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Systematic Review

Frameworks and Models for Digital Transformation in Engineering Education: A Literature Review Using a Systematic Approach

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Abstract: In response to the opportunities and challenges posed by rapid technological advancement, digital transformation (DT) has recently emerged as a key concept in higher engineering education. DT involves using digital technologies to transform educational and pedagogical practices to enhance the learning and teaching experiences, prepare students for the needs of industry, and foster innovation. Despite a growing number of small-scale empirical studies concentrating on digitalization at lower single-activity and classroom levels, the practices of traditional education largely remain. There is a need for more systematic and holistic frameworks to facilitate and guide DT in engineering education. This study reviews 13 studies, using a systematic approach to identify and analyze the literature on frameworks for DT of engineering education. Several characteristics are identified, including types of DT frameworks and models; drivers of DT; and digital learning tools and types. In addition, various anticipated outcomes of DT reported in the included studies are described at the micro, mezzo, and macro levels. Recommendations for future practices for engineering students, educators, and institutions and future research directions for engineering educational researchers are also proposed to support the further development of digital education.

Keywords: digital transformation; engineering education; framework; literature review

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1. Introduction

In the dynamic landscape of education, the integration of digital technologies has become imperative, particularly in fields lying at the forefront of technological innovation, such as engineering [1]. As the current "Industry 4.0" wave of development sees continued advancements in complex innovative technology (e.g., artificial intelligence, Internet of Things, 5G wireless networking, augmented reality (AR), virtual reality (VR), cybersecurity innovation), a deeper and more complex approach is needed to bring about true transformation in education driven by digital technology [2–4]. The advent of digital transformation (DT) in engineering education has thus become a priority. DT is fundamentally about change involving people, processes, strategies, structures, and competitive dynamics [5]. It represents a paradigm shift in education, revolutionizing traditional teaching methodologies and preparing individuals with the skills and knowledge demanded by the digital era [6]. Meanwhile, DT also introduces new challenges for engineering educators and students, such as changes in how courses are structured and delivered, new competences which must be developed, and the integration of new technical, managerial, and non-cognitive capabilities that were not previously seen as important [1,7]. The lockdowns during the COVID-19 pandemic have certainly sped up processes of digitalization, making education more flexible and accessible for students [8]. On the other hand, it presents challenges on how the process is achieved by engineering institutions, and the current implementation of digital technology in the engineering field must also undertake deeper consideration of fundamental pedagogical practices to break out of the role it currently occupies in the classroom, which is primarily one of supporting or replicating traditional modes of education [9]. In this sense, the full potential of the implementation of DT in engineering education still needs to be explored [1,10,11].

Due in part to its relatively recent emergence as a concept in academia and among practitioners, DT can be confusing and misused, and it lacks a universally agreed-upon definition. Systematically reviewing 134 well-received and published definitions on DT, Gong and Ribiere [12] developed a unified definition: “A fundamental change process enabled by digital technologies that aim to bring radical improvement and innovation to an entity (e.g., an organization, a business network, an industry, or society) to create value for its stakeholders by strategically leveraging its key resources and capabilities” (p.10). In educational settings, this form of transformation crosses boundaries between different (educational) systems, demanding significant efforts from all stakeholders to consider new practices of working with and thinking about digital platforms, methods, strategies, and cultures. DT is conceptually distinct from other related terms such as “digitization” and “digitalization”. “Digitization” refers to the shifting of information from analog to digital form, enabling its storage, processing, and transmission through digital means [13,14]. “Digitalization”, meanwhile, refers to the use of digital technologies and IT solutions to change existing societal or business models [12,15], meaning processes are entangled with digital technology. The three terms are thus interrelated but can be seen as distinct phases. In the engineering education field specifically, the progression from digitization to digitalization to DT reflects an increasingly holistic strategic vision of the leveraging of digital innovation [1,13].

Kræmmergaard and Sayers [16] developed a model for the implementation of DT in both industry and public institutions. This model envisions the DT process as a continuum marked by a series of milestones, from the initial implementation of IT at stage 1 to full DT at Stage 5. Specifically, in the educational context, Stage 1 involves the use of IT to support existing practices and services. In stage 2, systems are rapidly standardized and digitalization strategies are formulated centrally at the leadership level. For instance, during the COVID-19 pandemic, digital tools became standardized, teachers and students were required to adapt to online platforms, and the implementation of new technologies became more streamlined. From stage 3 onwards, digital technology assumes a more pivotal role and becomes a co-creator of educational practice and experience. Stage 3 focuses on how core practices and processes can be reinterpreted in a digitally native manner and how staff and students explore and take advantage of the new affordances of digital technology. In stage 4, the organization challenges itself to rethink its own core services through digitalization, e.g., collecting learner analytics and creating more personalized learning environments. Finally, in stage 5, technologies like AI, machine learning, and AR/VR become widespread and well-integrated in the identification and creation of new patterns and opportunities in combination with human decision-making. The majority of studies in the engineering education literature on digital technology focus on innovation at stages 1 and 2, reporting on small-scale, individual digital innovations at the single-activity and in-classroom levels. DT processes at stage 3 and above, in contrast, are underexplored in the literature, and it remains unclear what drives and characterizes DT within engineering education at these stages and how digital tools are used to create more fundamental transformation in learning experiences.

So why is it important for engineering education to move to higher stages of DT? Studies have found that digital versions of, for example, face-to-face experiences are inferior to more traditional modes [17,18]. This form of digital technology use became especially prevalent during the COVID-19 lockdowns [19] and has remained so since, leading to the emergence of remote teaching and a rush to the 1:1 transference of traditional pedagogical practice to digital versions [20]. However, Weller [21] considers the outcomes of such comparisons unsurprising and unfair, describing them as similar to comparing a live theater performance to seeing the same show on television. To avoid the drawbacks of such a 1:1 transference, which represents the lower stages of DT, it is necessary to gain a more holistic understanding of how digital technology, pedagogy, and the drivers of DT are entangled in frameworks or models for DT in engineering education. Full-fledged transformations are usually accompanied by frameworks or models which assess the maturity of a DT process and thus enable a clear vision of organizational strategies and changes, an assessment of whether goals have been reached throughout the change journey, and the further development of learning and teaching in ways that accommodate the requirements of the present stage of technological change.

