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Research Article

AIRI AS AN ADAPTIVE FRAMEWORK LINKING DIGITAL EDUCATION MANAGEMENT TO HOLISTIC INDUSTRY 4.0 READINESS

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Abstract
As schools rapidly adopt Education Management Information Systems (EMIS), data-driven decision-making, and technology-enhanced instruction, there is growing interest in understanding how digital education management shapes students' readiness for Industry 4.0. This study aims to clarify the systemic role of digitalization in developing students' cognitive, digital, and socio-adaptive competencies by proposing a comprehensive evaluation framework. A qualitative, theory-driven design was employed, synthesizing literature on digital education management, evaluation models, and readiness theory. The study developed the Adaptive-Integrated Readiness Index (AIRI), integrating concepts from CIPP, TPACK, and existing digital readiness indices to assess the combined influence of infrastructure, managerial processes, technological integration, instructional innovation, and institutional policies on multidimensional student readiness. Analysis indicates that current digitalization initiatives are fragmented and that prevailing evaluation approaches often focus narrowly on technology tools or user acceptance. AIRI demonstrates that students' readiness is best understood as a dynamic capability shaped by interconnected digital management processes rather than isolated interventions. By reconceptualizing readiness as an emergent property of integrated digital management, AIRI provides policymakers and practitioners with a diagnostic framework to assess the impact of digital initiatives, identify areas for improvement, and align technology investments with Industry 4.0–oriented learning outcomes. The study highlights the importance of systemic evaluation to ensure that digitalization efforts translate into meaningful, holistic student competencies.

Keywords: Applied Framework, Digital Education, Education Management, Evalution Model, Learning Outcomes.

INTRODUCTION

The Fourth Industrial Revolution is reshaping economic, industrial, and social structures through the convergence of Artificial Intelligence (AI), the Internet of Things (IoT), cloud computing, and other advanced technologies (Prasetyo & Sutopo, 2018; Sahai, & Rath, 2021; Chou, 2018). These

transformations intensify the global demand for digital literacy and twenty-first-century competencies to prevent widening disparities in competitiveness among nations and individuals (Schwab, 2016). UNESCO similarly emphasizes the urgency of national strategies that equip future workers with digital skills through integrated and adaptive learning systems (Vosloo, 2018). Consequently, education systems worldwide must undergo rapid change, as teaching and learning can no longer rely solely on traditional, place-bound, and teacher-centered practices. Instead, they must adopt digital solutions that enable flexible, personalized, and scalable learning environments (Hodges et al., 2020; Ramírez-Montoya, et al., 2022).

Digital transformation in education is inseparable from broader developments in the digital economy, where Information and Communication Technology (ICT) functions as the backbone of innovation and institutional performance (Kurniawati, 2020). Historically, technology played a supplementary role in education through audiovisual tools and instructional media. Today, however, technology has become integral to how education is administered, delivered, and evaluated. This shift has driven the digitalization of education management—marked by the transition from manual administrative processes to integrated, technology-enabled systems for planning, data management, governance, and communication (Heinich et al., 1985; Ngoc et al., 2020; Mohd et al., 2024; Diaz-Garcia et al., 2022).

At the center of this transformation are Education Management Information Systems (EMIS), which manage student records, curriculum data, finance, teacher performance, and institutional reporting (Tolley & Shulruf, 2009). EMIS and related digital ecosystems—including Learning Management Systems (LMS), cloud-based platforms, and school communication systems—enable streamlined administration, improved accuracy, and enhanced transparency. They also facilitate proactive decision-making through real-time data analytics, supporting early interventions and more strategic resource allocation (Çela et al., 2024; Santosa & Jazuli, 2022).

A growing body of research demonstrates the potential of digital management systems to enhance learning quality, stakeholder engagement, and governance (Said, 2023; Subroto et al., 2023; Hermawansyah, 2021). Digital platforms reduce repetitive administrative burdens, allowing educators to focus on instructional innovation, long-term planning, and student-centered support (Nadifa & Zulvani, 2024; Kasogi, 2024). They also strengthen parent–school communication and increase accountability, reinforcing public trust in educational institutions (Kusumaningrum et al., 2024).

More importantly, digitalization is shifting educational priorities from knowledge transmission toward competency-based development, in line with the demands of Industry 4.0. As automation expands, human value increasingly lies in mastering higher-order skills, adaptability, creativity, and problem-solving—competencies that underpin Education 4.0 (Wang et al., 2023; Lassari, 2025; Manuputty et al., 2025). Digital tools can enhance these competencies by enabling autonomous learning, collaboration, critical thinking, and digital fluency (Trilling & Fadel, 2009; Selwyn, 2016; Alhazmi & Rahman, 2019).

In Indonesia, major investments in digital infrastructure and initiatives such as AI-driven teacher tools, LMS adoption, and regional smart-school programs illustrate significant progress (Prabowo et al., 2021; Budiman et al., 2024; Astalini et al., 2024). Yet implementation remains uneven, with persistent gaps in access, digital competence, institutional culture, and data security (Maharani & Meynawati, 2024). Consequently, while digitalization continues to expand, its actual contribution to shaping student readiness for Industry 4.0 remains poorly understood.

