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A SYSML-BASED MODEL-BASED SYSTEMS ENGINEERING APPROACH FOR MANUFACTURING AUTOMATION SOFTWARE DEVELOPMENT: A SYSTEMATIC LITERATURE REVIEW

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Abstract

Model-Based Systems Engineering (MBSE) has become an important approach for managing the complexity of software-intensive manufacturing automation systems. This study aims to examine the role of Systems Modeling Language (SysML) as a model-based framework for supporting the design, integration, validation, and lifecycle management of manufacturing automation software. The study applies a Systematic Literature Review (SLR) supported by bibliometric analysis to identify research trends, benefits, challenges, and future directions related to SysML-based MBSE in industrial automation environments. The findings show that SysML-based MBSE improves requirements traceability, supports modular system architecture, enhances communication among multidisciplinary engineering teams, and strengthens verification and validation processes. The review also indicates that SysML-based MBSE is increasingly connected with Industry 4.0 technologies, including Digital Twins, Cyber-Physical Systems, and industrial automation platforms. However, implementation challenges remain, particularly regarding toolchain integration, interoperability, model complexity, and the need for skilled human resources. This study contributes by synthesizing recent developments in SysML-based MBSE and highlighting its potential to support reliable, scalable, and maintainable manufacturing automation software systems.

Keywords: *Model-Based Systems Engineering (MBSE), Systems Modeling Language (SysML), manufacturing automation, industrial software, Industry 4.0.*

Introduction

Although previous studies have discussed MBSE, SysML, interoperability, Cyber-Physical Systems, and Digital Twin technologies, the integration of SysML-based MBSE with manufacturing automation software development remains insufficiently addressed. Most existing studies focus on conceptual modeling, system architecture representation, or general systems engineering practices, while limited attention has been given to how SysML models can support automation software workflows, including requirements traceability, control logic design, PLC/SCADA integration, verification, validation, and lifecycle management. This gap is important because manufacturing automation software requires strong alignment between software, hardware, sensors, actuators, control systems, and industrial communication platforms. Therefore, the novelty of this study lies in synthesizing recent literature on SysML-based MBSE specifically for manufacturing automation software and identifying its role in improving integration, interoperability, validation, and Industry 4.0 implementation (Wilking et al., 2024).

Recent studies have emphasized the growing importance of interoperability and standardization in complex engineering systems. Effective interoperability should extend beyond modeling languages and engineering tools to include organizational processes, data exchange mechanisms, and lifecycle integration strategies. Such an approach enables improved collaboration, scalability, innovation, and reliability across multidisciplinary engineering environments. These findings reinforce the importance of integrating SysML-based MBSE with industrial communication standards and digital engineering ecosystems (Fonseca et al., 2026; Khandoker et al., 2026). Furthermore, the increasing adoption of Cyber-Physical Systems (CPS) in industrial environments has created new challenges for system modeling and integration. Ontology-enhanced SysML frameworks have been proposed to improve semantic consistency, interoperability, and knowledge representation within complex CPS architectures. By incorporating domain-specific ontologies into SysML models, these approaches facilitate intelligent system integration and support more adaptive and resilient industrial systems. Nevertheless, practical implementation remains challenging due to tool limitations, integration complexity, and the need for specialized expertise (Bakirtzis et al., 2022; Schumacher et al., 2025).

A comprehensive review of MBSE methodologies indicates that MBSE should not be regarded as a single fixed methodology, but rather as a collection of model-centric approaches tailored to specific industrial domains and engineering objectives. As an evolution of traditional document-based systems engineering, MBSE offers substantial benefits in managing complexity, improving traceability, and supporting system validation. However, successful implementation requires organizational readiness, workforce training, methodological adaptation, and effective toolchain integration. Therefore, gradual and context-driven adoption strategies are needed to support effective MBSE implementation in industrial environments (Wilking et al., 2024; Schumacher et al., 2025; Zhang et al., 2025). In addition, recent research on Model-Based Engineering (MBE) and SysML applications in embedded and industrial systems demonstrates that SysML effectively bridges software and hardware engineering activities while improving consistency, communication, and requirements traceability throughout the development lifecycle. Despite the growing body of literature, relatively few studies have specifically investigated the application of SysML-based MBSE in manufacturing automation software development integrated with OPC UA, Digital Twin technologies, and Industry 4.0 infrastructures. Therefore, this study aims to examine the role of SysML-based MBSE in supporting the design, integration, validation, and lifecycle management of manufacturing automation systems while identifying the associated benefits, implementation challenges, and future research opportunities for next-generation industrial software engineering (Schumacher et al., 2025; Zhang et al., 2025).