Previous reviews of DT literature have discussed the definition of DT, the state of DT in relation to higher education broadly, and the roles of various stakeholders in DT within the broader field of higher education in general [22,23]. However, there has been no review or analysis of holistic, transformative frameworks of DT in engineering education specifically, nor has there been an analysis of the complex entanglements of digital technology, pedagogy, and the drivers of DT. We are thus interested in uncovering frameworks with the potential to transform the relationship between technology and pedagogy, to identify the underlying drivers of DT, to propose transformative uses of digital technology/tools in learning, and to promote overall DT in engineering education. Thus, this study addresses the following three research questions by means of a literature review:

(1) What are the drivers and prevailing types of DT frameworks/models in engineering education through which digital technology and pedagogy can be understood and implemented?
(2) Within the identified DT frameworks/models, what types of digital tools are adopted, and how are they used in the implementation of DT?
(3) What are the anticipated outcomes reported by these DT frameworks/models?

2. Method

To answer these questions, this literature review identifies and synthesizes literature following a systematic approach. It applies rigorous and comprehensive search procedures, predetermined inclusion and exclusion criteria, and transparent and documented audit trail processes [24]. We conducted this review in five steps: (1) identifying the research question; (2) developing a review protocol; (3) selecting studies and appraising their quality; (4) charting the data; and (5) collating, summarizing, and reporting the results [24–26]. These stages and their objectives are shown in Table 1 and elaborated on in the sections below.

Table 1. Five steps in conducting the systematic literature review.

Step	Objectives
1: Identifying the research question	To determine the research questions, search terms, and databases
2: Developing a review protocol	To determine the range and focus of the search by defining inclusion and exclusion criteria
3: Selecting the studies	To filter and screen the studies and appraise their quality
4: Charting the data	To extract, analyze, and synthesize the findings of the included studies
5: Collating, summarizing, and reporting the results	To report and disseminate all relevant information from the included studies along with details of the review procedures

2.1. Stage 1—Identifying the Research Question

The research questions presented above situate this study in its context and determine the search terms and databases. Five databases were consulted to ensure broad coverage of the literature on the topic: (1) SCOPUS, (2) ERIC (via ProQuest), (3) Web of Science, (4) IEEE Xplore, and (5) Engineering Village. The first four databases are the most frequently used to conduct systematic literature reviews within the engineering education field [26,27]. The last, suggested by a local expert librarian, helped the researchers stay up to date and uncover insights with respect to research, analytical approaches, and tools. These five databases constitute a comprehensive and cross-disciplinary collection of high-quality research articles, conference proceedings, and other scholarly documents and cover a wide range of concepts, practices, research foci, and projects in the engineering field [26]. They enabled us to explore the range of current DT implementations, designs, and frameworks in engineering education across multiple countries.

The search strings initially developed by the authors were evaluated and revised by the librarian, who is an expert in database searches and literature reviews. The final strings, used in a search conducted in March 2023, are shown in Table 2.

Table 2. Keyword search strings.

Block	Keywords
Block 1	"Engineering education *"
AND	
Block 2	"Digital transform *" OR "digitally transform *"
AND	
Block 3	Framework * OR model * OR design *

* Truncation to broaden the search.

2.2. Step 2—Developing a Review Protocol

The research questions presented earlier situate this study and define a set of inclusion and exclusion criteria. First, the end date for the timeframe for sources was set to 1 March 2023; no articles published after that date were considered in our analysis. No start date limit on the timeframe was set, which allowed us to form a holistic picture of DT in engineering education over the past several decades. Second, the search was limited to peer-reviewed journal articles or conference papers. This ensured the quality of the sources to be analyzed and restricted them to a manageable number. Third, the selection of studies was limited to those offering educational or pedagogical insights and implications. Articles concerning only technological findings, such as those exploring technology use or DT in aspects of engineering other than education, were removed. Fourth, only papers with clear DT frameworks or models were included. Research papers, practice papers, and literature review studies that failed to incorporate DT frameworks were excluded. Finally, papers were only included if they addressed DT at a larger scale than a single course and at stage 3 or above on Kræmmergaard and Sayer's model [16] as discussed above. Full details of the inclusion and exclusion criteria are shown in Table 3.

Table 3. Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Date	No start date limit; published prior to 1 March 2023	Published 1 March 2023 or later
Language	English	Not written in English
Types of manuscripts	Peer-reviewed journal articles and conference papers	Blogs, book chapters, dissertations, proposals, reports, etc.
Context	Engineering education	Other disciplines
	Higher education	K–12 education, vocational education, and continuing education
Topic	1. Educational and pedagogical focus; 2. Clear DT framework or model; 3. Above the course level.	1. DT not related to educational change; 2. Small-scale innovation using digital technology, e.g., specific in-class exercises and activities.

2.3. Step 3—Study Selection

The review study adopted the selection method recommended by [28], which consists of four phases: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. In these phases, studies were identified in databases; screened by titles, keywords, and abstracts; and then read in full to assess for eligibility. Figure 1 shows a flowchart of these four phases.

