Alloys of Change: Digitalizing Metallurgical Engineering Education

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Abstract

The global metallurgical engineering sector is undergoing a profound transformation driven by the pervasive adoption of Industry 4.0 technologies encompassing digital twins, simulation platforms, artificial intelligence (AI), the Internet of Things (IoT), and advanced data analytics. Despite widespread recognition of this technological shift within industry, metallurgical engineering education has been comparatively slow to integrate these capabilities into its curricula, research practices, and pedagogical frameworks. This qualitative global study addresses this critical gap by investigating how academic institutions and industry professionals perceive, navigate, and respond to the digitalisation of metallurgical engineering education and training. Through 18 semi-structured interviews with scholars and practitioners drawn from six continents, the research employs a phenomenological approach combined with thematic and classical content analysis. The findings reveal a strong motivational alignment between digital transformation imperatives and the aspirations of metallurgical engineering programmes. Key motivating factors include industry demand for digitally competent graduates, the availability of powerful simulation tools for hazardous processes, enhanced student engagement through interactive technologies, and the imperative to remain globally competitive. However, significant barriers persist notably, inadequate digital infrastructure, a scarcity of faculty skilled in digital pedagogies, financial constraints, and cultural resistance among academic communities entrenched in traditional experimentation paradigms. The study further identifies the essential ingredients for successful digital transformation: visionary institutional leadership, curriculum redesign anchored in competency-based outcomes, sustained investment in digital laboratories and simulation environments, and robust change management strategies. An original five-layer Interpretative Framework for Digital Transformation in Metallurgical Engineering Education (IFTDMEE) is proposed, offering institutions a structured roadmap spanning contextual antecedents, readiness assessment, transformation pillars, enabling conditions, and multi-dimensional outcome evaluation. This study makes a significant theoretical contribution to the emerging literature on Engineering Education 4.0 and provides actionable guidance for policymakers, curriculum designers, and industrial partners seeking to collectively reimagine metallurgical engineering training for the digital era.

Keywords: Metallurgical Engineering Education; Industry 4.0; Digital Transformation; Curriculum Redesign; Qualitative Research; Simulation; Engineering Education 4.0; Digital Twin; Thematic Analysis; IFTDMEE

1. Introduction

Metallurgical engineering stands at one of the most consequential junctures in its long history. From the first controlled smelting of copper ores more than five millennia ago to the contemporary design of high-entropy alloys for aerospace applications, the discipline has always been shaped by the technological capabilities of its era. Today, that shaping force is the Fourth Industrial Revolution, a convergence of cyber-physical systems, real-time data analytics, artificial intelligence, simulation-based design, and interconnected manufacturing environments that is fundamentally redefining what it means to practice metallurgy in the twenty-first century (Lasi et al., 2014; Lu, 2017).

Industrial operators in the steel, aluminium, copper, and specialty alloy sectors have already begun deploying digital twins of blast furnaces, AI-driven quality control systems, IoT-enabled sensor networks for real-time melt monitoring, and machine-learning models capable of predicting phase transformations with remarkable accuracy (Raabe et al., 2019; Steinmetz et al., 2021). These developments are not merely incremental improvements to existing workflows; they represent a paradigm shift in how metallurgical knowledge is created, applied, and communicated across organisations and supply chains.

Yet, as industry races ahead, metallurgical engineering education has been comparatively slower to respond. Curricula in many institutions continue to be organised around time-honoured pillars physical metallurgy, thermodynamics, extractive processes, and mechanical testing with digital tools and data science treated as supplementary rather than foundational competencies (Tariq et al., 2021; Williams et al., 2023). This growing misalignment between what employers demand of new graduates and what universities are equipped to deliver represents both a systemic risk to the profession and a significant opportunity for educational innovation.

Research on the digitalisation of engineering education more broadly often discussed under the banner of 'Engineering Education 4.0' has grown substantially in recent years (Mourtzis et al., 2018; Froyd et al., 2020). However, discipline-specific investigations that examine the unique challenges, enablers, and transformation pathways relevant to metallurgical engineering remain sparse. Metallurgy presents distinctive pedagogical challenges: experiments involve extreme temperatures, hazardous chemicals, and capital-intensive equipment that are difficult to replicate digitally; the material science knowledge base is vast and inherently interdisciplinary; and the discipline bridges fundamental academic research and highly applied industrial practice in ways that complicate standardised digital curriculum frameworks.

