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The Evolution of Distributed Systems: Architectural Developments, Technologies, and Modern Computing Challenges

Evolusi Sistem Terdistribusi: Perkembangan Arsitektur, Teknologi, dan Tantangan Komputasi Modern

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Abstract

This study examines the evolution of distributed systems by analyzing architectural changes, technological transitions, and emerging challenges in modern computing environments. The research applies a Systematic Literature Review (SLR) approach to ensure a structured and transparent review process. Literature was collected from two main academic databases, namely Scopus and Google Scholar, using keywords such as "distributed systems evolution", "cloud computing architecture", "service-oriented architecture", "microservices", and "cloud-native systems". The initial search identified 50 relevant publications published between 2015 and 2025. After applying inclusion and exclusion criteria based on relevance, publication year, and scientific credibility, 25 articles were selected for further analysis. The selected studies were synthesized using thematic analysis to identify recurring themes, development phases, and major challenges in distributed systems. The findings reveal that distributed systems have evolved from client–server models to service-oriented architecture (SOA), followed by cloud computing and cloud-native microservices. This transformation is mainly driven by the increasing need for scalability, flexibility, fault tolerance, and real-time processing. However, the transition toward highly modular and decentralized systems also introduces new challenges, particularly in system complexity, security, data consistency, and operational management.

Abstrak

Studi ini mengkaji evolusi sistem terdistribusi dengan menganalisis perubahan arsitektur, transisi teknologi, dan tantangan yang muncul dalam lingkungan komputasi modern. Penelitian ini menerapkan pendekatan Systematic Literature Review (SLR) untuk memastikan proses peninjauan yang terstruktur dan transparan. Literatur dikumpulkan dari dua database akademis utama, yaitu Scopus dan Google Scholar, dengan menggunakan kata kunci seperti "evolusi sistem terdistribusi", "arsitektur komputasi awan", "arsitektur berorientasi layanan", "layanan mikro", dan "sistem cloud-native". Pencarian awal mengidentifikasi 50 publikasi relevan yang diterbitkan antara tahun 2015 dan 2025. Setelah menerapkan kriteria inklusi dan eksklusi berdasarkan relevansi, tahun publikasi, dan kredibilitas ilmiah, dipilih 25 artikel untuk dianalisis lebih lanjut. Studi yang dipilih disintesis menggunakan analisis tematik untuk mengidentifikasi tema yang berulang, fase pengembangan, dan tantangan utama dalam sistem terdistribusi. Temuan mengungkapkan bahwa sistem terdistribusi telah berevolusi dari model klien-server ke arsitektur berorientasi layanan (SOA), diikuti oleh komputasi awan dan layanan mikro cloud-native. Transformasi ini terutama didorong oleh meningkatnya kebutuhan akan skalabilitas, fleksibilitas, toleransi kesalahan, dan pemrosesan real-time. Namun, transisi menuju sistem yang sangat modular dan terdesentralisasi juga menimbulkan tantangan baru, khususnya dalam kompleksitas sistem, keamanan, konsistensi data, dan manajemen operasional.

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1. Introduction

The rapid advancement of information technology has brought fundamental changes to computing paradigms, particularly in how systems are designed, implemented, and managed. In its early stages, computer systems were dominated by centralized computing models with limited resources and simple processing capabilities (M. V. A. N. Steen & Tanenbaum, n.d.). s the demand for performance, reliability, and efficiency increased, computing architectures shifted toward distributed systems, enabling parallel processing across multiple interconnected nodes via networks (Coulouris et al., 2005). This shift has been further accelerated by the development of high-speed networks, cloud computing, and service-based architectures (Kratzke & Quint, 2017).

Today, distributed systems serve as the foundation for various modern applications, including enterprise systems, cloud-based services, the Internet of Things (IoT), and large-scale real-time applications (Kratzke & Quint, 2017). The adoption of cloud-native architectures and microservices has further strengthened the role of distributed systems in supporting flexibility, scalability, and rapid organizational innovation (Newman, 2015). However, increased modularity and decentralization have also introduced new challenges, particularly related to inter-service communication complexity, dependency management, and system orchestration (Dragoni et al., 2017). Other increasingly critical challenges include security, fault tolerance, and data consistency across services in distributed environments (Erikasari et al., 2025). Previous studies have examined distributed systems from specific technical perspectives, such as resource management, fault tolerance, or performance optimization, while others have focused on the application of cloud computing and microservices in industrial and enterprise contexts. Nevertheless, there remains a lack of studies that systematically integrate historical perspectives, architectural evolution, and contemporary challenges of distributed systems into a comprehensive analytical framework. This gap highlights the need for a more integrative literature review to fully understand the dynamics of distributed system evolution.