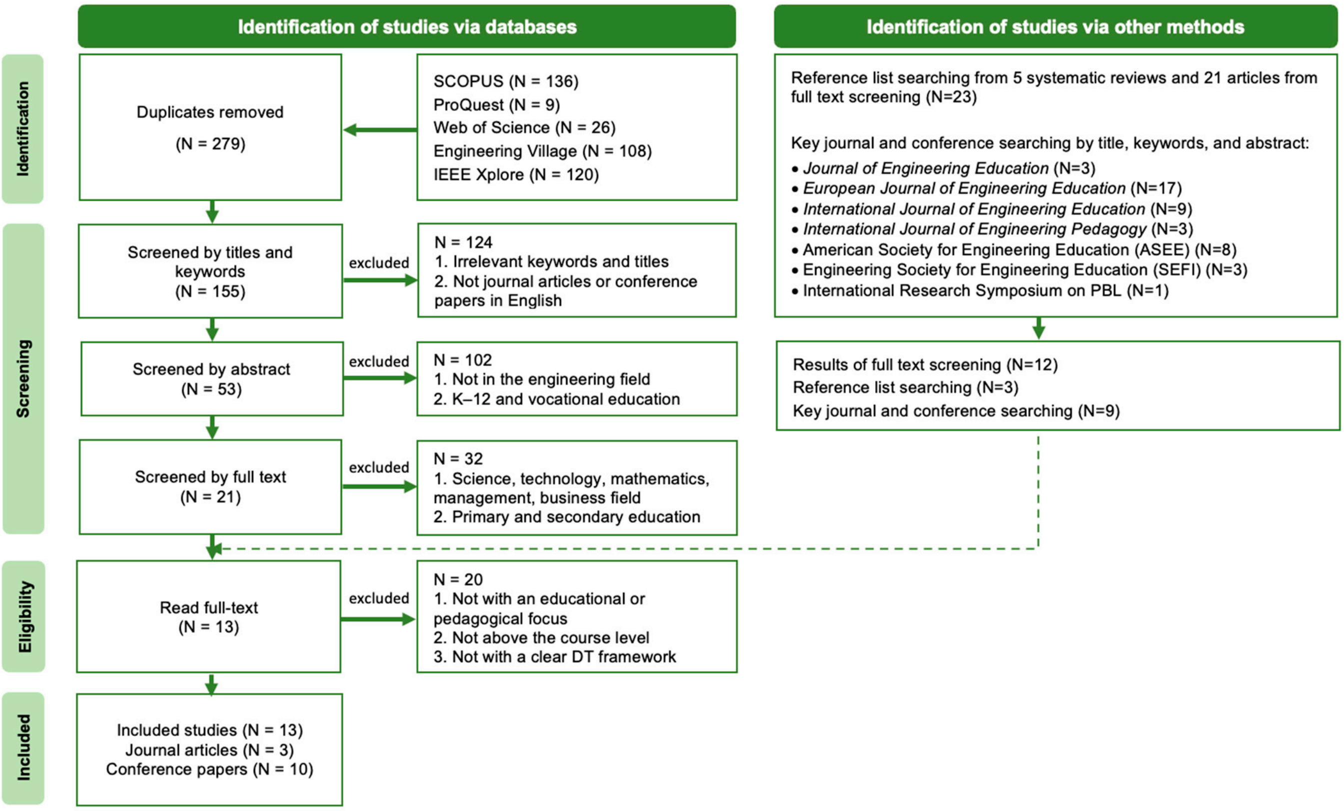

Figure 1. Flowchart for study selection.

The initial search of the four databases resulted in 279 relevant articles. After 120 duplicates were removed, 155 studies remained for further screening. The first phase of abstract and keyword screening reduced the number to 53. Next, in the abstract screening phase, two of the authors made decisions independently on whether the articles should be included, using the same Microsoft Excel template documenting the inclusion criteria. As a result, 32 articles were removed, reducing the number of studies in the remaining sample to 21. To ensure that no relevant published studies were missed in the electronic search, following Booth et al.'s [25] suggestion, additional manual searches were conducted by checking the reference lists of the selected sources and five systematic reviews related to DT [2,22,23,29,30] and searching key journals and conference papers in the engineering education field. The former method resulted in three additional articles, while the latter strategy yielded nine. Each screening phase was conducted twice to ensure that no relevant studies were mistakenly excluded. Following this, 12 additional studies were deemed eligible for inclusion in the next phase. In total, 20 out of 33 articles were excluded following full-text reading because they did not meet the inclusion criteria of including a clear DT model/framework, being situated above the course level, and focusing on educational and pedagogical insights. Ultimately, 13 studies were included for further analysis, comprising 10 conference papers and 3 journal articles.

2.4. Step 4—Charting the Data

Following the content analysis process outlined by [26], this study employed an integrated approach combined with inductive and deductive analyses. The initial codebook was developed through debriefing sessions among the authors to code the findings. The first clusters of themes include the studies' metadata (e.g., the authors' country in which their universities were located, year of publication, and source of publication), frameworks and models, and types of digital tools. These themes focused on the "how, what, when, and where" of DT frameworks for engineering education. Following Fawn's [31] work on the types of relationships between pedagogy and technology, the DT frameworks discussed in the reviewed studies were deductively coded as tech-driven, pedagogy-driven, or entangled. The remaining themes adopted inductive open-coding techniques. To explore the impacts of each framework, the second group of themes focused on the underlying ideological drivers and the promoted outcomes of DT. The "why" of the frameworks was explored through these categories. We followed Bisri et al.'s [23] recommendations and deductively coded and categorized the drivers of DT in each article into one of three categories: learning process, society, and organization. Through this process, market emerged inductively as a further driver. The types of digital tools and promoted outcomes documented in the studies were analyzed through inductive open coding, and the codes were sorted, reviewed, and organized into overarching sub-themes and categories. Table 4 shows an excerpt from the codebook.

Several efforts were made to minimize researcher bias and maximize the validity of the analysis. First, during abstract screening, the authors ensured that they shared a common understanding by performing random control checks of the same papers [32]. Second, during full-text screening, the first two authors independently screened each of the 53 papers from the databases and then held multiple rounds of discussion to arrive at a consensus on which articles should be selected for further full-text analysis. Third, all articles selected for full-text reading were read several times, and the coding process was led by the first author and triangulated by two experienced educational researchers in the research group. Fourth, to enhance inter-rater reliability (IRR), two of the authors independently worked on the Excel sheet with the same initial themes to code and compare the results at the initial theme level. The IRR results showed an acceptance rate of over 0.85 for each theme. Discrepancies are mainly shown in types, underlying drivers, and anticipated outcomes, but they were then discussed within the research group among all authors to revise codes and make agreement accordingly.