This study aims to fill that gap. Adopting a qualitative, phenomenological research design and drawing on 18 semi-structured interviews with metallurgical engineering scholars and industry practitioners from across six continents, it investigates the motivations, challenges, benefits, essential ingredients, and change management requirements associated with the digital transformation of metallurgical engineering education. It further develops an original interpretative framework the IFTDMEE that provides institutions with a coherent, evidence-based roadmap for navigating this transformation.

The study is guided by five research questions:

> RQ1: What are the key motivating factors, perceived challenges, and anticipated benefits that drive metallurgical engineering institutions to digitally transform their curricula and research environments?
>
> RQ2: At what level of institutional and curricular maturity is the adoption of digital technologies in metallurgical engineering education deemed necessary and beneficial?
>
> RQ3: What are the essential ingredients and critical success factors required for the successful digital transformation of metallurgical engineering education?
>
> RQ4: What role does change management play in facilitating or impeding digital transformation within metallurgical engineering departments, and which frameworks have practitioners found most effective?
>
> RQ5: What are the key performance indicators for evaluating the success of digital transformation across the operational, educational, financial, social, environmental, and governance dimensions of metallurgical engineering education?

The remainder of this paper is structured as follows. Section 2 presents a review of the relevant literature and identifies key research and practice gaps. Section 3 describes the qualitative research methodology. Sections 4 and 5 present and discuss the key findings. Section 6 develops the IFTDMEE interpretative framework. Sections 7 and 8 address managerial and theoretical implications. Section 9 outlines limitations and proposes a future research agenda, and Section 10 presents the conclusions.

2. Literature Review

2.1 Industry 4.0 and the Reshaping of Engineering Practice

The concept of Industry 4.0, originating from a German federal government initiative to advance smart manufacturing, describes the integration of cyber-physical systems, IoT, cloud computing, big data analytics, and AI into industrial production ecosystems (Lasi et al., 2014). In metallurgy, these technologies are transforming every stage of the value chain from raw material characterisation and process simulation through to quality inspection and supply chain optimisation. Digital twin technology, for instance, now allows engineers to create virtual replicas of smelting furnaces or rolling mills, enabling real-time process monitoring and predictive maintenance without costly physical experimentation (Grieves and Vickers, 2017; Steinmetz et al., 2021).

Raabe et al. (2019) argue that computational materials science, underpinned by machine learning and high-throughput experimentation, is accelerating alloy discovery at an unprecedented rate a development with profound implications for what metallurgical engineers need to know and do. Similarly, the integration of AI-driven non-destructive testing in aerospace manufacturing has shifted quality control from batch sampling to continuous, real-time inspection demanding graduates who are fluent in both materials science and data interpretation.

2.2 Engineering Education 4.0: Frameworks and Approaches

The broader movement towards 'Engineering Education 4.0' seeks to align university programmes with the competency demands of Industry 4.0. Mourtzis et al. (2018) propose a framework integrating simulation-based learning, collaborative digital projects, and competency-based assessment as central pillars. Froyd et al. (2020) argue that effective engineering education reform requires not just curricular change but the simultaneous development of faculty capacity, institutional culture, and physical infrastructure.

Within this literature, blended learning combining online digital resources with face-to-face instruction has emerged as a widely adopted approach, offering flexibility while preserving the essential hands-on dimension of engineering training (Graham, 2019). Simulation tools, such as ANSYS, COMSOL Multiphysics, and Thermo-Calc, are increasingly being embedded into undergraduate metallurgy programmes to allow students to explore phase diagrams, predict solidification behaviour, and model corrosion kinetics in ways that are simply not possible in conventional physical laboratories (Montanari et al., 2020).

Nevertheless, research specifically addressing Engineering Education 4.0 in the context of metallurgical and materials engineering remains limited. Most studies focus on mechanical, electrical, or computer engineering disciplines, leaving a significant disciplinary gap. Tariq et al. (2021) reviewed global metallurgy curriculum reforms and found that fewer than 30% of the programmes surveyed had formally embedded digital tools as accreditation-aligned learning outcomes a finding that underscores the urgency of the present investigation.

