

Digital Transformation in Engineering Education: A Systematic Review of University Operations

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Abstract

This review synthesizes research on "Digital Transformation in Engineering Education: A Systematic Review of University Operations" to address fragmented understanding of how digital technologies reshape institutional practices and curricula. The review aimed to taxonomize digital transformation frameworks, evaluate emerging technology integration, identify barriers, benchmark governance strategies, and assess transformation outcomes. A systematic analysis of peer-reviewed studies employing qualitative, quantitative, and bibliometric methods across diverse geographic contexts was conducted. Findings reveal that holistic, multi-dimensional frameworks integrating technological, pedagogical, and organizational elements predominate but lack empirical validation across varied institutions. AI, digital twins, and immersive technologies significantly enhance personalized learning and administrative efficiency, yet infrastructure deficits, ethical concerns, and faculty readiness impede adoption. Leadership and strategic governance emerge as critical enablers, though evidence on governance effectiveness and inclusivity remains limited. Outcome assessments indicate improvements in educational quality and stakeholder engagement, but standardized metrics and longitudinal evaluations are scarce. These findings converge to highlight the necessity for integrative, empirically grounded frameworks that address technological, organizational, and socio-cultural dimensions comprehensively. The review underscores implications for developing sustainable, inclusive digital transformation strategies that align engineering education with evolving industry demands and institutional goals.

Keywords

Digital transformation, Engineering education, Higher education institutions, University operations, Educational technology

1. Introduction

Research on digital transformation in engineering education has emerged as a critical area of inquiry due to its profound impact on university operations, teaching methodologies, and student learning experiences in the context of rapid technological advancement (Lyngdorf & Du, 2024 ; Bui & Nguyen, 2023). Since the early 2010s, the field has evolved from isolated digitalization efforts to comprehensive institutional strategies integrating artificial intelligence, Industry 4.0 technologies, and digital literacy frameworks (Joshi et al., 2024; Amuthakkannan et al., 2024). The COVID-19 pandemic further accelerated this shift, compelling higher education institutions (HEIs) worldwide to adopt digital tools for continuity and innovation (Nieto-Taborda & Luppigini, 2024; Matsieli & Mutula, 2024). With over 3.5 billion internet users globally, the digital revolution has reshaped educational access and delivery,

underscoring the social and practical significance of digital transformation in preparing engineering graduates for Industry 5.0 and beyond (Bui & Nguyen, 2023; Vieira, 2024).

Despite growing interest, significant challenges persist in effectively implementing digital transformation across university operations, including strategic vision deficits, infrastructural limitations, and faculty readiness (Singun, 2025; Saini et al., 2024; Prasetyaningtyas et al., 2023). Existing literature often focuses on discrete aspects such as AI integration, e-learning adoption, or digital literacy, yet lacks holistic, multi-dimensional analyses that encompass administrative, pedagogical, and technological domains simultaneously (Hasanah et al., 2025; Farias-Gaytan et al., 2024; Kumar et al., 2024). Moreover, controversies arise regarding the balance between technological innovation and ethical considerations, as well as the equitable inclusion of diverse student populations (Matsieli & Mutula, 2024)(Angélica et al., 2025). The consequences of these gaps include suboptimal educational outcomes, resistance to change, and missed opportunities for institutional advancement (Singun, 2025; Qamar & Shaiq, 2025).

This review adopts a conceptual framework that defines digital transformation as the strategic integration of digital technologies to fundamentally alter educational processes and organisational culture (Gkrimpizi et al., 2024; Lyngdorf & Du, 2024). It situates digital literacy and competency development as critical enablers within this transformation, linking technological adoption to improved learning outcomes and institutional sustainability(Muzulon et al., 2025; Rêgo et al., 2023). The framework draws on constructivist learning theory and digital maturity models to guide the systematic examination of university operations in engineering education (Kazimova et al., 2025; Bisri et al., 2023).

The purpose of this systematic review is to synthesize current knowledge on digital transformation in engineering education, focusing on university operations, to identify key drivers, barriers, and outcomes(Lyngdorf & Du, 2024)(Halkhoree et al., 2024). By addressing the identified gaps, this study aims to provide actionable insights for educators, administrators, and policymakers to foster effective, ethical, and inclusive digital transformation strategies(Singun, 2025; Dacholfany et al., 2024). This contribution is valuable for aligning engineering education with evolving industry demands and technological trends(Vieira, 2024; Muzulon et al., 2025).