Table 4. Coding scheme with the sample themes and data (* refers to deductive codes/themes).

	The First Cluster							The Second Cluster	
	Metadata			Frameworks/Models			Tools/Technology	Underlying Drivers	Anticipated Outcomes
Ref	Country	Year	Sources	Name	Types	Dimensions			
[33]	Vietnam and Japan	2021	Journal (Education Science)	The model of digital university in the context of 4IR	Pedagogy *	• Digital technology • Connectives theory • Learning ecosystem	ICT service systems of e-university	• Learning*: To support students' learning • Market: To provide qualified technology labor • Organization*: not specified • Society*: not specified	• Flexibility and obtaining access by all students • Increased personalized learning environment • Time-saving • Efficiency • Lifelong learning improvement

3. Findings

This paper elaborates on our findings and thus represents step 5 of the literature review process. This section presents detailed findings related to types of DT frameworks, drivers of DT informed by the frameworks, and digitalized learning activities, tools, and promoted outcomes.

3.1. Metadata of Included Papers

The metadata of the 13 included articles were categorized based on the following aspects: source of publication, country in which the authors' affiliated institutions were located, and year of publication.

Source of publication. The three articles were published in different journals, namely the *Journal of Manufacturing Technology Management*, *Education Science*, and the *International Journal of Engineering Pedagogy*. Of the 10 conference papers selected, most were originally presented at technology and engineering education conferences, namely the IEEE Global Engineering Education Conference (n = 2), the IEEE International Conference on Engineering, Technology, and Education (TALE) (n = 1), the IEEE International Conference on Smart Information Systems and Technologies (SIST) (n = 1), the International Symposium on Accreditation of Engineering and Computing Education (ICACIT) (n = 1), the World Engineering Education Forum/Global Engineering Deans Council (WEEF/GEDC) (n = 1), the Frontiers in Education Conference (FIE) (n = 1), the American Society for Engineering Education (ASEE) annual conference (n = 1), the eLearning and Software for Education Conference (n = 1), and the European Proceedings of Social and Behavioral Sciences (n = 1).

Authors' countries. Of the 13 included studies, 10 were written in a single country, either by a single author or by authors collaborating within an institution or across institutions. The countries represented in these 10 studies are Colombia (n = 1), Germany (n = 1), Kazakhstan (n = 2), Mexico (n = 2), Moldova (n = 1), Russia (n = 2), and the USA (n = 1). The three remaining studies were collaborations between authors in multiple countries, namely (1) Colombia and Peru, (2) Germany and the USA, and (3) Vietnam and Japan.

Year of publication. Figure 2 presents the number of included studies by year of publication. The earliest papers included were published in 2018. It indicates that while digital pedagogies have been introduced for decades, the research focusing on fundamental changes brought by digital technology in higher engineering education has only been reported in recent years. This is confirmed by prior systematic review studies on DT within the higher education field, where the earliest papers included are reported in the year 2016 [22] and 2018 [23], respectively. The number of articles in this study reaches its peak in 2021, during the COVID-19 pandemic (n = 6).

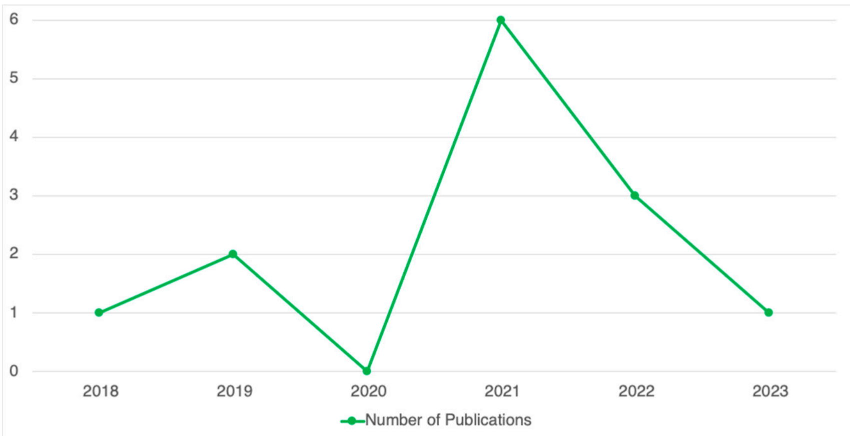

Figure 2. Year of publication and the corresponding number of articles.

3.2. RQ 1—What Are the Drivers and Prevailing Types of DT Frameworks/Models in Engineering Education through Which Digital Technology and Pedagogy Can Be Understood and Implemented?

Table 5 provides an overview of the various DT frameworks reported in the included studies. These frameworks are categorized according to types, dimensions, and drivers. Types describe the underlying beliefs about the relationship between digital technology and pedagogics in the frameworks, based on Fawns' [31] work on entangled pedagogy. We characterized the frameworks as predominantly technology-driven, pedagogy-driven, or entangled. Technology-driven frameworks regard technological change as a determinant of pedagogical thinking and practice. Conversely, pedagogy-driven frameworks take a pedagogy-first approach, insinuating that technology is malleable and can be implemented in various ways to serve a range of pedagogical ideas and practices. Finally, frameworks based on entangled understandings see digital technology and pedagogy as mutually shaping the purposes, contexts, values, methods, and technologies involved in teaching and learning and view the outcomes of DT as contingent on these complex relationships.

Table 5. DT framework types and drivers. * L = Learning process; O = organization; S = society; M = market.