Existing evaluation frameworks—such as CIPP, Kirkpatrick, digital readiness indices, and acceptance models—capture only isolated aspects of digitalization. They often focus on user satisfaction, technological adoption, or learning outcomes, without accounting for the interactions between digital management systems, institutional processes, and multidimensional student readiness (Ng, 2012; Stufflebeam & Zhang, 2017; Zhang et al., 2011). Moreover, current readiness measurement tools rarely incorporate adaptive, managerial, and ecosystem-level factors, despite evidence that institutional support, administrative efficiency, and integrated data systems strongly shape readiness (Al-Araibi et al., 2019; Ifenthaler & Yau, 2020).

These gaps point to an urgent need for an evaluation framework capable of capturing how digital education management—beyond the use of technology in classrooms—actually mediates and shapes student readiness for Industry 4.0. Such a model must recognize readiness as a dynamic construct influenced by cognitive, technical, socio-emotional, motivational, and adaptive dimensions (Pratama et al., 2023; Suyitno et al., 2020; Bandura, 1997). It must also reflect the complex interactions between infrastructure, digital governance, pedagogical practices, and policy integration.

In response, this study proposes the *Adaptive Integrated Readiness Index* (AIRI)—a comprehensive evaluation model designed to examine the impact of digitalized education management on student readiness for the Fourth Industrial Revolution. AIRI integrates digital, managerial, adaptive, and policy dimensions, offering a holistic lens through which to assess how digital transformation contributes to institutional effectiveness and learner competencies. By providing actionable insights for policymakers, school leaders, and practitioners, this framework aims to enhance the strategic implementation of digital transformation initiatives and strengthen education systems' responsiveness to Industry 4.0 (Lee & Martin, 2020). Ultimately, redefining how digital education management is evaluated is essential not only for improving accountability and guiding technological investment but also for ensuring that digitalization genuinely contributes to the development of the competencies demanded by a rapidly transforming global landscape (Peiró, & Martínez-Tur, 2022).

LITERATURE REVIEW

Digital Education Management

Digital education management has become a central topic in contemporary scholarship as educational institutions increasingly integrate ICT infrastructure to support both administrative and pedagogical functions. Modern digital education management is not limited to traditional uses of technology (e.g., online gradebooks or attendance tracking), but rather encompasses a systemic transformation in how institutions govern, plan, and deliver education. This includes the deployment of Learning Management Systems (LMS), data analytics tools, cloud-based administrative platforms, and leadership strategies geared toward digital maturity. As Gorshenin (2018) argues, educational IT-ecosystems should evolve beyond traditional LMS into fully integrated digital platforms that support not only content delivery but communication, analytics, and decision support.

A critical component of digital education management is governance. Institutional leadership must not only invest in technology, but also develop coherent digital strategies, policies, and ethical frameworks. García-Peñalvo (2021a) emphasizes that digital transformation raises serious governance challenges—particularly around data privacy, learning analytics, and equity. Without strategic leadership, digital platforms may be underutilized, used in ad hoc ways, or lead to unintended negative consequences, such as surveillance or exclusion of disadvantaged learners.

Pedagogical innovation is another key dimension. Digital education management must foster not just the infrastructure but also the pedagogical practices that take advantage of that infrastructure. This includes blended learning, adaptive learning systems, micro-credentials, and analytics-based feedback loops. These pedagogical practices rely heavily on coordination between IT departments, instructional designers, and academic leadership to ensure that digital tools are pedagogically aligned rather than siloed. In addition, human capital development is essential. Teachers, administrative staff, and leaders require digital literacy, not only in using the technical tools, but also in making data-driven decisions. Recent studies indicate that micro-courses can be highly effective for building digital competence among faculty. For instance, a literature review by researchers revealed that micro-courses help instructors strengthen areas of low digital proficiency in flexible, contextualized ways (Turner, 2019). Such capacity-building is critical, because even with advanced infrastructure, the success of digital management depends on people who know how to leverage it.

Continuous monitoring and evaluation form the backbone of digital education management. Institutions need to measure digital maturity, adoption levels, and usage patterns to make informed decisions. For example, a recently validated instrument called *DT-Smarty* assesses technological maturity of Higher Education Institutions (HEIs) across dimensions like cyber-physical systems, data analytics, organizational platforms, and security/continuity plans (Redecker, & Punie, 2013). This kind of data-driven evaluation enables institutions to identify gaps, allocate resources strategically, and steer their digital transformation in a sustainable, evidence-based way.

Industry 4.0 Student Readiness

Student readiness for Industry 4.0 (4IR) refers to learners' preparedness to engage with highly digitalized, automated, and intelligent environments, both academically and professionally. In the context of the Fourth Industrial Revolution, readiness is not merely about owning technology—it involves acquiring digital competencies, self-regulated learning strategies, adaptive mindsets, and socio-emotional resilience. Alshammari (2024) has empirically shown that technical skills, attitudes, and background

knowledge significantly influence students' readiness to use 4IR technologies, highlighting that readiness is multidimensional.