Methodology

This study uses a Systematic Literature Review (SLR) supported by bibliometric analysis to examine the application of SysML-based MBSE in manufacturing automation software development. The SLR approach was used to identify, select, and synthesize relevant studies, while bibliometric analysis was applied to map publication trends, research themes, and emerging topics in the field.

Formulation of Research Questions

Model-Based Systems Engineering (MBSE) is a system development approach that places models, rather than documents, at the center of the engineering process. Systems Modeling Language (SysML) is used to represent complex systems involving hardware, software, human actors, and information components. In this study, the research questions are formulated to guide the SLR and bibliometric analysis by focusing on research trends, reported benefits and challenges, integration with Industry 4.0 technologies, and future research directions. Therefore, the RQs are designed to be answered through literature synthesis and bibliometric mapping, without implying direct empirical testing or industrial case-study experimentation.

RQ1: What are the main research trends in SysML-based MBSE for manufacturing automation software development based on the reviewed literature?

RQ2: What benefits and challenges of SysML-based MBSE implementation in manufacturing automation are reported in previous studies?

RQ3: How have SysML-based MBSE approaches been integrated with Industry 4.0 technologies, such as Digital Twins, Cyber-Physical Systems, and industrial automation platforms?

RQ4: What research gaps and future directions can be identified from the SLR and bibliometric analysis?

Developing the Research Approach

To address the research questions (RQ1-RQ4), this study adopts a Systematic Literature Review (SLR) supported by bibliometric analysis. The SLR approach is used to identify, select, evaluate, and synthesize relevant studies on SysML-based MBSE in manufacturing automation software development. Bibliometric analysis is applied to map publication trends, dominant research themes, and emerging topics related to MBSE, SysML, Industry 4.0, Digital Twins, and Cyber-Physical Systems.

This methodological approach is appropriate because the study does not conduct empirical testing, prototype implementation, or industrial case-study experimentation. Instead, the analysis focuses on reviewing and synthesizing existing literature to identify reported benefits, challenges, research gaps, and future directions. The selected studies were categorized according to research themes, application domains, methodological approaches, and reported contributions.

Search Strategy and Selection Criteria

To establish a robust theoretical foundation and strengthen the methodological framework of this study, a systematic literature search and selection process was conducted. The review procedure followed established systematic review principles commonly applied in software engineering, systems engineering, and industrial automation research. The objective was to identify, evaluate, and synthesize relevant studies addressing the application of Model-Based Systems Engineering (MBSE), Systems Modeling Language (SysML), and their integration within manufacturing automation environments (Schumacher et al., 2025).

The literature search was performed across several major scientific databases, including IEEE Xplore, ACM Digital Library, SpringerLink, and Scopus. A combination of keywords related to Model-Based Systems Engineering, SysML, manufacturing automation, industrial software engineering, Digital Twin, and Cyber-Physical Systems was employed to retrieve relevant publications. Following the initial search phase, a multi-stage screening process was conducted. First, duplicate records identified across multiple databases were removed. Subsequently, title and abstract screening was performed to eliminate studies that were not directly related to systems engineering, manufacturing automation, software engineering practices, or industrial applications. The remaining articles were then assessed using predefined inclusion and exclusion criteria (Fonseca et al., 2026).