The review employs a rigorous systematic literature methodology, applying inclusion and exclusion criteria to select relevant peer-reviewed studies published between 2019 and 2025(Lyngdorf & Du, 2024; Nieto-Taborda & Luppisini, 2024). Analytical frameworks such as thematic synthesis and bibliometric analysis organize findings across technological, pedagogical, and administrative dimensions(Joshi et al., 2024; Yang et al., 2024). The subsequent sections present a detailed synthesis of frameworks, applications, challenges, and future directions for digital transformation in engineering education within university settings.

1.1. Objective

The objective of this report is to examine the existing research on "Digital Transformation in Engineering Education: A Systematic Review of University Operations" in order to synthesize comprehensive insights into how digital technologies are reshaping educational practices, institutional processes, and operational frameworks within engineering faculties at universities. This review is important because it addresses the accelerating integration of advanced digital tools such as artificial intelligence, digital twins, and Industry 4.0/5.0 paradigms, which are transforming curriculum design, teaching methodologies, and administrative functions. By systematically analyzing the current state of knowledge, this study aims to identify prevailing frameworks, challenges, and outcomes associated with digital transformation initiatives, thereby informing future strategies for effective implementation and fostering innovation in engineering education at the institutional level.

1.2 Extended Objectives

To taxonomize existing frameworks and models guiding digital transformation in engineering education and university operations.

To evaluate the role of emerging technologies such as AI, digital twins, and metaverse platforms in transforming engineering curricula and pedagogy.

To identify and synthesize challenges and barriers faced by higher education institutions during digital transformation processes.

To benchmark institutional strategies and governance approaches that facilitate successful digital transformation in engineering education.

To compare anticipated outcomes and impacts of digital transformation on teaching, learning, and administrative efficiency within universities.

2. Research Methodology

This study adopts a systematic literature review (SLR) approach to examine the state of research on digital transformation in engineering education and university operations (Figure 1). The SLR methodology was selected due to its rigor, transparency, and ability to synthesize a large body of scholarly work in a structured and replicable manner. To enhance analytical depth, the review is complemented by a bibliometric analysis, enabling visualization of research trends, collaborations, and thematic structures within the field. The primary data source for this study was Google Scholar, chosen due to its extensive coverage of peer-reviewed journal articles, conference proceedings, and interdisciplinary research outputs. The initial research query, “Digital Transformation in Engineering Education: A Systematic Review of University Operations,” was systematically expanded into a series of targeted search queries to ensure broader and more comprehensive literature coverage.

These expanded queries incorporated key thematic areas such as artificial intelligence in engineering education, Education 4.0 and 5.0 frameworks, digital twins, and metaverse-enabled learning environments, as well as governance, ethics, and institutional transformation. This structured query expansion strategy ensured that both established foundational studies and emerging research domains were adequately captured, thereby strengthening the depth and relevance of the systematic review. The study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, which consists of four sequential phases: Identification, Screening, Eligibility, and Inclusion. In the identification phase, a total of 528 records were retrieved from database searches, and an additional 78 records were obtained through backward and forward citation chaining, resulting in 606 records in total.

During the screening phase, titles and abstracts were assessed against predefined inclusion and exclusion criteria, leading to the exclusion of 420 records and the retention of 186 studies for full-text review. In the eligibility phase, the remaining full-text articles were carefully evaluated for methodological rigor and relevance to the research topic, which resulted in the exclusion of 136 studies that did not meet the required standards. Finally, in the inclusion phase, 50 studies were deemed highly relevant and were selected for qualitative synthesis and analysis. The overall study selection process is visually presented in the PRISMA flow diagram.