One crucial dimension is digital competence, which includes information/data literacy, communication, content creation, security, and problem-solving in digital environments. Beke, Horváth, and Takács-György (2020), citing Kluzer and Priego (2018), define digital competence in this broad sense, pointing out that students must not only consume digital content but also create and interact with it in safe and meaningful ways. This competence is a foundation for navigating future workplaces shaped by AI, IoT, and big data. Another key dimension is self-regulated learning and metacognition. In 4IR learning environments—especially blended or fully online formats—students must manage their own learning, set goals, monitor progress, and adapt strategies. This capability is increasingly vital, as autonomous learning becomes more common and learners navigate complex digital platforms with minimal direct supervision.

Psychological readiness is also critical. Students need self-efficacy, openness to innovation, and resilience to technical failures. In her study, Alshammari (2024) found that attitude toward technology strongly mediates readiness. Without confidence and positive disposition, even students with technical knowledge may resist using advanced tools or fully engage with digital learning. In addition, institutional support and environment significantly shape readiness. Rakhmadi, Lestari, Suriansyah, Nofirman, and Rukhmana (2022) argue that policy, resource allocation, teacher training, and infrastructure influence how ready students actually feel and can perform. Even highly skilled students may underperform in 4IR contexts if their institution lacks robust digital infrastructure, guidance, or support systems. Thus, student readiness must be understood not as a purely individual attribute, but as the product of interaction between learners and their institutional environment.

Evaluation Models (CIPP, TPACK, Readiness Indices, etc.)

Evaluation models play a foundational role in understanding and guiding digital transformation in education. Among the most widely used is the CIPP model (Context, Input, Process, Product), developed by Stufflebeam. In educational settings, CIPP supports comprehensive program evaluation by assessing contextual needs, the adequacy of resources, the fidelity of implementation, and the outcomes of interventions. While CIPP is versatile and widely adopted, it has limitations in the Industry 4.0 context: it does not explicitly account for technological maturity, data governance, or predictive readiness for future innovations.

Another influential theoretical framework is TPACK (Technological, Pedagogical, and Content Knowledge), which describes the types of knowledge educators need to integrate technology effectively (Mishra & Koehler, 2006). TPACK helps to explain how teachers navigate the intersection between content, pedagogy, and technology. However, TPACK is focused primarily on teacher competencies, and does not address institutional infrastructure, learner readiness, or digital governance. As such, while TPACK is critical for pedagogy, it offers only a partial lens for evaluating comprehensive digital readiness. In addition, technology acceptance models, such as the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), are widely used to explain how and why individuals adopt new technologies. They typically explore perceived usefulness, ease of use, behavioral intention, and other psychosocial drivers. Although these models are useful for understanding adoption behavior, they fall short of evaluating systemic readiness. They do not sufficiently address institutional capacity, technological infrastructure, or strategic governance.

Researchers have also developed readiness indices, often through survey instruments, to gauge how prepared students or institutions are for digital learning or transformation. These indices typically cover digital access, skills, attitudes, and resource readiness. While valuable, many existing indices are static, capturing a snapshot of readiness rather than tracking changes over time. They generally lack predictive power or adaptability to emerging technologies like cyber-physical systems or AI. More recently, maturation models tailored to Industry 4.0 contexts have emerged. For example, the DT-Smarty Instrument (González-Pérez et al., 2025) was developed and validated to assess an institution's digital maturity specifically in terms of cyber-physical systems, educational platforms and analytics, organizational platforms, and continuity/security planning. This model is a significant advance because it integrates technological infrastructure, organizational strategy, and governance in a way that is specifically relevant for 4IR digital transformation.

Gaps in Existing Evaluation Approaches

Despite the proliferation of evaluation models, critical gaps remain, particularly regarding their adequacy for assessing readiness in digital education management aligned with Industry 4.0. First, there is a significant fragmentation of focus. Many evaluation tools concentrate on a single dimension (e.g., teacher readiness via TPACK, or technology adoption via TAM) but fail to integrate critical domains such as infrastructure, governance, pedagogy, and student competence as parts of a unified system. This fragmentation can lead to siloed decision-making and disjointed transformation strategies.

Second, adaptability is a major shortcoming in existing tools. Most readiness indices and evaluation frameworks provide static assessments at a single time point, lacking mechanisms to update themselves dynamically as technologies and institutional contexts evolve. Given the accelerating pace of technological change associated with 4IR, a readiness model that cannot adapt to new paradigms (e.g., AI, IoT, cyber-physical systems) becomes quickly obsolete. Third, many models lack predictive capability. While they assess current readiness, they often fail to forecast future needs. This is problematic for institutional planning, as educational leaders need to make strategic decisions about resource allocation, technological investment, and capacity building. Without foresight, institutions risk being reactive rather than proactive in their digital transformation journey.

Fourth, the ethical and governance dimensions of digital transformation are often under-examined. Data privacy, equity, learning analytics ethics, and transparency are central concerns in digital education, yet they are rarely embedded in mainstream readiness or maturity models. As García-Peñalvo (2021b) warns, ignoring these dimensions may lead to institutional decisions that compromise trust, inclusivity, or privacy. Therefore, existing models often lack context sensitivity. Institutional readiness and student competence vary greatly depending on socio-economic, cultural, and regional factors. A one-size-fits-all readiness assessment fails to account for these differences, which are critical in multi-national or resource-diverse environments. Instruments like DT-Smarty begin to address this by combining technical maturity with organizational context, but a truly holistic model remains elusive.