Framework/Model							
Ref.	**Name**	**Types**	**Dimensions**	**L**	**O**	**S**	**M**
1. [33]	Model of a digital university in the context of Industry 4.0	Pedagogy	• Digital technology • Connectives theory • Learning ecosystem	X			
2. [34]	A hybrid model for post-COVID normality	Pedagogy	• Collaborative learning • Problem-solving • Video technology use	X		X	
3. [35]	CDIO-FCDI-FFCE models for DT implementation	Pedagogy	• Foresight: Innovation planning and technological foresight • Forecast: Assessing knowledge-intensive technology needs • Conceive: Considering customer needs, developing advanced conceptual, technical, and business strategies • Design: Developing innovative product, process, or system thinking • Implement: Online coding, testing, and validation of engineering products • Operate: Maintaining, evolving, and retiring systems through online tools and resources	X			X
4. [36]	Digital transformation model	Pedagogy	• Ecosystem • Structural vision • Strategic map • Architectural components of DT • Digital architecture • Computational-mathematical perspective • Matrix of media ends • The dynamic model				X
5. [37]	Instructional Design Model for Engineering Education (IDMEE)	Technology	• Four stages of organizational transformation: • "What" should be taught: digital twins and predictive maintenance; • "Who" should be trained: IT developers and maintenance managers; • "How" education should take place: approaches based on learning theories, such as cognitivism and constructivism (e.g., project-oriented learning methods); • "By which means": selection of appropriate educational technologies.		X		X

Table 5. *Cont.*

Framework/Model							
Ref.	**Name**	**Types**	**Dimensions**	**L**	**O**	**S**	**M**
6. [38]	A digital lab transformation maturity model	Entangled	• Universality and accessibility • User management • Scalability and extensibility • Learning support	X	X	X	X
8. [39]	DIGIFORME didactic model	Entangled	Three phases in implementation of distance engineering education: • Identification of teachers' training needs and applications for ensuring distance teaching; • Preparation of the distance didactic process; • Implementation of distance teaching activities.	X	X		X
9. [40]	Taxonomy of digital transformation	Entangled	Five components of taxonomy: • Principles: user-centered approach, cultural change, hyper-connectivity; • Facilitators: technologies, business models, abilities/competencies; • Adoption mechanisms: digital strategies, standards, dynamic capacities, enterprise architecture, platforms, infrastructure, governance mechanisms; • Impact areas: value creation, operational efficiency, client experience, business models, digital economy, employees' roles and abilities, ecosystem, innovation, culture and context; • Evaluation mechanisms: maturity models, indicators systems.	X	X	X	X
10. [41]	Digital transformation educational framework	Entangled	• Operations and value chains • Products and services • Business models and customer engagement • Environmental context • Leadership and culture	X		X	X
11. [42]	Integrated model of the digital space of engineering education	Entangled	• Digital strategy • Behavioral model • Collaboration tools • Feedback		X	X	X
12. [43]	A pragmatic futuristic framework	Entangled	• Shift in mindset • Changes in infrastructure • Leveraging digital technology	X	X	X	X
13. [44]	Input–output–outcome–impact (IOOI) logic of a digital university	Entangled	• Layers of IOOI logic: • Agile virtual teams involving collaboration among lecturers, staff, and students; • Individual learning trajectories with a blended learning approach; • Innovations for competences and knowledge for a digital, project-based, and service-oriented future.		X		X

As shown in Table 5, four studies exhibit a pedagogy-first perspective, framing students and educators as the primary agents and technology as a tool to support existing teaching approaches and strategies [33–36]. These frameworks place strong emphasis on learners' needs, student engagement, cognitive development, pedagogical practice, and meaningful learning experiences in a digitalized environment. One article adopts a technology-first perspective, in which technology determines educational principles, activities, and outcomes, and students are instructed in using tools [37]. The remaining studies represent an entangled perspective, whereby pedagogy is constituted not just by methods and technology but also by the purposes, contexts, and values of teachers, students, and other stakeholders. All these elements are entangled and together transform educational activities.

Table 5 also shows the specific ideologies and drivers (e.g., values, visions, and principles) behind the transformation documented in each study. The analysis reveals that DT is driven by a combination of internal and external factors, which can be divided into four categories: learning process, organization, society, and market. The drivers analyzed in each framework are shown in Table 5, with a more detailed analysis of these drivers presented in Table 6. Drivers in the learning process category are factors that motivate individuals to undertake actions such as acquiring new knowledge on technology and digitalization, developing digital skills, or changing behaviors in regard to digital learning. Organization-related drivers include the key factors that influence the decisions and guide the learning and teaching approaches of universities or engineering programs, shape organizational norms and values, and achieve strategic goals. The drivers in the society category are the influential factors that support society as a whole to adopt digital technologies and processes, including international applicability, sustainability, and innovation. Finally, market-oriented drivers are those which arise from market dynamics, customer demand, resource availability, productivity, efficiency, etc.

Table 6. Number of articles reporting each type of driver within their DT frameworks/models.

Drivers			
Learning Process (*n* = 9)	**Organization (*n* = 8)**	**Society (*n* = 7)**	**Market (*n* = 11)**
1. To be more student-centered [33,34]	1. To help stakeholders identify essential issues and communicate effectively [42,45]	1. To support international applicability [38]	1. To ensure an affordable price and reduce cost [38,43]
2. To improve students' online learning experiences and enhance their satisfaction, interest, and motivation [34,38]	2. To improve the quality of engineering programs and ensure that they meet the current requirements on DT [40,44]	2. To boost advanced innovation [40,45]	2. To maximize availability of information and use of e-resources [35,38,44]
3. To increase proactive adoption of digital learning [45]	3. To ensure the sustainability of engineering distance education [39]	3. To improve sustainability in daily life [41]	3. To accommodate changing market demands for resources and digital specialists [36,37,40–43,45]
4. To produce qualified professionals and increase students' digital competence and literacy [33,34,39–41,43,45]	4. To provide students and teachers with personalized environments via digital platforms [38,43]	4. To offer new opportunities in line with economic, technological, information, and communication capabilities [42]	4. To address competitiveness and the division of labor in the engineering profession [35,36]
5. To enhance effectiveness in meeting intended learning outcomes [35]	5. To provide tailored training programs and promote the transition to higher-stage DT [37]	5. To adapt to social change and continue the digital revolution after the COVID-19 pandemic [34,43]	5. To integrate digital technologies into products and services, value chains, and business models [39,41]
6. To prepare students for complex, innovative, and research-led engineering activities [35]	6. To attract and retain more students in the university [44,45]		6. To improve productivity and efficiency [36–39,45]
			7. To convert to a postindustrial knowledge-based economy [44]

3.3. RQ 2—Within the Identified DT Framework/Model, What Types of Digital Tools Are Adopted, and How Are They Used in the Implementation of DT?