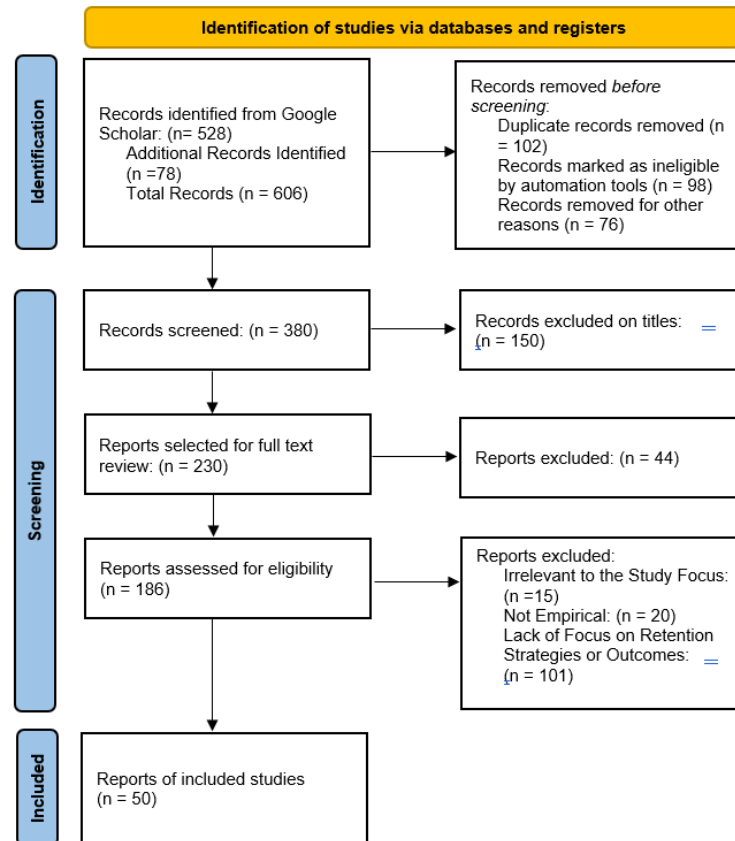


Figure 1. Systematic literature review

To ensure the quality and relevance of the reviewed literature, clearly defined inclusion and exclusion criteria were applied. The inclusion criteria comprised peer-reviewed journal articles and conference papers focusing on engineering education and higher education institutions, particularly those addressing digital transformation, artificial intelligence, Industry 4.0/5.0, or related emerging technologies. Only studies published between 2020 and 2025 were considered to ensure contemporary relevance. In contrast, the exclusion criteria eliminated non-academic or grey literature, studies unrelated to engineering or higher education, duplicate records, and papers lacking sufficient methodological rigor. For data extraction and analysis, information from the selected studies was systematically extracted and organised into key analytical dimensions, including framework typologies, technology adoption trends, barriers and challenges, governance and strategic approaches, as well as reported outcomes and impacts. A thematic synthesis approach was then applied to analyse the extracted data, allowing for the identification of recurring patterns, similarities, and differences across studies. This process supported the development of structured and coherent insights into the evolution, current state, and emerging directions of digital transformation within engineering education.

2.1 The Bibliometric Analysis Using VOSviewer

To complement the systematic review, a bibliometric analysis was conducted using VOSviewer to construct and visualise relational networks within the literature, thereby providing additional insights into research trends and collaboration patterns. For data preparation, bibliometric information such as author names, article titles, and keywords was extracted from the selected studies obtained via Google Scholar. The dataset was then cleaned and standardised to ensure consistency, which included harmonising keywords and removing duplicate records. A co-authorship network analysis was subsequently performed to explore collaboration patterns among researchers in the field. In the resulting visualisation, nodes represent individual authors, while node size reflects publication frequency or scholarly influence. Links between nodes indicate co-authorship relationships, and the distance between nodes represents the strength of collaboration, with closer proximity indicating stronger collaborative ties. Additionally, node colours were used in an overlay visualisation to represent the average publication year, allowing for temporal analysis of research development. The interpretation of the VOSviewer map indicates a dense yet decentralised

network structure, suggesting that research in this field is distributed across multiple independent clusters rather than being dominated by a single cohesive group. Although several localised collaboration clusters are evident, the relatively weak interconnections between them point to limited cross-institutional collaboration. Furthermore, the overlay visualisation demonstrates a clear temporal progression in research activity, with more recent publications (2024–2025) becoming increasingly prominent. This trend reflects the growing emphasis on emerging technologies such as artificial intelligence, digital twins, and immersive learning environments within engineering education research (Figure 2).