Based on this background, this study aims to examine the evolution of distributed systems through an analysis of architectural developments, technological shifts, and key challenges in modern computing environments. The study adopts a Systematic Literature Review (SLR) approach, analyzing 25 selected sources published between 2015 and 2025, including both classical works and recent studies related to cloud computing, microservices, and modern distributed systems (Dragoni et al., 2017; Erikasari et al., 2025; Kratzke & Quint, 2017; Newman, 2015; M. V. A. N. Steen & Tanenbaum, n.d.). The analysis process employs thematic analysis to identify development patterns, evolutionary phases, and challenges emerging at each stage of architectural transformation. The findings are expected to provide a more structured conceptual framework and serve as a theoretical foundation for researchers and practitioners in designing adaptive, secure, and sustainable distributed systems.

Based on these objectives, this study formulates several research questions to guide the literature analysis process:
RQ1: How has the architecture of distributed systems evolved from early models to modern approaches such as cloud computing and microservices?
RQ2: What technologies support the development of modern distributed systems?
RQ3: What are the main challenges faced in implementing distributed systems in modern computing environments?

2. Literature Review

2.1 Fundamental Concepts of Distributed Systems

A distributed system is defined as a collection of computing devices interconnected through a network that work in a coordinated manner to accomplish a task, appearing to users as a single integrated system (M. V. A. N. Steen & Tanenbaum, n.d.). Each node in the system maintains control over its local resources while interacting with other nodes through predefined communication mechanisms and protocols. The main characteristics of distributed systems include system transparency, coordination among components, and efficient resource sharing. Transparency allows users to access services without needing to know the physical location of data or computational processes occurring across different nodes in the network (Coulouris et al., 2005). Meanwhile, coordination mechanisms ensure that nodes can communicate, synchronize processes, and handle data conflicts effectively. In modern computing, distributed systems serve as the foundation for various technological platforms such as cloud computing, large-scale data centers, and microservices-based application architectures. These environments require systems that not only deliver high performance but also handle failures, dynamic workloads, and device heterogeneity (M. V. A. N. Steen & Tanenbaum, n.d.).

2.2 Evolution of Distributed System Architectures

The evolution of distributed systems reflects significant architectural transformations over time. In the early stages, the client–server architecture was the most widely adopted model, separating service providers (servers) from service consumers (clients), thereby improving system management efficiency compared to centralized computing approaches (Ilham et al., 2025). owever, this architecture has limitations in scalability and resilience due to its reliance on a single central server, which may become a single point of failure. As the need for system integration and service flexibility increased, Service-Oriented Architecture (SOA) emerged, emphasizing modularity and service reusability. SOA enables applications to communicate through independent services, facilitating more flexible system integration. Nevertheless, several studies indicate that SOA implementation often faces challenges related to interoperability and service dependency management (Dragoni et al., 2017). The next transformation phase is marked by the emergence of cloud computing, which provides elastic and service-based computing resources such as Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). This approach enables organizations to manage infrastructure more efficiently while significantly improving system scalability (Lindsay et al., 2021).

2.3 Cloud Computing and Microservices

In the past decade, cloud-native architectures and microservices have become dominant paradigms in modern distributed system development. Microservices enable applications to be built as a collection of small, independent services that can be developed, tested, and deployed independently (Newman, 2015). Container technologies such as Docker, along with orchestration systems like Kubernetes, play a crucial role in supporting microservices architectures by enhancing portability and simplifying the management of distributed applications (Bernstein, 2014). This approach allows organizations to develop applications more flexibly and respond more rapidly to changing business requirements.

However, several studies highlight that an increasing number of microservices can lead to higher operational complexity. Common challenges include inter-service communication, system monitoring, and service dependency management (Celesti, 2016). Therefore, implementing microservices typically requires support from modern software engineering practices such as Continuous Integration/Continuous Delivery (CI/CD), observability, and effective configuration management (ADESAPUTRA, 2022).