Digital transformation requires the strategic application of various tools and technologies to foster innovation and improve learning and teaching. The digital tools identified in the included studies can be summarized in a typology describing how different tools address five key purposes in relation to teaching and learning. Table 7 shows examples of the different tools reported by the included studies, while the paragraphs below explain the five purposes associated with their use.

Table 7. Types of tools/technology used to transform learning activities and the number of articles reporting them.

Digitalization Types and Learning Activities				
Content Digitization (*n* = 7)	**Cognitive Facilitation (*n* = 4)**	**Physical Emulation (*n* = 5)**	**Interaction (*n* = 8)**	**Creation (*n* = 4)**
1. Software: • Microsoft 365 [44]; • Student journey configurator [44]. **2. Learning management system:** • Canvas platform [34,45]; • Moodle [39,44]; • Digital Lean Thinking Learning Space (DLTLS) platform [41]; • lectii.utm.md video collection platform [39]. **3. Website** • e-library [45] • e-information portal [33] **4. Digital videos or texts** [34,35]	**1. Software:** • Microsoft 365 [44]. **2. System and platform:** • DIRECTUM management platform [45]; • Intelligent management information system [36]; • Manufacturing execution system [37].	**1. Devices and software:** • IoT wearables [41]; • Kaspersky [44]. **2. Simulation system:** • Virtual labs [35]; • Digital architecture 360° [36]; • Smart factory and operators [37]; • Digital twins [37]; • DLTLS platform [41]. **3. AR/VR** [37,41]	**1. Software:** • Zoom [34]; • MS Teams [39]; • Messenger apps [34]; • Email [33,44,45]; • Blog [44]; • Adobe Connect Pro Meeting [45]. **2. Platform and system:** • DLTLS platform [41]; • ICT service systems of e-university [33]; • Digital forum [44]. **3. Cloud computing and collaboration tools:** • Google G Suite [45]; • Collaborative robots [41]; • Cisco [44]; • Human–machine interface [37]. **4. Mobile devices** [37,43,44]	**1. AI** [37,41,43,45]

Content digitization: tools for digitizing content used to help students acquire and master knowledge (e.g., podcasts, videos, texts, etc.). As shown in the table, along with software, websites, and digital text and video content, some studies also reported the use of learning management systems, which can be used for tasks such as delivering online lectures and managing online content and materials (e.g., [39,41]).

Cognitive facilitation: tools that support and enhance processes such as project planning, decision-making, and brainstorming (e.g., whiteboards, internal project management tools, etc.). Among the examples, several studies reported the use of management systems and platforms allowing students and teachers to visualize elements related to planning, ideation, and decision-making [36,45].

Physical emulation: tools that replicate or augment physical experiences (e.g., augmented reality (AR) and virtual reality (VR) glasses, three-dimensional modeling). Several studies reported on the use of simulation systems which allow their users to conduct experiments [37], emulate data [36], and enable greater flexibility for learning and customization for interfaces [35,37].

Interaction: tools that facilitate communication and interaction between people (e.g., MS Teams, Zoom, Messenger, etc.). These tools include online meeting software, social media, email, and other platforms that enable synchronous and asynchronous interaction and collaboration.

Creation: tools that generate content based on human input and foster creativity and innovation. Four studies mentioned AI as an emerging and developing tool in recent years, noting that it can help spark inspiration and overcome creative blocks by providing novel perspectives and generating diverse alternatives [37,41,43,45].

The majority of the specific tools identified in the included studies were used for interaction and content digitization purposes. Some of these tools have multiple purposes and functions, such as learning management systems like the Digital Lean Thinking Learning Space (DLTLS) platform. Due to the cost limitations, pedagogical preferences, and resource constraints, fewer tools were reported for physical emulation and cognitive facilitation and, due to their novelty, even less is said about creative tools such as AI.

3.4. RQ 3—What Are the Anticipated Outcomes Reported by These DT Frameworks/Models?

All the included articles reported numerous expected benefits and advancements achievable through DT. These were classified into micro, mezzo, and macro levels, shown in Figure 3. The micro level focuses on the growth of individual competence, knowledge, understanding, affection, and behaviors in a digitalized environment. The mezzo level explores the elements that digitalization can promote across departments and universities. The macro level encompasses larger global and societal perspectives, examining social, economic, environmental, and technical aspects that could be promoted by DT in engineering education.