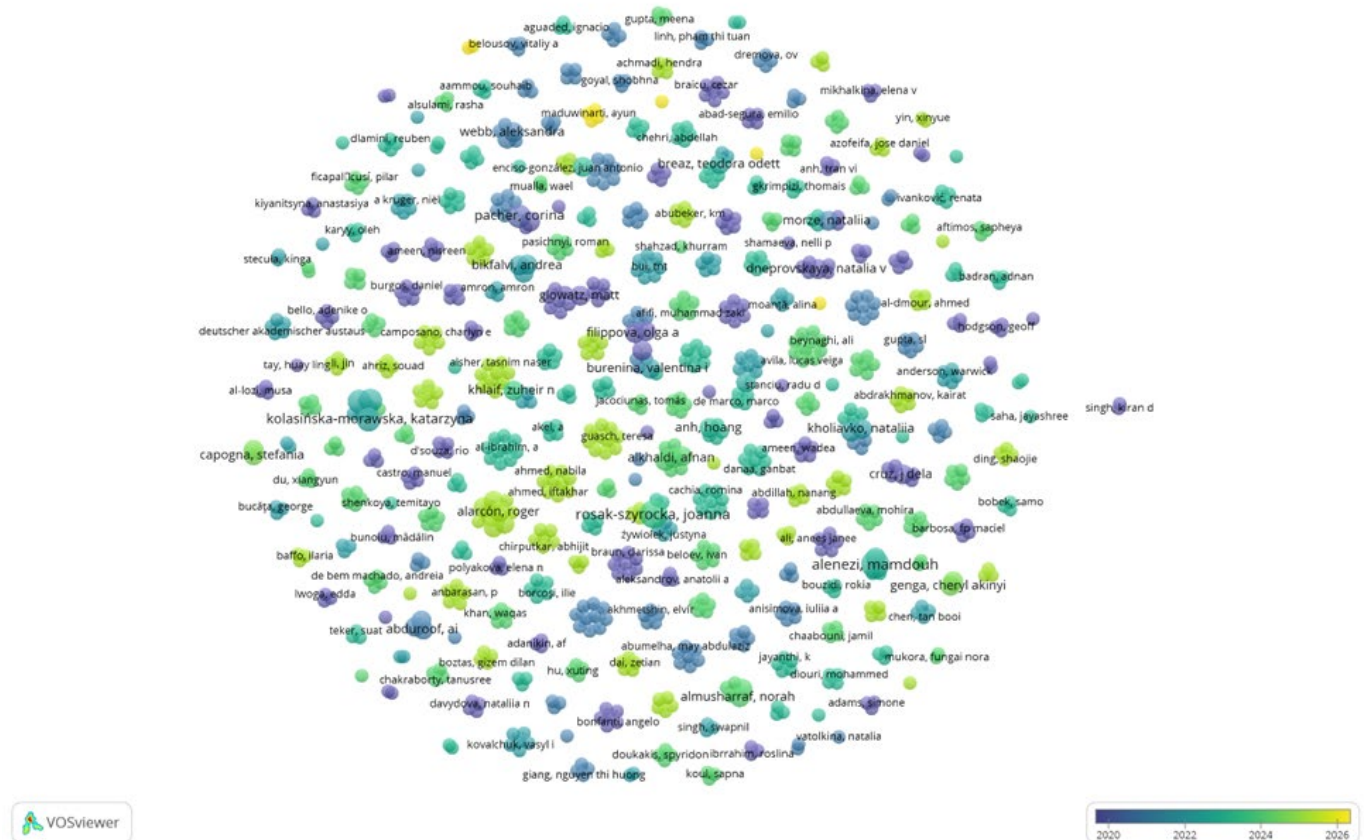


Figure 2. Bibliometric Analysis Using VOSviewer

2.2 Reliability and Limitations

While the adopted methodology ensures a systematic and transparent approach, several limitations are acknowledged. Firstly, the reliance on Google Scholar as the primary database may introduce selection bias, as not all relevant peer-reviewed studies may be indexed or equally accessible. Secondly, the rapid pace of technological advancement in areas such as artificial intelligence and digital transformation may affect the currency and long-term relevance of the findings. Thirdly, there is a limited availability of longitudinal and empirical studies within the field, which constrains deeper analysis of long-term impacts and trends. Despite these limitations, the integration of a systematic literature review with bibliometric analysis strengthens the overall robustness and comprehensiveness of the study by allowing both structured qualitative synthesis and quantitative mapping of research patterns. In summary, this study adopted a rigorous PRISMA-aligned systematic literature review combined with bibliometric mapping using VOSviewer to examine digital transformation in engineering education. This integrated methodological approach enabled both qualitative synthesis of key themes and quantitative visualisation of research networks, thereby providing a comprehensive understanding of emerging research trends, thematic structures, and collaboration patterns within the field. While the adopted methodology ensures a systematic and transparent approach, several limitations are acknowledged. Firstly, the reliance on Google Scholar as the primary database may introduce selection bias, as not all relevant peer-reviewed studies may be indexed or equally accessible. Secondly, the rapid pace of technological

advancement in areas such as artificial intelligence and digital transformation may affect the currency and long-term relevance of the findings. Thirdly, there is a limited availability of longitudinal and empirical studies within the field, which constrains deeper analysis of long-term impacts and trends. Despite these limitations, the integration of a systematic literature review with bibliometric analysis strengthens the overall robustness and comprehensiveness of the study by allowing both structured qualitative synthesis and quantitative mapping of research patterns. In summary, this study adopted a rigorous PRISMA-aligned systematic literature review combined with bibliometric mapping using VOSviewer to examine digital transformation in engineering education. This integrated methodological approach enabled both qualitative synthesis of key themes and quantitative visualisation of research networks, thereby providing a comprehensive understanding of emerging research trends, thematic structures, and collaboration patterns within the field.