2.4 Challenges in Modern Distributed Systems

Despite offering high flexibility and scalability, modern distributed systems face various complex technical challenges. One of the primary issues is system security, particularly as cloud and edge computing environments expand the attack surface of system infrastructures. Additionally, data consistency remains a critical challenge, especially in real-time applications and event-driven architectures. The CAP theorem states that distributed systems cannot simultaneously guarantee consistency, availability, and partition tolerance, requiring system designers to make trade-offs based on application requirements (M. Van Steen & Pierre, 2012). Other studies emphasize the importance of observability, monitoring, and fault tolerance mechanisms to ensure the stability of large-scale systems. Without these mechanisms, failures in a single service can propagate and impact the entire system (Mukwevho & Celik, 2018). Several previous studies have examined various aspects of distributed systems, ranging from fundamental concepts and architectural evolution to the implementation of modern technologies such as cloud computing and microservices. To provide a comparative overview of studies relevant to this research topic, selected prior works are summarized in Table 1.

Table 1. Comparison of Previous Studies

Authors	Research Focus	Approach	Key Findings
(Dragoni et al., 2017)	Evolution of microservices	Literature review	Microservices improve modularity but increase system complexity
(Kratzke & Quint, 2017)	Cloud-native applications	Systematic mapping study	Cloud-native enhances system scalability and flexibility
(Lindsay et al., 2021)	Evolution of distributed computing	Conceptual analysis	The evolution of distributed systems is driven by scalability requirements
(Ilham et al., 2025)	Enterprise distributed system architecture	Architectural design study	SOA improves interoperability but increases

			integration complexity
(Erikasari et al., 2025)	Blockchain and edge computing	Literature review	Integration of new technologies improves distributed system efficiency

Based on Table 1, most previous studies have focused on specific technical aspects of distributed systems, such as microservices implementation, cloud computing, or fault tolerance mechanisms. However, there is still limited research that comprehensively examines the evolution of distributed system architectures from a historical perspective to contemporary challenges. Therefore, this study aims to address this gap through a Systematic Literature Review approach combined with thematic analysis.

3. Research Metodology

This study employs a Systematic Literature Review (SLR) approach to systematically examine the development of distributed systems based on relevant scientific publications. The SLR method is chosen because it enables the processes of literature collection, evaluation, and synthesis to be conducted in a structured, transparent, and reproducible manner. Through this approach, the study aims to identify the evolution of distributed system architectures, the technologies supporting their implementation, and the challenges emerging in modern computing environments.

3.1 Research Design

This study adopts a descriptive-analytical design using a systematic literature review approach. It does not involve direct experimentation or system testing but focuses on analyzing scientific publications that discuss distributed systems from historical perspectives to modern technological developments. This approach allows the identification of architectural evolution patterns, technological paradigm shifts, and key issues in the development of distributed systems.

3.2 Research Questions

To provide clear direction in the literature review process, this study formulates several research questions (RQs) that guide the analysis. These questions are designed to identify the evolution of distributed system architectures, supporting technologies, and challenges in modern distributed system implementation. The research questions are as follows:

RQ1: How has the architecture of distributed systems evolved from early models to modern approaches such as cloud computing and microservices?

RQ2: What technologies support the development of modern distributed systems?

RQ3: What are the main challenges faced in implementing distributed systems in modern computing environments?

3.3 Data Collection Method

Data collection in this study was conducted through literature searches in two major academic databases: Scopus and Google Scholar. These databases were selected due to their extensive coverage of scientific publications and widespread use in information

technology and computer science research. The literature search process utilized several keywords relevant to the research topic, including *distributed systems evolution*, *distributed system architecture*, *cloud computing architecture*, *service-oriented architecture*, *microservices architecture*, and *cloud-native systems*. These keywords were used both individually and in combination to obtain articles discussing the evolution of distributed system architectures, supporting technologies, and challenges in modern computing implementations.

3.5 Population dan Sample

The population in this study consists of all scientific publications addressing distributed systems and the evolution of modern computing architectures. The literature search in Scopus and Google Scholar resulted in 50 articles relevant to the research keywords. A selection process was then conducted based on predefined inclusion and exclusion criteria. The inclusion criteria included scientific articles discussing distributed systems, cloud computing, or microservices, published between 2015 and 2025, and appearing in credible academic journals or conference proceedings. The exclusion criteria included non-peer-reviewed articles, studies not directly related to the evolution of distributed system architectures, and publications focusing solely on technical implementation without addressing architectural evolution. Based on this selection process, 25 articles met the criteria and were used as the research sample for further analysis.