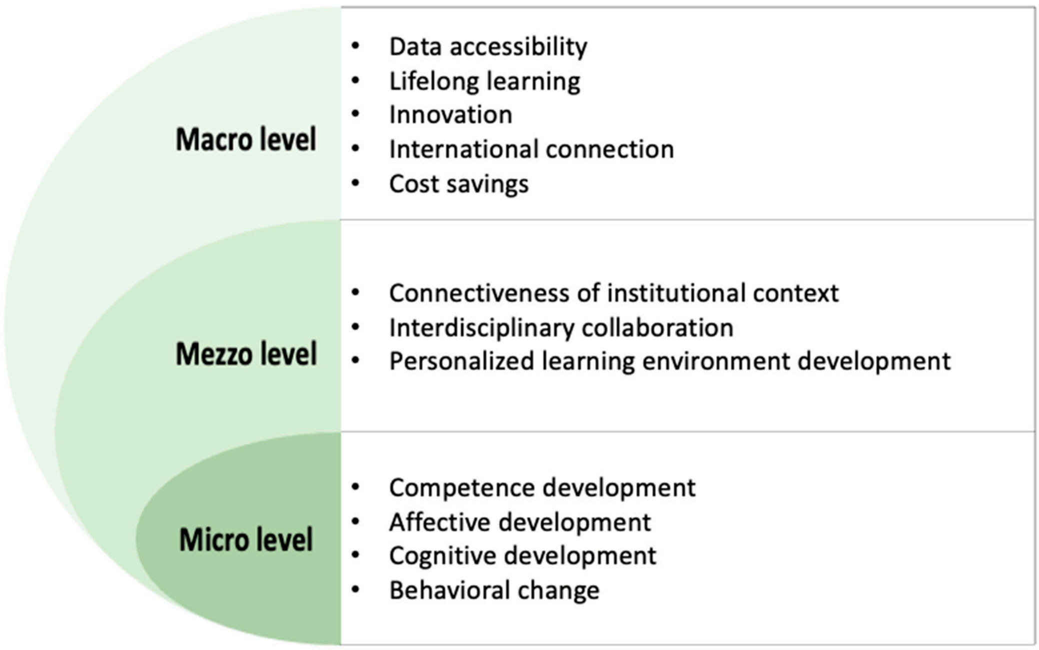

Figure 3. Promoted pedagogical outcomes of DT.

3.4.1. Micro Level

The first theme that emerged at this level was competence development among students and teachers. The included studies reported an expectation that students and teachers will experience improvements in their technical skills and professional competence [34,41], independent learning and self-management skills [34,42], transferable skills and job-related competence for future employability [35,39,43], and other soft skills, such as critical thinking, creativity, and leadership [41–43]. It is also expected that this will lead to an improvement in students' and teachers' ability to solve more complex problems, take more responsibility for their learning, and communicate and collaborate better with instructors and peers from diverse backgrounds [40].

The second theme that emerged was students' affective development, which is expected to be enhanced via DT's positive effects on their educational experience, including the innovation of new learning activities, e-resources [34] fostering improved motivation, and increased self-efficacy and confidence [34,41,42].

The third theme was students' cognitive development, including the knowledge they gain about technology [35] and the transfer and exchange of technical information [43,44].

The fourth theme related to behavioral changes among instructors and students specifically was the expectation that students would become more active in learning and actively engage in digital learning activities under the guidance of pedagogical models [43]. In addition, the digital learning context can be expected to provide students and teachers with greater flexibility in terms of time and space [33,34,39,42,43] and allow them to use technology strategically to create new value propositions [41,43].

3.4.2. Mezzo Level

DT at the mezzo level involves the development of learning environments for the department or university as a whole. It provides students with a more practice-oriented and problem-driven environment by aligning online curricula, resources, and learning methods [38,41]; a personalized environment by combining technology and pedagogical online strategies to meet their needs and preferences [33,35,38,43–45]; an interdisciplinary environment to promote collaboration between different departments and faculties and to combine knowledge and experience from the administration, business and social sciences [40–44]; and a more connective environment in which all stakeholders can create a collaborative community and universities can collaborate with local communities and other universities [33,40,44,45]. It also provides an environment for management change in the university. Specifically, the included studies reported that the mezzo level of DT encourages more digital natives to design engineering educational programs [40], to provide students with better and alternative educational resources [42], and to support faculty to focus more on teaching students how to learn [43].

3.4.3. Macro Level

The macro level focuses primarily on the promoted pedagogical outcomes. The results of the 13 included studies show that DT should give more people (including students, teachers, experts, employers, professionals, and regulatory organizations) access to online data and resources [33–35,38,39,42,45], encourage lifelong learning [33,43], and create a new digital culture [45]. Moreover, it should promote technological and pedagogical innovation in learning practices, educational management, and communication from a broader sociocultural perspective [40,42,44,45]. Technically, DT supports institutions to invest in developing their IT infrastructure and to improve technology use, monitoring, control, design, and programming [43]. Economically, DT also entails benefits such as cost savings and increased profitability, resource efficiency, and productivity [33–35,37–39,43]. DT has also been reported to improve the international applicability of online resources, promote global citizenship, and increase the emphasis placed on addressing global challenges [38–40].

4. Discussion of the Findings and Implications for Research and Practice

In the previous section, we reported our findings from the review. Below, we discuss possible connections between the drivers and ideologies underlying DT, the relationship between technology and pedagogy, and the anticipated outcomes proposed by DT frameworks and models in engineering education. The emergence of different types of digitalization is discussed in relation to frameworks for learning activities and modes of learning in order to explore possible connections between them.

In response to our first research question, this study first analyzed the underlying drivers of DT in the engineering field. The drivers identified were divided into four categories, namely learning process, organization, society, and market. Studies focusing on market-oriented drivers were the most numerous. This might reflect the fact that the field of engineering education was not founded on any particular ideological or philosophical basis but rather developed in a tight relationship with industry, with a very specific focus on application and less emphasis on basic or fundamental research [46,47]. Discourses on marketization, applicability, functionalism, interdisciplinarity, employability, problem-solving, etc., are quite strong in the engineering field, with some of these exemplified in the focus on versions of industry (3.0, 4.0, and now 5.0). Therefore, the underlying drivers of DT in engineering education may be distinct from those in other fields of higher education [23]. It is thus recommended that greater emphasis be placed on basic pedagogical values and their entanglement with technology to influence DT in engineering education to promote learning processes. This could include, for example, pedagogical thinking or combinations of pedagogy with technology when implementing new digital technology in education and accommodating the current need for rapid educational change.

In addition, these drivers are reflected in the ways in which DT models and frameworks are informed and oriented. However, management, strategy documents, providers of digital technologies, and other powerful stakeholders rarely declare understandings, ideological drivers, or value statements in relation to DT, which can make it challenging to deduce the logic and drivers underlying DT. Thus, it is not always apparent how DT frameworks are informed or to what specific understandings, purposes, and directions for engineering education they relate. Examining DT frameworks or models in the engineering education field by means of the process used in this study suggests a way to connect drivers to pedagogical and technological understandings, making these connections more visible and comparable. Fawns [31] warned that deterministic thinking in digital education can lead to simplistic thinking about complex problems. The author suggested that technology and pedagogy should be considered as entangled, i.e., mutually shaping each other, rather than as separate, isolated phenomena. Such an approach can lead to better understanding and innovation when using digital technology in engineering education. Based on this review, we categorize DT models and frameworks in the context of engineering as tech-driven, pedagogy-driven, or entangled. However, this work also calls for more explicit and structured frameworks to facilitate the understanding, analysis, and evaluation of DT in engineering education and more awareness among engineering educators of the need to carefully consider the values and ideologies driving DT in connection with the complex relationship between digital technology and pedagogy.