Conceptual Basis for an Adaptive-Integrated Readiness Index (AIRI)

In response to the identified gaps, the concept of an *Adaptive-Integrated Readiness Index* (AIRI) emerges as a theoretically grounded and practically relevant solution. The fundamental premise of AIRI is to offer a comprehensive, dynamic, and ethically informed evaluation framework that integrates the multiple dimensions of digital education readiness: institutional governance, infrastructure, educator capacity, and student preparedness. By doing so, AIRI addresses the fragmented, static, and predictive limitations of existing models. The conceptual foundation of AIRI draws on socio-technical systems theory, which posits that organizations consist of interdependent social and technical subsystems (Pasmore, 1995). In the context of digital education, the social subsystem includes educators, administrators, and learners, while the technical subsystem comprises ICT infrastructure, platforms, and data systems. A socio-technical lens ensures that readiness is not measured purely in terms of hardware or software, but in how these tools are embedded in institutional practices, governance, and culture.

Additionally, AIRI incorporates innovation diffusion theory (Rogers, 2016). According to Rogers, the adoption of innovations depends on characteristics such as relative advantage, compatibility, complexity, trialability, and observability. In AIRI, these attributes can be operationalized as part of readiness indicators—e.g., how compatible new digital tools are with existing institutional culture, or how observable the benefits of learning analytics are to decision-makers. AIRI is also grounded in learning analytics theory. Rather than relying solely on self-report or cross-sectional survey data, the index aims to leverage predictive analytics and longitudinal usage data to forecast readiness trajectories. This modern approach allows institutions to identify early-warning signals (such as low student engagement or inadequate infrastructure usage) and proactively address them.

Operationally, AIRI has four interlinked domains: (1) Institutional Governance Readiness, including digital strategy, policies for data use, leadership commitment, and budget allocation; (2) Infrastructure Readiness, encompassing LMS maturity, cybersecurity, interoperability, and continuity planning; (3) Educator Readiness, which covers digital pedagogy, assessment design, and innovation mindset; and (4) Student Readiness, measuring digital competence, self-regulation, psychological readiness, and access to technology. Finally, adaptivity is a core principle. AIRI must not be a fixed tool but a dynamic index that can be recalibrated over time. Institutions should be able to weight dimensions differently based on their context (e.g., developing *vs.* advanced HEIs), and periodically update the index

as new technologies emerge. This adaptivity ensures that AIRI remains relevant, forward-looking, and aligned with the demands of the Fourth Industrial Revolution (*see* Table 1 and Table 2).

Table 1. Key Constructs and Indicators of AIRI

Domain	Indicators / Metrics	Sources
Institutional Governance	Leadership commitment, digital policy alignment, budget allocation, strategic planning, monitoring	Schwab, 2016; UNESCO, 2023; Abnoulgid et al., 2025
Infrastructure Readiness	LMS maturity, interoperability, cybersecurity, cloud-based systems, accessibility, continuity planning	OECD, 2016; Gadre & Deoskar, 2024; Chounta et al., 2024
Educator Readiness	Digital pedagogy skills, professional development, ICT integration, willingness to adopt innovations	Mishra & Koehler, 2006; Trilling & Fadel, 2009; Ifenthaler & Yau, 2020
Student Readiness	Digital literacy, 21st-century skills (critical thinking, creativity, collaboration, communication), adaptability, self-regulation	Wang et al., 2023; Lassari, 2025; Al-Araibi et al., 2019; Ng, 2012
Adaptivity / Feedback Loop	Recalibration based on analytics, institutional context, and emerging technologies	Means et al., 2014; Ifenthaler & Yau, 2020; Martin et al., 2020

Table 2. Comparison of Existing Evaluation Models

Model / Framework	Focus / Scope	Strengths	Limitations / Gaps
CIPP (Context, Input, Process, Product)	Program evaluation, outcome measurement	Comprehensive, widely used	Limited in capturing digital management integration
TPACK (Technological, Pedagogical, Content Knowledge)	Teacher readiness for digital teaching	Focused on pedagogical-technology synergy	Does not include governance, infrastructure, or student readiness
Digital Readiness Indices (e.g., D4L, HEI Digital Maturity)	Institutional ICT capacity	Quantitative, comparative	Often ignores adaptability, student learning outcomes
Existing Student Readiness Indices	Assess student digital and cognitive readiness	Easy to administer, relevant for learner-focused interventions	Fragmented; rarely integrates institutional or educator readiness
AIRI (Proposed)	Integrated, adaptive evaluation of digital education management and student readiness	Holistic, adaptive, considers governance, infrastructure, educators, students	Requires complex data collection and analytics capability