The inclusion criteria were as follows: (1) publications published between 2020 and 2025; (2) studies focusing on MBSE, SysML, software engineering, manufacturing automation, industrial automation, or related Industry 4.0 technologies; (3) peer-reviewed journal articles, conference papers, and recognized technical reports; (4) full-text articles available in English; and (5) studies providing empirical evidence, conceptual frameworks, case studies, or methodological contributions relevant to the research objectives.

After applying the inclusion and exclusion criteria, the number of studies was systematically reduced. A total of 98 publications satisfied the eligibility requirements and were subjected to detailed full-text analysis. Subsequently, thematic synthesis and quality assessment were conducted, resulting in 67 studies being selected for the final review. These publications served as the primary sources for the in-depth analysis and discussion presented in this study (Paul et al., 2021).

The overall selection procedure followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, reproducibility, and methodological rigor throughout the review process. The literature selection process was conducted in four stages: identification, screening, eligibility assessment, and final inclusion. A total of 290 articles were initially identified from ACM Digital Library, IEEE Xplore, SpringerLink, and Scopus. After removing 140 duplicate records, 150 articles were screened based on titles and abstracts. From this stage, 98 full-text articles met the eligibility requirements, and 67 studies were finally included in the review (Aliyah1 et al., 2026).

Table 1. PRISMA-Based Literature Selection Process

PRISMA Stage	Search Activity	Output
Identification	Literature search across ACM Digital Library, IEEE Xplore, SpringerLink, and Scopus	290 articles identified
Duplicate removal	Duplicate records removed from the initial dataset	140 records removed
Screening	Title and abstract screening	150 articles screened
Eligibility	Full-text review based on inclusion and exclusion criteria	98 articles eligible
Included	Final studies selected for thematic synthesis and bibliometric analysis	67 studies included

During the identification stage, a comprehensive literature search was conducted using predefined keywords across four major scientific databases: ACM Digital Library, IEEE Xplore, SpringerLink, and Scopus. The search produced 290 potentially relevant publications, consisting of 57 articles from ACM Digital Library, 102 articles from IEEE Xplore, 37 articles from SpringerLink, and 94 articles from Scopus. After duplicate removal, 150 articles were retained for title and abstract screening. Then, 98 articles were assessed through full-text eligibility review, and 67 studies were finally selected for detailed thematic synthesis and bibliometric analysis (Fonseca et al., 2026).

Data Extraction and Analysis

The data extraction and analysis process constituted a critical stage of the Systematic Literature Review (SLR). Initially, 290 articles were identified from the selected databases. After removing 140 duplicate records, 150 articles were screened based on titles and abstracts. From this stage, 98 articles were retained for full-text eligibility assessment, and 67 studies were finally included in the review.

Each selected study was examined based on its research focus, methodology, application domain, reported benefits, implementation challenges, and relevance to SysML-based MBSE in manufacturing automation software development.

The extracted data were synthesized thematically to identify dominant research themes, technological developments, implementation challenges, and research gaps. The bibliometric analysis complemented the thematic synthesis by mapping database sources, keyword co-occurrence patterns, and emerging topics related to SysML, MBSE, manufacturing automation, Digital Twin, CPS, interoperability, and validation.

Results and Discussion

The descriptive analysis conducted in this study provides an overview of scientific publications addressing SysML-based Model-Based Systems Engineering (MBSE) in manufacturing automation software development. Based on the SLR covering publications from 2020 to 2025, the reviewed literature indicates increasing attention to model-based engineering approaches in industrial automation, smart manufacturing, Digital Twin, and Cyber-Physical Systems (CPS). The reviewed studies show that SysML is commonly used to model requirements, software architectures, component interactions, and system behavior, while supporting traceability throughout the system development lifecycle (Wilking et al., 2024; Schumacher et al., 2025).

The analysis also revealed that several SysML diagram types were consistently discussed across the selected studies. Requirements Diagrams, Block Definition Diagrams (BDD), Internal Block Diagrams (IBD), Activity Diagrams, and State Machine Diagrams were frequently associated with requirements modeling, architectural representation, behavioral specification, and system validation. The reviewed literature also indicates that model-based approaches may improve system transparency, multidisciplinary communication, design consistency, and verification and validation activities in manufacturing automation projects (Zhang et al., 2025).