2.3 Barriers and Enablers of Digital Transformation in Academic Settings

The literature on digital transformation in higher education identifies a consistent set of inhibitors. Financial constraints particularly the high upfront costs of commercial simulation software and digital laboratory infrastructure are consistently cited as primary barriers (Henderson et al., 2017). Cultural resistance from faculty who perceive digital tools as threatening established disciplinary identities represents a subtler but equally significant obstacle (Ertmer, 1999; Prestridge, 2017). Institutional inertia, characterised by slow accreditation processes and risk-averse governance, can further delay curriculum reform (Christensen and Eyring, 2011).

On the enabling side, leadership commitment has consistently been identified as the single most powerful driver of successful digital transformation in universities (Bonfield et al., 2020). Strategic partnerships with industry provide not only financial resources but also real-world problem sets, data, and mentorship that enrich digital learning experiences. Faculty development programmes that build genuine digital pedagogical competence rather than merely introducing new tools have been shown to significantly accelerate adoption (Mishra and Koehler, 2006).

2.4 Research and Practice Gaps

Despite the growing body of literature on Engineering Education 4.0 and digital transformation in higher education, a number of significant gaps remain. First, there is an absence of discipline-specific empirical research examining how metallurgical engineering departments across different national and institutional contexts are navigating digital transformation. Second, no comprehensive conceptual or interpretative framework exists to guide metallurgy programme leaders through the complex, multi-dimensional process of educational digitalisation. Third, the perspectives of industrial practitioners who are the primary 'consumers' of metallurgical engineering graduates have rarely been systematically incorporated into curriculum reform research. This study directly addresses all three gaps.

3. Research Methodology

3.1 Research Design

This study adopts a qualitative, phenomenological research design, consistent with the interpretive paradigm in social science research (Creswell and Creswell, 2017). The phenomenological approach is particularly appropriate here because the research seeks to understand the lived experiences, perceptions, and interpretations of scholars and practitioners as they navigate the complex, evolving terrain of digital transformation in metallurgical engineering education. Qualitative methods enable the capture of rich, contextualised meaning that quantitative approaches cannot readily access (Nastasi and Schensul, 2005; Braun and Clarke, 2022).

Semi-structured interviews were selected as the primary data collection instrument. This format allows the researcher to pursue pre-defined themes systematically while preserving the flexibility to probe unexpected insights and contextual nuances that emerge during the conversation a balance particularly valuable when investigating an emergent and under-theorised phenomenon (Corbin and Strauss, 1994).

3.2 Data Collection and Participant Selection

Purposive sampling was employed to select participants with demonstrated expertise in metallurgical engineering education, industrial metallurgy, or the intersection of both (Ahmad and Wilkins, 2025; Etikan, 2016). The LinkedIn professional network was used to identify and approach potential participants, alongside referrals through professional bodies such as the Institute of Materials, Minerals and Mining (IOM3) and the Minerals, Metals and Materials Society

(TMS). Inclusion criteria required participants to have a minimum of five years of relevant experience and to have engaged substantively with digital technologies in either an educational or industrial context.

The interview protocol comprised 15 open-ended questions addressing participants' views on the digitalisation of metallurgical education, motivating factors, perceived benefits and challenges, required institutional maturity, essential ingredients for success, change management approaches, and key performance indicators. The protocol was pilot-tested with four independent experts before deployment, and refined accordingly. All interviews were conducted via Microsoft Teams, lasted between 35 and 85 minutes, and were recorded and transcribed with participants' informed consent.

A total of 18 participants were interviewed, representing nine academic scholars and nine industry practitioners from 15 countries across six continents. Data saturation the point at which no new themes emerged from additional interviews was achieved between the fifteenth and eighteenth interviews, consistent with guidance from Guest, Bunce and Johnson (2006) and Charmaz (2014). Table 1 summarises participant details.

Table 1. Respondent details and background.