Table 1 and Table 2 collectively illustrate the conceptual and comparative foundation of the Adaptive-Integrated Readiness Index (AIRI). Table 1 details the key constructs and measurable indicators of AIRI across five domains: institutional governance, infrastructure readiness, educator readiness, student readiness, and adaptivity/feedback mechanisms. Each domain encompasses specific metrics, such as leadership commitment, LMS interoperability, digital pedagogy skills, 21st-century competencies, and recalibration based on analytics, drawn from authoritative sources including UNESCO (2023), Mishra and Koehler (2006), and Wang (2023). This table operationalizes AIRI's multidimensional approach, showing how governance, technology, pedagogy, learner capacity, and adaptive mechanisms interconnect to support Industry 4.0 readiness. Table 2 situates AIRI within the broader landscape of existing evaluation models by comparing its focus, strengths, and limitations with widely used frameworks such as CIPP, TPACK, and other digital or student readiness indices. Unlike prior models, which often focus

on single aspects—either program outcomes, teacher competencies, or institutional ICT capacity—AIRI integrates governance, infrastructure, educators, and student competencies while emphasizing adaptivity to evolving technologies. Together, the tables demonstrate both the operational structure of AIRI and its added value over conventional evaluation models, highlighting its potential as a holistic and adaptive tool for assessing digital education management and student readiness.

RESEARCH METHOD

This study employs a qualitative, theory-driven, conceptual, and normative approach to investigate how digital education management shapes student readiness for Industry 4.0. A qualitative design is appropriate because the study seeks to explore complex interactions, underlying mechanisms, and conceptual linkages rather than statistical correlations. The research is theory-driven in that it systematically engages with established educational, technological, and management theories, including the Technological Pedagogical Content Knowledge (TPACK) framework, Education Management Information Systems (EMIS) theory, and digital readiness models. Conceptually, the study aims to synthesize these theoretical perspectives into a cohesive, integrated framework. The normative aspect involves the critical assessment of best practices, policy recommendations, and strategic implications for enhancing digitalized education management. This combination ensures that the proposed Adaptive-Integrated Readiness Index (AIRI) is grounded in theory, practically relevant, and adaptable to diverse educational contexts.

The primary sources of data for this study include scholarly literature, theoretical models, and policy documents relevant to digital education management and student readiness. The literature corpus encompasses peer-reviewed journal articles, conference proceedings, and seminal books on Industry 4.0, digital pedagogy, learning management systems, and educational evaluation frameworks. Theoretical models reviewed include CIPP, TPACK, digital readiness indices, and other relevant assessment tools. Policy documents comprise national and regional digital education strategies, government guidelines, and UNESCO recommendations regarding digital literacy and educational transformation. By integrating academic, theoretical, and policy perspectives, the study ensures a comprehensive understanding of the domain and identifies gaps in current evaluation practices.

The research procedure for developing the *Adaptive-Integrated Readiness Index* (AIRI) follows a structured five-step process designed to ensure rigor, comprehensiveness, and practical relevance. The first step, identification and selection of models, involves an extensive review of theoretical, conceptual, and empirical frameworks related to digital education management and student readiness, with selection criteria emphasizing relevance, empirical support, theoretical robustness, and applicability within Industry 4.0 contexts. The second step, thematic synthesis, entails extracting core themes and dimensions from the selected models, systematically coding recurring concepts such as institutional governance, infrastructure readiness, educator competencies, and student learning outcomes. The third step, analytical mapping, focuses on elucidating relationships among the identified themes, highlighting interdependencies and causal linkages to inform the integration of domains and indicators into a coherent framework. In the fourth step, AIRI framework construction, the synthesized themes and mapped relationships are consolidated into a unified, multidimensional model encompassing governance, infrastructure, educator readiness, student readiness, and adaptive feedback mechanisms. Finally, the fifth step, expert validation, involves reviewing the framework with practitioners, policymakers, and academic experts to assess content validity, practical applicability, and contextual adaptability, ensuring that AIRI is both theoretically sound and operationally robust across diverse educational settings.

Given the conceptual and qualitative nature of the study, instruments focus on structured documentation and systematic coding. Data collection involves extracting information from academic publications, policy documents, and existing frameworks. A data extraction matrix is used to systematically record key constructs, indicators, and evaluation criteria from each source. Where expert validation is applied, structured questionnaires, interviews, or Delphi techniques can be employed to collect feedback on framework comprehensiveness, clarity, and applicability. All data are collected and stored in a digital repository to ensure traceability and transparency in the analytic process.

The data analysis process for developing the Adaptive-Integrated Readiness Index (AIRI) employs a combination of qualitative techniques to ensure a rigorous, systematic, and theory-driven framework. Content analysis serves as the initial step, involving a systematic examination of academic literature, policy documents, and theoretical models to identify recurring concepts, definitions, and theoretical positions related to digital education management and student readiness. Following this,

thematic coding is conducted to extract, categorize, and organize core themes, sub-themes, and indicators across the reviewed models, enabling coherent synthesis of the multidimensional constructs. Model integration and construct mapping then allows for cross-comparison of existing frameworks to identify complementary and overlapping dimensions, which informs the conceptual structure and practical content of AIRI. Additionally, comparative analysis is applied to highlight the strengths, gaps, and limitations of prior evaluation approaches, ensuring that the proposed framework addresses the full spectrum of institutional, infrastructural, educator, and student readiness while incorporating adaptive feedback mechanisms. Collectively, these methods provide a transparent, systematic, and evidence-based foundation for constructing AIRI, supporting both theoretical robustness and practical applicability in assessing digital education management within the evolving context of Industry 4.0.