To further investigate research trends and identify potential research gaps, bibliometric data were collected using the Publish or Perish software. The resulting publication dataset was analyzed to identify dominant research themes, methodological approaches, and emerging topics within the field. The graphical visualization presented below illustrates the distribution of publications and research directions extracted from the bibliometric analysis. This analysis serves as a foundation for identifying existing knowledge gaps and establishing the novelty of the proposed study within the context of SysML-based Model-Based Computer Engineering for manufacturing automation software development (Ali Abaker Omer & Dong, 2025).

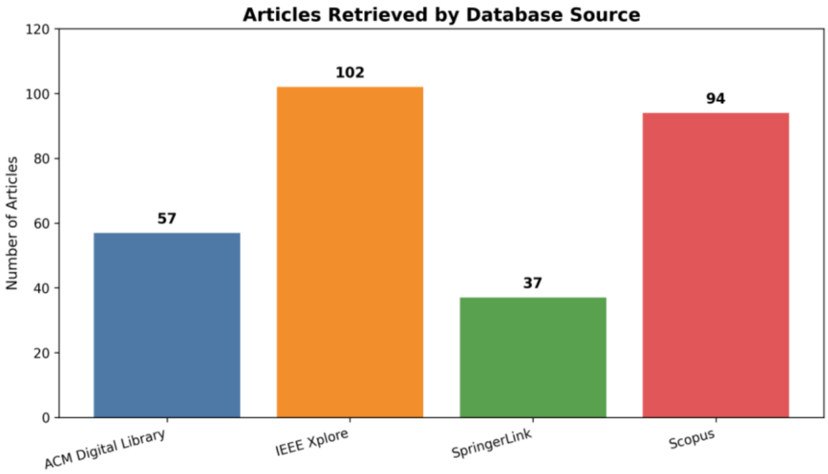

Figure 1. Articles Retrieved by Database Source

Figure 1 shows the number of articles retrieved from each database source. The literature search identified 290 articles in total, consisting of 57 articles from ACM Digital Library, 102 articles from IEEE Xplore, 37 articles from SpringerLink, and 94 articles from Scopus. IEEE Xplore contributed the highest number of articles, while SpringerLink contributed the lowest number.

The bibliometric analysis was conducted to identify research trends, thematic relationships, and emerging topics related to SysML-based Model-Based Systems Engineering (MBSE) and its applications in manufacturing automation software development. The VOSviewer visualization in Figure 2 presents the keyword co-occurrence network generated from the selected literature dataset.

