equality of distributions across all time horizons. This null hypothesis could be rejected, indicating a development from now on till five years in the future is taking place. We then conducted a pairwise comparison using the Wilcoxon test to identify which time horizons differ in their distributions. This was the case for all comparisons, indicating that development occurs between each time horizon under consideration. To analyse further which development is taking place, we first tested that there is no equal distribution of the granularity levels (see table 5). We then analysed the frequency table (see appendix table 8). This response shows that today, almost 25% of the responders operate or offer MES/MOM solutions that are monolithic. However, almost 60% of a core monolithic solution is supplemented with individual services. Already within three years in the future, the number of monolithic-only solutions will drop to just under 10%, whereas solutions fully composed of individual software services rise to just under 19%. This trend continues in the further distant future to only 3% of monolithic-only solutions and over 60% of solutions composed of individual software services. We conclude that currently, monolithic architectures are still prevalent to some extent, but there is a noteworthy development towards distributed architectures in the near future.

Table 5: H2 statistical tests and results

Test	Variables	Test statistic	P-value	H_0 Decision
Friedman Test	All time horizons	52.26	<0.00001	Reject
Wilcoxon Test	Today vs <3 years future	42.0	<0.00001	Reject
	Today vs. 3-5 years future	39	<0.00001	Reject
	<3 years future vs. 3-5 years future	0.0	<0.00001	Reject
Chi-square test	Today	19.91	<0.00001	Reject
	3 years future	29.45	<0.00001	Reject
	3-5 years future	34.64	<0.00001	Reject

5.3 H3 –Use of cloud-only technology

For analyzing the industry's stance towards cloud-only technology, we followed a procedure similar to H2 but with tests adjusted to the categorical scale type. The null hypothesis that the three distributions differ statistically could not be rejected. This was also the case for the pairwise comparisons (see table 6). This can be easily confirmed by the frequency tables (see appendix table 8), which show hardly any difference for the three time horizons. Around 80% of the responders do not want to operate the MES/MOM solution through cloud technology only across all time horizons. In consequence, it also confirms the statistical difference between the two levels. In conclusion, the industry widely rejects cloud-only MES/MOM solutions across all time horizons under consideration.

Table 6: H3 statistical test results

Test	Variables	Test statistic	P-value	H_0 Decision
Cochran’s Q Test	All time horizons	0.100	0.951	Accept
McNemar's test	Today vs <3 years future	0.011	1.000[1]	Accept
	Today vs. 3-5 years future	0.011	1.000[1]	Accept
	<3 years future vs. 3-5 years future	0.0	1.000[1]	Accept
Chi-square test	Today	64.58	<0.00001	Reject
	3 years future	73.34	<0.00001	Reject
	3-5 years future	81.50	<0.00001	Reject

[1] P-value adjusted for multiple test according to Bonferroni method.

6. Limitations

It is important to acknowledge the limitations of our study. Firstly, the sample size of our survey is too small to conclude for the general population. While our sample size was sufficient for our analysis, a larger sample size would allow for a more comprehensive analysis and generalizability of our findings. Additionally, as we recruited survey participants through the contacts of our research institute, there may be a bias introduced in our results. Companies cooperating with research institutes may be more inclined to adopt new technologies, which could impact our findings. Another limitation of our study is that the researchers may bias the construction of the hypotheses. We involved three MES/MOM systems experts to help us construct the hypotheses to mitigate this bias. While this approach may not eliminate bias entirely, it has minimized the impact of our own biases on the hypotheses. Despite these limitations, our study provides valuable insights into the current state of MES/MOM systems and their adoption by industry practitioners.

7. Conclusion

In the paper, we aim to clarify the gap between research trends and industrial adoption of MES/MOM design and architecture. We first identify the trends systematically. In the research community, distributed system architectures, cloud technology, and the use of standards for designing and building MES/MOM systems can be identified. To clarify the adoption of these trends by the industry, we conducted a survey among industry practitioners from manufacturing-related organizations in Germany, Austria, and Switzerland. The statistical testing of these results shows that at least the VDI5600 standard is relevant in practice. Although there is still a considerable share of monolithic MES/MOM systems today, the analysis shows that practitioners anticipate a noteworthy shift to more distributed architectures in the near future. However, regardless of the time frame, practitioners are reluctant towards cloud-only technology.