The co-authorship network visualization generated using VOSviewer reveals that research on digital transformation in engineering education is a rapidly evolving and globally distributed field characterized by a dense yet decentralized structure. The absence of a dominant central cluster suggests that scholarly contributions are spread across multiple independent research groups rather than concentrated within a single leading network. While several localized clusters indicate active collaboration within specific institutions or thematic areas, the relatively weak connections between these clusters highlight limited cross-institutional and interdisciplinary collaboration. The overlay visualization further demonstrates a clear temporal progression, with recent studies (2024–2025) gaining prominence, reflecting growing interest in emerging technologies such as artificial intelligence, digital twins, and immersive learning environments. Overall, the map underscores that although the field is expanding and attracting new contributors, it remains fragmented, indicating the need for stronger collaborative networks and more integrated research approaches to advance digital transformation in engineering education and university operations.

3. Literature Review

The concept of digital transformation in engineering education has evolved into a multidimensional research field that integrates technological innovation, pedagogical reform, and institutional restructuring. Existing literature consistently highlights that digital transformation extends beyond mere technology adoption to encompass organizational culture, governance, and strategic alignment within universities. Studies such as Lyngdorf & Du (2024) and Benavides et al. (2022) emphasize holistic frameworks that operate across micro (classroom), mezzo (faculty), and macro (institutional) levels, demonstrating the systemic nature of transformation.

A dominant theme across the literature is the integration of emerging technologies, particularly artificial intelligence (AI), Industry 4.0/5.0 tools, digital twins, and immersive environments such as the metaverse. Research indicates that these technologies significantly enhance personalized learning, adaptive assessment, and administrative efficiency (Hasanah et al., 2025; Díaz et al., 2025; Almeman et al., 2025). AI-driven systems such as intelligent tutoring platforms and large language models are increasingly embedded within engineering curricula, enabling data-driven and student-centered learning experiences. Similarly, virtual laboratories and digital twins provide simulation-based environments that bridge theoretical knowledge with real-world applications.

Despite these advancements, the literature identifies several persistent barriers to effective digital transformation. Key challenges include inadequate digital competencies among faculty and students, insufficient infrastructure, resistance to change, and ethical concerns related to data privacy and algorithmic bias (Singun, 2025; Saini et al., 2024). Strategic and governance-related issues, such as the absence of clear digital visions and weak leadership, further complicate implementation processes (Nieto-Taborda & Luppardini, 2024). These barriers are particularly pronounced in developing countries, where resource constraints and policy limitations hinder progress (Prasetyaningtyas et al., 2023).