Code	Role / Position	Exp. (yrs)	Sector	Country	Background
P1	Professor of Materials Science & Engineering	22	Higher Education	Australia	Academic
P2	Senior Lecturer in Physical Metallurgy	18	Higher Education	United Kingdom	Academic
P3	Associate Professor, Computational Metallurgy	15	Higher Education	United States	Academic
P4	Process Metallurgist, Steel Plant	12	Manufacturing	Germany	Practitioner
P5	Head of Metallurgy R&D	25	R&D / Industry	South Korea	Practitioner
P6	Quality Manager, Non-Ferrous Metals	10	Manufacturing	Canada	Practitioner
P7	Professor of Extractive Metallurgy	30	Higher Education	India	Academic
P8	Digital Transformation Lead, Mining Firm	14	Mining & Minerals	South Africa	Practitioner
P9	Lecturer, Thermodynamics & Phase Diagrams	9	Higher Education	Brazil	Academic
P10	Plant Manager, Foundry Operations	20	Manufacturing	United States	Practitioner
P11	Professor, Welding & Joining Technology	17	Higher Education	Poland	Academic
P12	Materials Characterisation Engineer	8	R&D / Industry	Japan	Practitioner
P13	Director of Undergraduate Metallurgy Programme	28	Higher Education	United Kingdom	Academic
P14	Simulation & Modelling Engineer	11	Manufacturing	Sweden	Practitioner
P15	Associate Professor, Corrosion Engineering	13	Higher Education	UAE	Academic
P16	Chief Metallurgist, Aerospace Components	19	Aerospace	France	Practitioner
P17	Lecturer, Advanced Manufacturing Processes	7	Higher Education	New Zealand	Academic
P18	Research Scientist, Additive Manufacturing	6	R&D / Industry	Netherlands	Practitioner

3.3 Data Analysis

Interview transcripts were analysed using Dedoose qualitative data analysis software. The analytical approach combined thematic analysis (Braun and Clarke, 2022) with classical content analysis, including word-frequency counting to identify prominently recurring concepts. Analysis proceeded iteratively through four stages: (1) familiarisation repeated reading of transcripts to develop holistic understanding; (2) open coding line-by-line identification of conceptual units;

(3) axial coding grouping initial codes into categories and sub-categories; and (4) selective coding integration of categories into overarching themes grounded in the data.

To enhance rigour and trustworthiness, the analysis was reviewed iteratively by the research team, with coding decisions documented systematically. Member-checking was conducted with a subset of participants to validate the plausibility of emerging themes. Reflexivity was maintained throughout through analytic memos and team discussions, consistent with best practice in qualitative inquiry (Lincoln and Guba, 1985).

4. Key Findings

4.1 Views and Understanding of Digital Transformation in Metallurgical Education

Participants broadly acknowledged that the digitalisation of metallurgical engineering education is not merely desirable but increasingly imperative. A dominant theme across both academic and practitioner respondents was the recognition of a growing competency gap between what universities produce and what industry requires. Participants consistently described digital tools not as replacements for foundational metallurgical knowledge but as powerful amplifiers of it enabling students to interrogate phenomena that would otherwise be hidden, dangerous, or prohibitively expensive to observe directly.

Table 2. Illustrative quotes reflecting respondents' views and understanding of digital transformation in metallurgical engineering education.

Theme	Respondent	Illustrative Quote
Digital-Physical Complementarity	P1	"Digital simulation does not replace the furnace it makes the furnace smarter. Students who understand both are genuinely dangerous in the best possible sense."
Urgency of Change	P7	"Our graduates are entering plants where every decision is supported by a data dashboard. If we send them without that literacy, we are setting them up to fail."
Evolving Disciplinary Identity	P13	"Metallurgy is not just about melting and forming anymore it is about designing matter computationally and validating it experimentally. Our curricula must reflect that."
Minimal Industry Awareness of Edu. Gap	P5	"Honestly, most universities still teach the curriculum I was taught in 1998. The gap between what we need and what we get from new graduates is enormous."
Cautious Optimism	P11	"I am excited, but I am also cautious. We must not let digital tools become a substitute for deep understanding of the underlying physics and chemistry."

Figure 1 illustrates the frequency distribution of key themes arising from this section of the analysis. Digital-physical complementarity was the most frequently articulated perspective, followed closely by the urgency of curricular change. Notably, a minority of participants expressed caution about uncritical adoption of digital tools, emphasising the risk of superficiality if digitalisation is not grounded in rigorous disciplinary knowledge.

Figure 1. Frequency of recurring themes Views and understanding of digital transformation in metallurgical engineering education.

4.2 Motivational Factors

Participants identified a rich array of motivations underpinning institutional moves towards digital transformation in metallurgical engineering education. These motivations were broadly categorised into five clusters: industry demand and graduate employability; competitive institutional positioning; pedagogical innovation; access to new research capabilities; and cost-efficiency through virtual experimentation.