Our results are relevant for practitioners and researchers. For practitioners, it provides information on which standards to consider when implementing MES/MOM solutions and which architecture style to use. This can be valuable to both solutions providers and users regarding their MES/MOM strategy.

This poses further interesting questions for the research community about the reluctance to use cloud-only technology. Furthermore, anticipating more non-monolithic MES/MOM solutions will require new concepts for testing, integrating, and operating. The research community needs to go beyond showing the feasibility of these solutions to the efficient and practical use of such distributed solutions in alignment with industrial requirements.

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Appendix

The following tables show the response frequencies for the survey questionnaire related to H1, H2, and H3.

Table 7: H1 frequency table

IEC 62264	VDI 5600	NAMUR	MESA
R1: 16	R1: 17	R1: 5	R1: 10
R2: 7	R2: 13	R2: 2	R2: 7
R3: 5	R3: 8	R3: 16	R3:8
R4: 36	R4: 26	R4: 41	R4: 39
Missing: 36	Missing: 36	Missing: 36	Missing: 36

Table 8: H2 frequency table

Today	< 3 years in the future	3 to 5 years in the future
R1: 15	R1: 4	R1: 2
R2: 39	R2: 40	R2: 23
R3: 12	R3: 22	R3: 41
Missing: 34	Missing: 34	Missing: 34

Table 9: H3 frequency table

Today	< 3 years in the future	3 to 5 years in the future
R1 + R2: 18	R1 + R2: 19	R1 + R2: 18
R3 + R4: 71	R3 + R4: 70	R3 + R4: 71
Missing: 11	Missing: 11	Missing: 11

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Biography

Michael Oberle (*1984) is a computer scientist working in the field of smart manufacturing. He obtained his Master’s degree from the University of Auckland, New Zealand, in 2012 and joined the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), Germany, working as a researcher in the Competence Center for digital tools in manufacturing. Initially focusing on manufacturing control in the semiconductor industry, he began leading projects with a focus on the digitalization of battery manufacturing since 2014. One of his main achievements is the fully connected cloud-controlled battery manufacturing pilot line at the Fraunhofer IPA center for battery cell manufacturing. Today, he leads the group for Data and Application Services for Digital Production, focusing on data-driven and event-driven production control services.

Daniel Schel (*1986) is group manager of the team "IT Architectures for Digital Production" in the department "DigITools for Manufacturing" at Fraunhofer IPA. He is active in the field of IT-based manufacturing systems, including the topics Dynamic Manufacturing Networks, Cloud-based Manufacturing, Industrie 4.0 and Smart Production using cyber-physical systems. He holds a bachelor's degree in software engineering and has managed and conducted a number of research projects as technical director and software architect, focusing on novel approaches to IT solutions in production.

Monika Risling (*1997) is a research associate at the Fraunhofer Institute for Manufacturing Engineering and Automation IPA since 2021 where she is working in the department competence centre for Digital Tools in Manufacturing and in the field of smart manufacturing. She studied Industrial Engineering with focus on Digital Production Management and Computer Science.

Thomas Bauernhansl (*1969) has been Director of the Fraunhofer Institute for Manufacturing Engineering and Automation IPA in Stuttgart, Germany since September 2011. He is also Director of the University of Stuttgart’s Institute of Industrial Manufacturing and Management (IFF). His scientific focus is on production organization, factory planning, energy-efficient production, surface engineering, automation and process engineering, and digital and biological transformation. Bauernhansl studied mechanical engineering at RWTH Aachen University. After completing his Ph.D. with honors in 2002, he embarked on his career with Freudenberg in 2003, advancing to become Director of the Technology Center at Freudenberg Sealing Technologies. Bauernhansl was responsible for the regions Europe, North and South America, optimizing the “global footprint” of the production network made up of over 50 production sites.