Governance and leadership emerge as critical enablers of successful digital transformation. The literature emphasizes the importance of strategic planning, stakeholder engagement, and continuous professional development in driving institutional change (Bisri et al., 2023; Dacholfany et al., 2024). Effective governance models align digital initiatives with institutional goals while promoting ethical practices and inclusivity. However, empirical evidence evaluating the long-term effectiveness of these governance strategies remains limited.

Another significant strand of research focuses on competency development and curriculum transformation. Engineering education is increasingly shifting toward competency-based models that incorporate digital, cognitive, and social skills aligned with Industry 4.0/5.0 demands (Vieira, 2024; Muzulon et al., 2025). While these frameworks

highlight the need for curriculum realignment, there is limited empirical validation of their effectiveness in practice. Faculty development and continuous training are frequently cited as essential yet underdeveloped components in facilitating this transition.

In terms of outcomes, digital transformation is widely associated with improved teaching quality, enhanced student engagement, and increased operational efficiency. However, most studies rely on qualitative or descriptive assessments, with a notable lack of standardized metrics and longitudinal data to measure sustained impact (Delgado et al., 2024; Kumar et al., 2024). This gap limits the ability to benchmark progress and develop evidence-based policies. The literature reveals a fragmented yet rapidly evolving field characterized by strong theoretical contributions but limited empirical validation. While there is broad consensus on the transformative potential of digital technologies, future research must focus on developing integrated frameworks, conducting longitudinal studies, and establishing standardized evaluation metrics. Addressing these gaps is essential for achieving sustainable and inclusive digital transformation in engineering education and university operations.

4. Conclusion

The collective body of literature on digital transformation in engineering education and university operations reveals a multifaceted and evolving landscape shaped by rapid technological advancements, institutional dynamics, and socio-cultural factors. The reviewed studies consistently underscore the critical need for holistic frameworks that integrate technological, organizational, pedagogical, and ethical dimensions to guide sustainable digital transformation initiatives. Such frameworks often emphasize multi-level outcomes, from classroom innovations to institutional restructuring, highlighting the importance of aligning digital strategies with broader educational and operational goals. While several competency-based and Education 4.0/5.0 paradigms provide valuable insights into evolving skill requirements, the literature points to fragmented adoption and calls for more comprehensive, empirically validated models that account for diverse university contexts.

Emerging technologies such as artificial intelligence, digital twins, and immersive metaverse platforms are increasingly recognized as transformative forces that personalize learning, automate administration, and foster industry-aligned competencies. However, successful integration is uneven across institutions, hindered by infrastructural deficits, ethical concerns, and limited faculty preparedness. The rapid pace of technological change frequently outstrips empirical research, leaving gaps in longitudinal impact assessments and scalability studies. These challenges are compounded by a pervasive emphasis on identifying barriers rather than evaluating the efficacy of mitigation strategies, resulting in limited evidence on how overcoming these obstacles translates into improved educational quality and operational efficiency.

Institutional governance and leadership emerge as pivotal factors influencing digital transformation success. Effective strategies tend to involve visionary leadership, stakeholder engagement, and comprehensive policy frameworks that promote continuous training, ethical governance, and inclusivity. Yet, there remains a scarcity of empirical studies analyzing the longitudinal outcomes of governance models, particularly concerning their adaptability to evolving technologies and commitment to social justice and equity. Comparative analyses highlight variability between public and private institutions, underscoring the contextual complexity of digital transformation pathways.

Outcome measurement in digital transformation initiatives is often descriptive and anecdotal, with a pressing need for standardized metrics and longitudinal research to enable rigorous impact evaluation. Positive outcomes reported include enhanced teaching quality, personalized learning experiences, administrative efficiencies, and improved student engagement and employability. Sustainability and inclusiveness are increasingly prioritized as integral dimensions of digital transformation, connecting institutional innovation to global development goals.

Finally, the literature identifies significant opportunities and gaps in curriculum realignment and competency development, emphasizing the integration of digital literacy, soft skills, and ethical training alongside technical expertise. Faculty development and continuous reskilling are critical yet under-addressed components necessary to support pedagogical innovation effectively. Methodologically, while systematic reviews and bibliometric analyses provide valuable overviews, empirical, longitudinal, and interdisciplinary research remains limited, especially within developing country contexts. Addressing these gaps is essential to fostering comprehensive, equitable, and effective digital transformation in engineering education and university operations.

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