3.6 Literature Selection Process

The literature selection process in this study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure a systematic and transparent selection procedure. In the identification stage, the database search yielded 50 relevant articles. The next stage, screening, involved filtering articles based on titles and abstracts to ensure alignment with the research focus, during which several articles were excluded due to lack of direct relevance to distributed system evolution. The eligibility stage involved a full-text evaluation of articles based on the predefined inclusion and exclusion criteria. After completing this process, 25 articles were deemed eligible and selected as the primary sources for analysis in this study. The literature selection process is illustrated in the PRISMA diagram in Figure 1.

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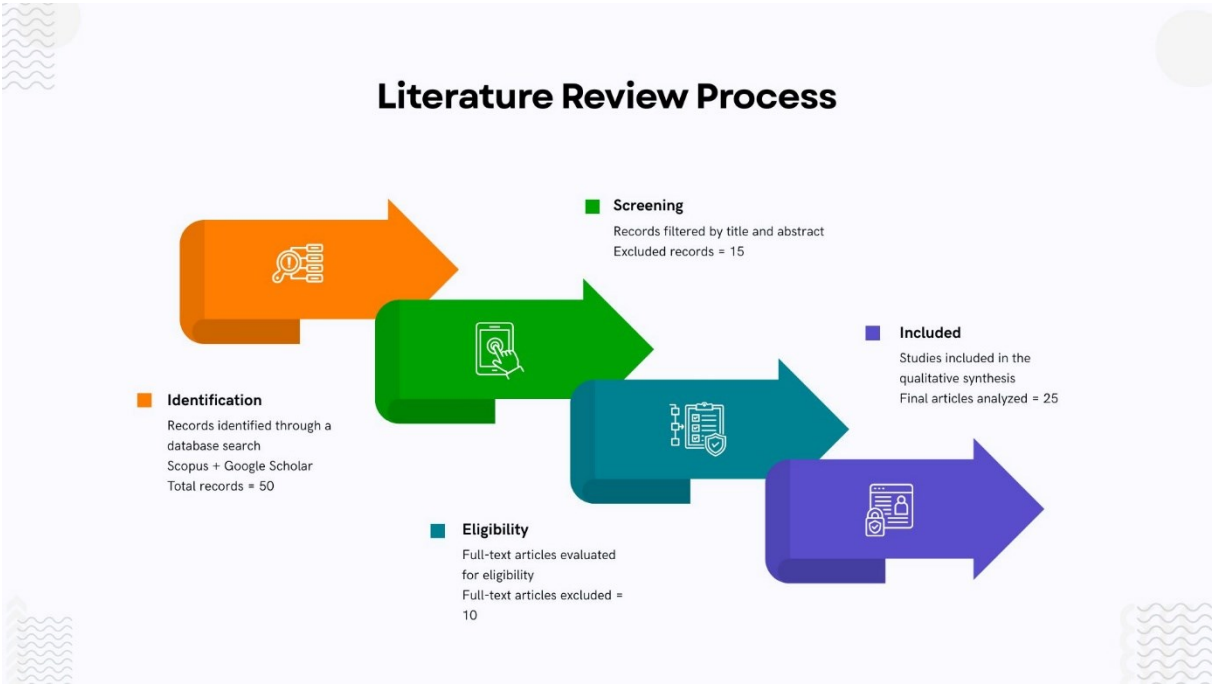

Figure 1. Literature Selection Process

3.6 Data Analysis Technique

Data analysis in this study employs a thematic analysis approach to identify key themes emerging from the literature on the evolution of distributed systems. This approach enables the researcher to synthesize findings from various studies to provide a more comprehensive understanding of the development of distributed system architectures. The analysis process involves examining each selected article to identify key concepts, research approaches, and findings relevant to the study topic. These concepts are then grouped based on similarities to form thematic categories representing different phases in the evolution of distributed systems. Through this synthesis process, the study identifies relationships among prior works and formulates a conceptual framework that explains the evolution of distributed system architectures from early models to cloud-native and microservices approaches in modern computing environments.