RESULTS AND DISCUSSION

Mapping Digital Education Management Components and Their Implications

The analysis of literature, policy documents, and existing evaluation frameworks reveals four core components of digital education management that significantly influence student readiness in the context of Industry 4.0: (1) institutional governance, (2) infrastructure readiness, (3) educator competencies, and (4) the digital learning environment. Institutional governance encompasses leadership commitment, alignment of digital policies, budget allocation, strategic planning, and performance monitoring. This finding aligns with the arguments of Fullan (2007) and Schwab (2016), who emphasize that strategic leadership and governance are critical drivers for systemic educational transformation.

Infrastructure readiness includes the maturity of Learning Management Systems (LMS), interoperability, cybersecurity measures, cloud-based platforms, accessibility, and continuity planning. OECD (2016) underscores that robust ICT infrastructure is the foundational backbone for digital transformation in education, enabling scalable and efficient delivery of learning processes. Educator competencies cover digital pedagogical skills, professional development, ICT integration, and willingness to adopt innovations. These dimensions are consistent with the TPACK framework proposed by Mishra and Koehler (2006), which highlights the critical intersection of technological, pedagogical, and content knowledge for effective digital teaching.

The digital learning environment provides flexible, personalized learning experiences and promotes competency-based approaches that prepare students for the dynamic requirements of the Fourth Industrial Revolution (Voogt & Roblin, 2012). This confirms that digital education management constitutes a complex ecosystem, where interdependent components interact dynamically to influence student readiness. Figure 1 illustrates the interrelationships between these components, reflecting systems theory Ludwig von Bertalanffy (1901-1972) as cited by Hammond (2003), which posits that the constituent elements of an organization work synergistically to achieve overall objectives.

Further analysis highlights the critical role of governance and infrastructure as enabling conditions for both educator and student readiness. Without strategic leadership and adequate infrastructure, even technologically proficient educators cannot fully translate digital tools into effective pedagogical practice, confirming prior observations by Means et al. (2014) and Schwab (2016). These findings underscore the importance of integrated digital management as a multidimensional and interactive system rather than a collection of isolated interventions.

Multidimensional Student Readiness: Indicators and Conceptualization

Student readiness for Industry 4.0 is inherently multidimensional, encompassing cognitive, technical, socio-emotional, and adaptive competencies. Cognitive and digital literacy competencies, including critical thinking, creativity, problem-solving, and digital literacy, are central to employability and lifelong learning in the 21st century (Trilling & Fadel, 2009; Lassari, 2025). Technical readiness includes the ability to navigate LMS platforms, utilize digital resources effectively, and make data-informed decisions, as highlighted by Ifenthaler and Yau (2020).

Socio-emotional readiness, including self-regulation, resilience, and collaboration, draws on Bandura's (1997) self-efficacy theory, emphasizing the interplay between confidence, motivation, and performance outcomes. Adaptive readiness involves the capacity to respond to evolving technologies, curriculum changes, and novel problem contexts. This aligns with Schwab's (2016) assertion that flexibility and adaptability are core competencies in the Fourth Industrial Revolution.

Through thematic synthesis, these dimensions were operationalized into measurable indicators for the proposed AIRI framework. The integration of these dimensions ensures that evaluation does not

focus solely on digital skill acquisition but also captures cognitive, socio-emotional, and adaptive aspects critical for holistic student development. This multidimensional conceptualization addresses gaps in existing readiness indices, which often remain narrowly focused on either ICT skills or student cognition, without accounting for institutional or educator influences (Al-Araibi et al., 2019; Ng, 2012). Furthermore, the dynamic nature of student readiness highlights the need for a feedback-informed approach, where continuous monitoring of performance data informs adaptive interventions, consistent with theories of experiential learning and adaptive education (Kolb, 1984; Ifenthaler & Yau, 2020). This reinforces the conceptual premise of AIRI as an integrated and adaptive evaluation framework.

Development of the AIRI Conceptual Model: Integration and Adaptive Mechanisms

Based on thematic synthesis and analytical mapping, the Adaptive-Integrated Readiness Index (AIRI) was developed. The framework integrates institutional governance, infrastructure readiness, educator competencies, student readiness, and adaptive feedback mechanisms into a unified model. Institutional governance acts as the primary driver, shaping infrastructure and educator development, which, in turn, influence student competencies. This supports Almeida and Simoes (2019), who argue that managerial efficiency and strategic alignment enable pedagogical innovation and student-centered learning.

The adaptive feedback loop in AIRI ensures continuous recalibration based on emerging data, trends, and technologies, in line with Means et al. (2014), who emphasize evidence-informed, proactive interventions as essential for enhancing student outcomes. By combining macro-level governance and micro-level student competencies, AIRI bridges the gap between policy, management, and learning practice, creating a coherent and theoretically grounded model for evaluating digital education management.

Notably, the integration of adaptive mechanisms addresses a limitation of existing models, which often adopt a static or linear approach, failing to accommodate ongoing technological evolution or dynamic learning needs (Martin et al., 2020). AIRI operationalizes the theoretical principle that educational ecosystems function as interconnected and adaptive systems, as proposed in systems theory (von Bertalanffy) and organizational learning frameworks (Argyris & Schön, 1996).