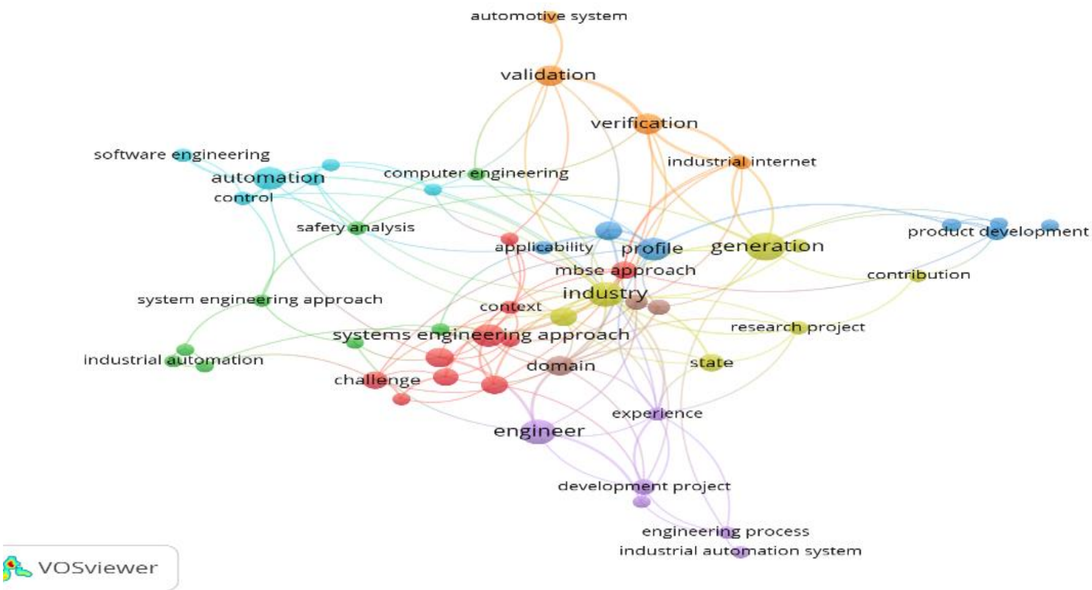

Figure 2. VOSviewer Keyword Co-occurrence Network of SysML-Based MBSE Studies

Figure 2 presents a VOSviewer keyword co-occurrence network generated from the bibliometric dataset. The visualization shows thematic relationships among keywords related to SysML-based MBSE and manufacturing automation software development. The red cluster represents core modeling and systems engineering concepts, including modeling approach, requirements, and system engineering. The green and blue clusters indicate software engineering, architecture, and automation system integration topics. The yellow cluster highlights verification, validation, and high-level modeling activities, while the purple cluster reflects engineering process and industrial automation implementation themes. Overall, the network indicates that research on SysML-based MBSE is strongly connected with requirements modeling, software engineering, validation, and industrial automation system development.

The visualization results reveal several dominant thematic clusters within the literature. The first cluster is related to SysML and MBSE concepts, including system modeling, requirements traceability, and model-based engineering. The second cluster focuses on manufacturing automation software, including control systems, PLC-based automation, industrial software, and system architecture. The third cluster is associated with Digital Twin and Cyber-Physical Systems (CPS), indicating the growing integration between virtual models and physical manufacturing systems. The fourth cluster highlights interoperability and standardization, including data exchange, toolchain integration, and industrial communication frameworks. The fifth cluster emphasizes verification, validation, and lifecycle management as important aspects for ensuring system reliability and consistency. Overall, the cluster analysis shows that SysML-based MBSE research is strongly connected with automation software development, industrial system integration, and Industry 4.0 technologies (Wilking et al., 2024).

Model-Based Systems Engineering (MBSE) has emerged as a model-centric engineering paradigm that uses models as the main artifacts throughout the system development lifecycle. SysML is widely used within MBSE because it provides a standardized framework for representing system requirements, structures, behaviors, and interfaces through visual and structured models. Based on the reviewed literature, SysML-based MBSE has been increasingly discussed in industrial systems, especially manufacturing automation, smart manufacturing, Digital Twin, and CPS contexts.

The reviewed literature indicates that SysML-based MBSE contributes to requirements traceability, system architecture modeling, verification, validation, interoperability, and lifecycle management. These capabilities are important because manufacturing automation systems require coordination among software, hardware, sensors, actuators, control systems, PLC/SCADA platforms, and industrial communication frameworks (Schumacher et al., 2025; Zhang et al., 2025).

However, the literature also shows that practical integration remains challenging. Several studies report barriers related to toolchain integration, model complexity, interoperability, organizational readiness, and the need for skilled MBSE practitioners. Therefore, further synthesis is needed to clarify how SysML-based MBSE can support manufacturing automation software workflows in Industry 4.0 environments (Wilking et al., 2024; Khandoker et al., 2026).

Theoretical Studies and Research Gaps

Model-Based Systems Engineering (MBSE) is a systems engineering approach that employs models as primary artifacts from requirements definition to verification and validation. In manufacturing automation software engineering, MBSE supports the integration of software, hardware, control systems, sensors, actuators, and industrial processes within a structured framework. SysML is particularly relevant because it provides diagram-based representations for system requirements, behavior, structure, interfaces, and relationships among system components.