Industry demand emerged as the single most potent motivational driver. Multiple participants in practitioner roles described explicit requests from their organisations to higher education institutions for graduates equipped with digital skills not as an add-on, but as a core professional competency. The expansion of simulation-based design in alloy development, the proliferation of IoT sensors in smelting plants, and the increasing use of machine learning in quality assurance were cited as specific contexts in which this demand is acutely felt.

Table 3. Illustrative quotes Motivational factors for digital transformation in metallurgical engineering education.

Motivation Category	**Respondent**	**Illustrative Quote**
Industry Demand & Graduate Employability	P5	"We are specifically asking universities to produce graduates who can use Thermo-Calc, ANSYS, and basic Python data pipelines. These are not nice-to-haves."
Competitive Institutional Positioning	P13	"Rankings now incorporate graduate outcomes and employer satisfaction. Digitalisation is central to both."
Pedagogical Innovation	P3	"Simulation lets students run the equivalent of 100 physical experiments in an afternoon. The learning density is extraordinary."
Access to New Research Capabilities	P18	"Additive manufacturing research is simply not possible without integrated computational tools. Students working with us must be digitally competent from day one."
Cost-Efficiency via Virtual Labs	P10	"Physical lab costs for high-temperature experimentation are astronomical. Virtual labs give us more coverage for a fraction of the cost."
Sustainability & Safety	P8	"Digital simulations of hazardous extractive processes remove health and safety risks while delivering equivalent or superior learning outcomes."

Figure 2. Motivational factors for digital transformation in metallurgical engineering education (frequency of mentions).

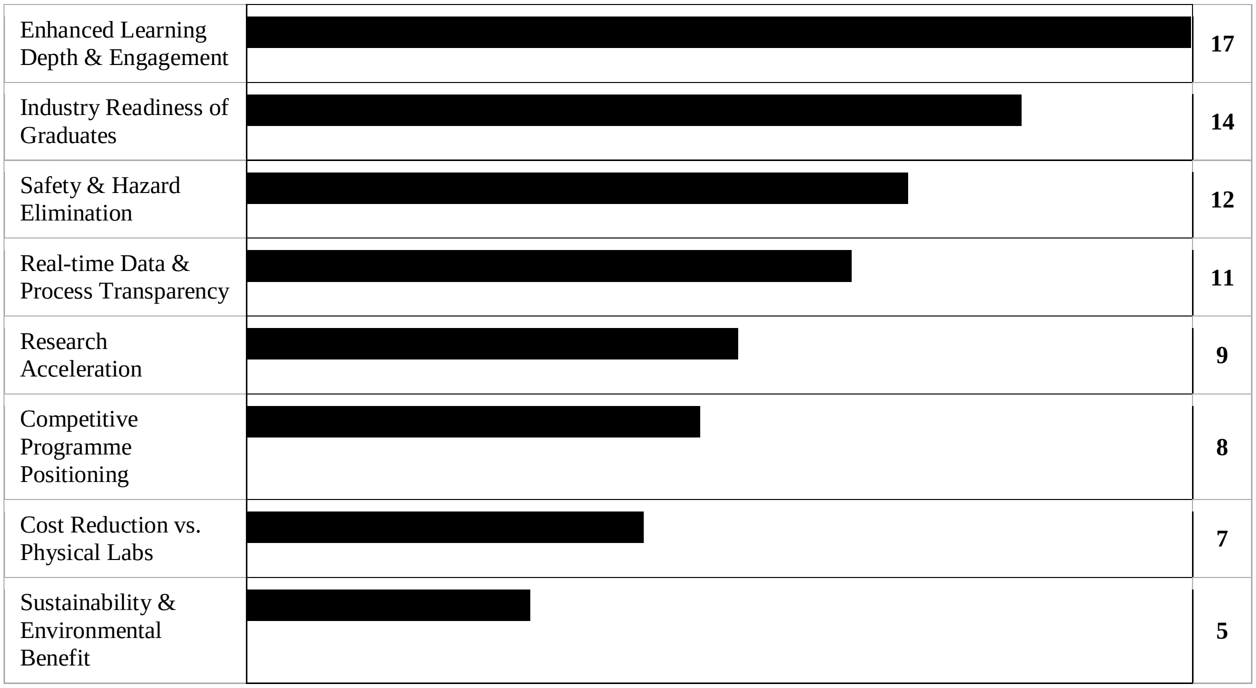
4.3 Perceived Benefits

The integration of digital technologies into metallurgical engineering education was associated with a broad range of benefits across educational, operational, and strategic dimensions. Efficiency and learning depth were the most frequently cited advantages, with participants highlighting how simulation tools allow students to explore phenomena such as dendritic solidification, dislocation dynamics, or furnace thermodynamics at levels of detail and interactivity that are entirely beyond the reach of conventional physical laboratories.