In our findings, different digital tools were identified and classified according to their role in learning. The types of digitalization identified included content digitalization, facilitation of cognitive processes, physical emulation, interaction, and creation. The use of digital tools in learning activities focused mainly on content digitization and interaction. As Kræmmergaard and Sayer [16] point out, digital replicas of analog practices, such as face-to-face courses using Zoom, will not lead to transformation. Engineering students and faculty should explore and co-create new, digitally native educational practices and experiences that, e.g., enhance collaborative work [34,42,44] and allow for better accessibility and scalability [34]. Furthermore, engineering institutions should challenge themselves to overhaul their own core services through digitalization and integrate more complex systems, for example, by using learner analytics to create more personalized learning experiences [40,44]. The integration of emerging tools such as AI, machine learning, and AR/VR could allow the creation of new patterns and opportunities in decision-making [37,41,43,45].

However, few of the included studies described in detail how certain digital tools could be used in relation to supporting specific learning activities and modes. There was also a lack of discussion about how tools enable creation based on human input (e.g., AI-related tools). Therefore, it would be of interest for future research to collect or conduct empirical, micro-level studies in engineering education to further investigate various types of digitalization and the possible connections between different types, activities, and modes of learning, and possibly the actual learning outcomes. Establishing such connections might be valuable for developing pedagogical frameworks and designing learning modes and activities. For instance, some prior studies have provided greater understanding of activities and modes of learning. Laurillard [48], for example, described six learning activities (acquisition, inquiry, discussion, practice, collaboration, and discussion), while Chi [49] and Chi and Wylie [50] identified the four overt modes of learning in the interactive–constructive–active–passive (ICAP) framework. Linking those activities and modes of learning with a typology of digital tools might require further exploration of the introduction of digital technologies, such as VR, and the extent to which such tools support students' active, passive, constructive, or interactive learning in engineering education. Similarly, it is also interesting to see how digital tools and activities that facilitate cognitive processes, such as mind maps and project timelines, can be connected to activities such as inquiry and constructive modes of learning [30]. Under extreme circumstances such as the COVID-19 lockdowns, one of the greatest challenges for DT has been engineering teachers' and students' lack of digital competences, resulting in negative learning experiences that lead to widespread resistance to DT [51,52]. A typology, such as the one suggested in this study, could also facilitate engineering teachers better aligning digital technology with specific learning activities and goals instead of merely focusing on its implementation [53], leading to more meaningful experiences for both teachers and students, and in turn to a reduction in such resistance.

To address the third research question, the 13 studies were examined to identify the anticipated outcomes and challenges of DT in engineering education. Despite the various benefits of DT in engineering education that have been reported at the micro, mezzo, and macro levels, relatively little is known about how DT promotes institutional development in universities. Changing institutional digitalization trends takes time, and engineering students and staffs need to adapt to new practices, invest resources, and promote digitalization skills with the support of their institutions [52]. Therefore, future research and practice in university-level education could pursue the development of curricula supporting engineering students' digital literacy and offering more hands-on, problem-based learning activities. It would also be beneficial to develop online courses, microcredentials, and certificate programs to create more flexible and autonomy in educational paths that better promote individual learner agency, which has been called for especially in first year engineering programs, for students from diverse cultural or interdisciplinary backgrounds [54–56], and for professional engineers' continuing education to upgrade their technical skills and to build partnerships with companies to accommodate industrial digitalization needs.

5. Conclusions

Through a literature review, this study identified 13 articles to describe the types of DT frameworks advanced in the existing literature in the engineering education field, the underlying drivers for DT transformation in engineering education, the types of digital tools adopted through DT processes and how they are implemented, and the anticipated outcomes reported within each framework. This study identified several gaps and phenomena that have possible implications for engineering education research and practice that could be further explored in micro-level empirical studies. These include the possible connections between the drivers, beliefs about the relation between digital technology and pedagogy, the emergence of a typology of digitalization in relation to learning activities and modes, and more focus on the outcomes from the university level.

The main limitations of this study were the use of five databases and the restriction to peer-reviewed conference proceedings and journal articles published in the English language. Other databases and types of sources, such as institutional reports and strategy papers, non-academic articles, and sources in other formats, were not included in the analysis. However, the limitations stemming from the use of a limited number of databases have been reduced by manually checking the reference lists of selected papers and searching key journals and the proceedings of major conferences in the engineering education field. Furthermore, the results reported in the studies mentioned are dependent on what the studies chose to observe, and the findings are likely subject to the file-drawer effect, where non-significant findings are less likely to be reported. The issue of potential bias from limited sources may have been reduced by the auditing process described in Section 2.4, which may also have minimized the risk of researcher bias and allowed us to present our results more objectively. Transformative innovations in education might go beyond the known contexts of formal education and therefore might be difficult to identify and include. Therefore, another limitation might be the exclusion of manuscripts describing educational innovations which did not use the term "digital transformation". To address this limitation, instead of merely employing database searching, this study made efforts to supplement with manual searching (key journal and conference searching and citation list searching) to identify articles where the level of indexing is limited due to errors, inaccuracy, or concepts lacking appropriate subject headings. In this literature review study, narrowing down the search strings could also help us restrict the included articles to a manageable number for screening process, differentiate DT from other interrelated terms, and identify more DT-related articles. Using this search string is also suggested by two recent systematic review studies within higher education to capture a more holistic picture on DT [22,23].

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