Although previous studies have investigated SysML, MBSE, Digital Twin technologies, CPS, and interoperability, several research gaps remain. Most existing studies emphasize general system modeling and architecture representation, while limited attention has been given to the practical integration of SysML-based MBSE into manufacturing automation software workflows. In particular, further review is needed on how SysML models can support control logic design, industrial software platforms, toolchain integration, real-time implementation, and lifecycle validation.

These limitations highlight the need for a focused synthesis of SysML-based MBSE for manufacturing automation software development. This study therefore examines recent literature to identify the benefits, challenges, integration areas, and future directions of SysML-based MBSE in industrial automation and smart manufacturing environments.

Table 2. Verified Literature Summary of SysML-Based MBSE in Manufacturing Automation

Author(s) (Year)	Title	Publication Source	Relevant Contribution
Bataleblu (2023)	Model-Based Systems Engineering in Smart Manufacturing: Future Trends Toward Sustainability	Technical/academic publication	Discussed MBSE in smart manufacturing, emphasizing systems thinking, sustainability, and future manufacturing transformation.
Bakirtzis et al. (2022)	An Ontological Metamodel for Cyber-Physical System Safety, Security, and Resilience Coengineering	Software and Systems Modeling	Developed an ontology-based metamodel relevant to CPS safety, security, resilience, model consistency, and interoperability.
Wilking et al. (2024)	Utilization of System Models in Model-Based Systems Engineering	Design Science	Reviewed how system models are used in MBSE to support communication, documentation, model integration, and future research directions.
Schumacher et al. (2025)	SysML Process Chains in MBSE: Systematic	Digital Engineering	Reviewed SysML process chains and identified issues

	Literature Review and Future Research Directions		related to model transformation, simulation integration, and toolchain linkage.
Zhang et al. (2025)	MBSE 2.0: Toward More Integrated, Comprehensive, and Intelligent MBSE	Systems	Discussed future MBSE directions toward integrated, comprehensive, and intelligent modeling, simulation, verification, and validation.
Object Management Group (2025)	Systems Modeling Language (SysML) Version 2.0 Specification	OMG Specification	Established SysML 2.0 as a standard for modeling requirements, behavior, structure, analysis, verification, and interoperability.

The studies summarized in Table 2 indicate that SysML-based MBSE has been widely discussed in relation to system modeling, requirements traceability, CPS, interoperability, toolchain integration, and verification activities. These studies show that SysML can support the representation of system requirements, structures, behaviors, and interfaces in complex industrial systems. In manufacturing automation environments, this capability is important because software, hardware, sensors, actuators, control systems, and industrial communication platforms must be integrated consistently (Schumacher et al., 2025; Zhang et al., 2025).

However, the reviewed literature also shows that practical implementation challenges remain. These challenges include the integration of SysML models with industrial automation software platforms, toolchain limitations, model complexity, the need for skilled MBSE practitioners, and organizational resistance to model-centric engineering practices. Therefore, the research gap addressed in this study is the limited synthesis of how SysML-based MBSE can support manufacturing automation software development, particularly in relation to control logic design, interoperability, Digital Twin integration, CPS, verification, validation, and lifecycle management (Wilking et al., 2024; Khandoker et al., 2026).

Conclusion

The review indicates that SysML-based Model-Based Systems Engineering (MBSE) has the potential to support manufacturing automation software development through a systematic, structured, and collaborative modeling approach. Based on the reviewed literature, SysML-based MBSE may improve requirements traceability, consistency across engineering disciplines, system architecture representation, and verification and validation activities. These capabilities are relevant for modern manufacturing environments because automation systems increasingly require integration among software, hardware, control logic, Digital Twin technologies, Cyber-Physical Systems, and industrial communication platforms.

The findings should be interpreted cautiously because this study is based on a Systematic Literature Review and bibliometric analysis, without direct empirical testing or industrial case-study validation. Therefore, the results mainly reflect patterns, themes, and insights reported in previous studies. Future research should conduct empirical industrial case studies, prototype implementation, and quantitative evaluation in real manufacturing automation environments to validate the practical effectiveness of SysML-based MBSE.

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