Framework Structure, Indicator Relationships, and Theoretical Alignment

The AIRI framework consists of five interrelated domains: (1) governance, (2) infrastructure, (3) educator readiness, (4) student readiness, and (5) adaptive feedback. Table 3 maps each domain to specific indicators, demonstrating hierarchical and interdependent relationships. Governance directly influences infrastructure readiness, which mediates educator competencies. Educator readiness, in turn, affects student readiness, while adaptive feedback mechanisms enable systemic recalibration to optimize outcomes.

These multidirectional relationships are conceptually aligned with systems theory and adaptive learning theories, which posit that continuous interaction among components produces emergent properties at the system level (Hammond, 2003; Kolb, 1984). The integration of governance and adaptive feedback ensures that AIRI not only measures current readiness but also guides dynamic improvements in digital education management and learning outcomes. Moreover, the framework operationalizes contemporary educational management theories emphasizing evidence-based decision-making, transparency, and accountability (UNESCO, 2023; OECD, 2016). By capturing both direct and mediated effects of management components on student readiness, AIRI provides a more comprehensive and realistic representation of the educational ecosystem than existing models, such as CIPP or TPACK, which tend to focus on isolated domains.

Table 3. Mapping of Digital Education Management Components and Indicators

Domain	Indicators / Metrics	Theoretical Basis / Scholars	Implications for Readiness
Institutional Governance	Leadership commitment, digital policy alignment, budget allocation,	Schwab (2016); Fullan (2007); UNESCO (2023)	Governance drives infrastructure and educator support; aligns strategy with readiness goals

Domain	Indicators / Metrics	Theoretical Basis / Scholars	Implications for Readiness
	strategic planning, monitoring		
Infrastructure Readiness	LMS maturity, interoperability, cybersecurity, cloud systems, accessibility, continuity planning	OECD (2016); Gadre & Deoskar (2024); Chounta et al. (2024)	Enables efficient learning delivery, scalable systems, and secure digital management
Educator Readiness	Digital pedagogy skills, professional development, ICT integration, innovation adoption	Mishra & Koehler (2006); Trilling & Fadel (2009); Ifenthaler & Yau (2020)	Mediates translation of technology into learning practices; enhances student engagement and competency development
Student Readiness	Digital literacy, 21st-century skills (critical thinking, creativity, collaboration, communication), adaptability, self-regulation	Wang et al. (2023); Lassari (2025); Al-Araibi et al. (2019); Ng (2012)	Reflects preparedness for Industry 4.0; shaped by governance, infrastructure, and educator competencies
Adaptive Feedback / Recalibration	Data-informed adjustments, response to emerging technologies, iterative learning	Means et al. (2014); Martin et al. (2020); Ifenthaler & Yau (2020)	Ensures continuous improvement; connects monitoring and decision-making to readiness outcomes

Table 4. Comparison of Existing Evaluation Models *vs*. AIRI

Model / Framework	Focus / Scope	Strengths	Limitations / Gaps	AIRI Advantage
CIPP (Context, Input, Process, Product)	Program evaluation, outcome measurement	Comprehensive, widely used	Limited in capturing digital management integration	AIRI adds integration of governance, infrastructure, and adaptive feedback
TPACK (Technological, Pedagogical, Content Knowledge)	Teacher readiness for digital teaching	Focused on pedagogy-technology synergy	Ignores governance, infrastructure, student readiness	AIRI incorporates educator readiness within broader ecosystem
Digital Readiness Indices (D4L, HEI Digital Maturity)	Institutional ICT capacity	Quantitative, comparative	Often ignores adaptive mechanisms and student learning outcomes	AIRI adds multidimensional student readiness and feedback loops
Existing Student Readiness Indices	Assess student digital and cognitive readiness	Easy to administer	Fragmented; rarely integrates institutional or educator readiness	AIRI links student readiness to governance, infrastructure,

Model / Framework	Focus / Scope	Strengths	Limitations / Gaps	AIRI Advantage
				and educator factors
AIRI (Proposed)	Integrated, adaptive evaluation	Holistic, adaptive, systemic	Requires complex data collection	Captures governance, infrastructure, educator, student readiness, and adaptive recalibration

Table 3 presents the key components and indicators of digital education management across five domains: Institutional Governance, Infrastructure Readiness, Educator Readiness, Student Readiness, and Adaptive Feedback/Recalibration. Each domain is linked to specific metrics and grounded in established theoretical frameworks (e.g., Schwab, 2016; Mishra & Koehler, 2006; Wang et al., 2023). Governance emphasizes leadership commitment and strategic alignment, guiding infrastructure development and educator support, while infrastructure readiness ensures scalable, secure, and interoperable digital systems. Educator and student readiness capture digital pedagogy, ICT integration, and 21st-century skills, reflecting the capacity to translate technology into effective learning. Adaptive feedback enables iterative improvement through data-informed adjustments. Table 4 compares existing evaluation models (CIPP, TPACK, digital readiness indices) with the proposed AIRI framework, highlighting that while traditional models assess specific areas, they often overlook interdependencies across governance, infrastructure, and stakeholders. AIRI provides an integrated, adaptive, and systemic approach, linking all components to support comprehensive assessment and evidence-based decision-making in digital education.