4. Results and Discussion

4.1 Profile of Analyzed Articles

Based on the literature selection process using the Systematic Literature Review (SLR) method, a total of 25 articles met the inclusion criteria and were included in this study. These articles were sourced from various scientific journals and conference proceedings discussing the development of distributed systems, cloud computing, and microservices architectures in modern computing environments. Most of the analyzed studies were published between 2015 and 2025, indicating a growing interest in distributed system architecture development alongside the advancement of cloud computing technologies and large-scale applications. The selected articles employ diverse research approaches, including conceptual studies, literature reviews, experimental studies, and system architecture analyses.

To provide an overview of the analyzed studies, Table 3 presents a summary of the articles included in this review.

Table 2. Summary of Analyzed Articles

Author	Year	Research Focus	Method
(ADESAPUTRA, 2022)	2022	CI/CD implementation in microservices	Implementation study
(Bernstein, 2014)	2014	Containerization and cloud infrastructure	Technical analysis
(Celesti, 2016)	2016	Microservices scheduling in the cloud	Conceptual study
(Coulouris et al., 2015)	2015	Fundamental concepts of distributed systems	Reference book
(Dragoni et al., 2017)	2017	Evolusi microservices	Literature review
(Erikasari et al., 2025)	2025	Blockchain and edge computing	Literature review
(Ilham et al., 2025)	2025	Enterprise distributed system architecture	Design study
(Kratzke & Quint, 2017)	2017	Cloud-native applications	Systematic mapping study
(Lindsay et al., 2021)	2021	Evolution of distributed computing	Conceptual analysis
(Mukwevho & Celik, 2018)	2018	Fault tolerance distributed systems	Experimental study
(Newman, 2015)	2015	Microservices architecture design	Technical framework
(M. V. A. N. Steen & Tanenbaum, 2017.)	2017	Distributed systems architecture	Reference book
(M. Van Steen & Pierre, 2012)	2012	Large scale distributed systems	Conceptual analysis
(Pahl, 2015)	2015	Containerization in cloud platforms	Conceptual study
(Zhang et al., 2015)	2015	Distributed cloud architecture	Survey study
(Dragoni et al., n.d.)	2018	Trends in microservices architecture	Conceptual study
(Villamizar et al., 2016)	2016	Comparison of microservices and monolithic architectures	Empirical study
(Pautasso & Leymann, 2026)	2026	RESTful services in distributed systems	Architectural analysis
(Balalaie et al., 2016)	2016	Migration to cloud-native architecture	Conceptual study
(J LewisM Fowler -	2015	Definition of microservices architecture	Survey study

MartinFowle, 2015)			
(Zhang et al., 2010)	2015	Cloud computing research challenges	Conceptual study
(Pahl, 2025)	2026	Architectural principles of cloud software	Case study

5. Conclusion

This study aims to examine the evolution of distributed systems through an analysis of architectural developments, supporting technologies, and emerging challenges in modern computing environments using a Systematic Literature Review (SLR) approach. Based on the literature selection process conducted on Scopus and Google Scholar databases, 25 scientific articles were identified and analyzed using a thematic analysis approach. The results indicate that distributed systems have undergone significant architectural evolution over time, beginning with the client–server model, progressing to Service-Oriented Architecture (SOA), then transitioning to cloud computing, and more recently evolving into cloud-native architectures based on microservices. This evolution has been driven by the need for more flexible, scalable systems capable of handling large-scale computational workloads. In addition to architectural advancements, this study also identifies several key technologies that support the implementation of modern distributed systems, including containerization, cloud platforms, and container orchestration systems such as Docker and Kubernetes. These technologies enable more efficient management of distributed applications and support modern software development practices such as DevOps and Continuous Integration/Continuous Delivery (CI/CD). However, the findings also reveal that modern distributed systems continue to face several challenges, including system complexity, security issues, and data consistency in distributed computing environments. These challenges require new approaches in system architecture design, including the implementation of fault tolerance mechanisms, system monitoring, and more adaptive system management practices. Overall, this study provides a comprehensive overview of the evolution of distributed systems and the factors influencing their development. The findings are expected to serve as a reference for researchers and practitioners in understanding the progression of distributed system architectures and in designing more adaptive, scalable, and sustainable computing solutions. For future research, further studies may conduct empirical or experimental analyses to evaluate the implementation of various distributed system architectures in real-world contexts, as well as explore the integration of emerging technologies such as edge computing, the Internet of Things (IoT), and artificial intelligence in the development of distributed systems.

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