AIRI presents three primary contributions to educational research and practice. First, its adaptive capability enables continuous alignment with technological advancements, learner needs, and institutional priorities, overcoming the static limitations of conventional evaluation frameworks (Schwab, 2016; Ifenthaler & Yau, 2020). Second, its integrative structure links governance, infrastructure, educators, and students, providing a holistic lens absent in most existing models. Third, systemic alignment ensures consistency between policy, management practices, pedagogy, and learning outcomes, echoing recommendations from OECD (2016) and UNESCO (2023) on effective digital education governance. From a policy perspective, AIRI offers a strategic tool for guiding digital transformation, prioritizing investments, and benchmarking institutional progress. For educational institutions, it supports data-driven decision-making, gap analysis, and targeted interventions to enhance learning efficiency and student readiness. Within applied educational science, AIRI operationalizes theory-practice integration, facilitating evaluation, planning, and continuous improvement in digitally managed learning ecosystems.

Despite its comprehensive design, the AIRI framework faces several practical challenges. Implementing a multidimensional evaluation that spans governance, infrastructure, educator, and student readiness demands substantial institutional resources, including time, funding, and technical expertise. Smaller institutions or those with limited digital infrastructure may find it difficult to collect, process, and analyze the necessary data comprehensively. Furthermore, aligning institutional policies and practices with the framework's multidomain requirements may encounter resistance due to organizational inertia or competing priorities. These practical considerations underscore that while AIRI is conceptually robust, its real-world implementation may vary significantly depending on institutional capacity and context.

A second limitation concerns the adaptive feedback component, which is central to AIRI's iterative improvement process. The effectiveness of this mechanism relies on accurate, timely, and comprehensive data collection, as well as robust analytics capable of translating insights into actionable recommendations. Institutions with underdeveloped data systems or limited expertise in educational data analytics may struggle to leverage adaptive feedback effectively, potentially reducing the framework's impact. This highlights the need for complementary tools and training to ensure that feedback loops function as intended.

As a conceptual framework, AIRI also requires empirical validation to establish its generalizability across diverse institutional types, cultural contexts, and educational systems. While its

design draws on established theories and models, the framework's assumptions and interdependencies between governance, infrastructure, educator competencies, and student readiness must be tested in practice. Comparative studies across higher education institutions, vocational schools, and international contexts would help identify potential contextual adaptations and limitations, ensuring that the framework is both flexible and robust in real-world applications.

Future research should focus on several key areas to strengthen AIRI's utility and empirical grounding. First, the development of quantitative indicators and measurement tools is essential for operationalizing each domain and ensuring reliability and consistency in assessment. Second, integrating advanced analytics, such as predictive modeling and learning analytics dashboards, can enhance the adaptive feedback loop and provide evidence-based guidance for institutional decision-making. Third, assessing the framework's predictive validity, particularly its ability to improve student readiness outcomes and overall digital learning effectiveness, will provide crucial evidence of its practical value. Together, these directions will advance AIRI from a conceptual model to a validated, actionable tool for comprehensive digital education management.

CONCLUSION

This study introduces the AIRI framework as a comprehensive and adaptive model for digital education management, integrating Institutional Governance, Infrastructure Readiness, Educator Readiness, Student Readiness, and Adaptive Feedback/Recalibration. Key findings demonstrate that AIRI addresses limitations of existing evaluation models by linking institutional, educator, and student factors within a holistic and systemic approach, while emphasizing continuous improvement through adaptive feedback. The framework contributes theoretically by bridging gaps between program evaluation, teacher readiness, and digital maturity indices, and offers practical guidance for institutions to assess, monitor, and enhance digital learning capacity. Policymakers and practitioners are encouraged to prioritize leadership commitment, resource allocation, infrastructure development, professional development, and student digital competencies, while establishing iterative monitoring mechanisms to respond to emerging technological and pedagogical trends. Future research should focus on empirical validation across diverse contexts, development of quantitative indicators, integration of advanced analytics, assessment of predictive validity, and scalability studies to ensure AIRI's robustness and adaptability across various educational settings.

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AUTHOR CONTRIBUTIONS

Author 1 (*Budi Argap Situngkir*) led the conceptualization of the study, designing the AIRI framework, and overseeing the overall research process. This author was primarily responsible for framing the research questions, integrating theoretical foundations, and ensuring coherence across all sections of the manuscript. Author 2 (*Suwito Eko Pramono*) managed data collection and analysis, translating the theoretical framework into measurable indicators and metrics. This author developed the operational definitions for each domain, analyzed comparative data, and contributed substantially to the methodology and results sections. Author 3 (*Syaiful Amin*) conducted an extensive literature review, critically evaluating existing evaluation models, and synthesizing relevant theoretical and empirical studies. This author drafted the introduction, discussion, and comparative analysis sections, highlighting the unique contributions of the AIRI framework. Author 4 (*Ridwan Arifin*) coordinated manuscript preparation, editing, and formatting, ensuring consistency and clarity across all sections. Additionally, this author integrated feedback from co-authors, polished the final draft, and finalized the structure, language and model of article.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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