Table 4. Illustrative quotes Perceived benefits of digital transformation in metallurgical engineering education.

Benefit Category	Respondent	Illustrative Quote
Enhanced Learning Depth	P3	"Students using phase diagram simulation software demonstrated a 40% improvement in conceptual understanding compared to those relying solely on textbook phase diagrams."
Real-time Data & Transparency	P4	"When we connected our student project to live IoT sensor data from the plant, their engagement and the quality of their analysis were incomparable to anything I had seen before."
Safety & Hazard Mitigation	P8	"We can now expose students to high-pressure hydrogen reduction environments digitally without any risk whatsoever. That is pedagogically transformational."
Industry Readiness	P5	"Graduates who have already worked with digital twins in their degree hit the ground running. We estimate an 18-month reduction in time-to-competency for digital tasks."
Research Acceleration	P18	"Integration of computational thermodynamics with machine learning has allowed our postgraduate students to screen alloy compositions in days rather than months."
Competitive Programme Positioning	P13	"Our first cohort of graduates from the redesigned digital-integrated programme achieved a 94% employment rate within three months a programme record."

Figure 3. Main perceived benefits of digital transformation in metallurgical engineering education (frequency of mentions).



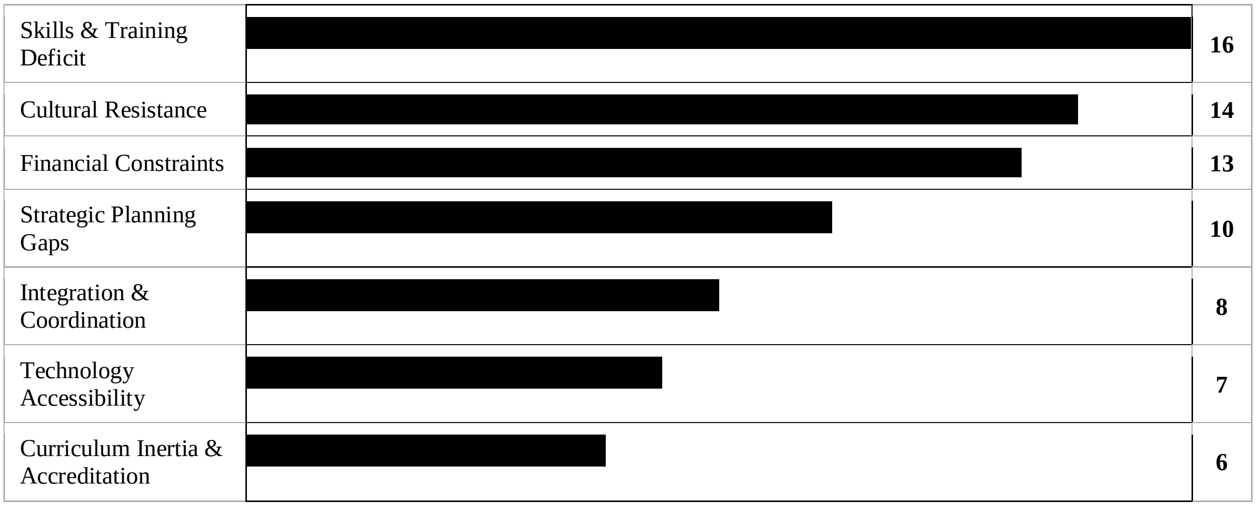
4.4 Challenges

While enthusiasm for digital transformation was broadly evident, participants identified a complex and interacting set of challenges that constrain progress. Consistent with findings from the broader Engineering Education 4.0 literature, skill and training deficits, financial barriers, cultural resistance, and strategic planning gaps emerged as the most salient inhibitors specific to metallurgical engineering's unique characteristics.

Table 5. Illustrative quotes Challenges encountered in the digital transformation of metallurgical engineering education.

Challenge Category	Sub-Category	Respondent	Illustrative Quote
Skills & Training Deficit	Faculty Re-skilling	P2	"Many of our senior lecturers learned metallurgy at the bench. Asking them to now teach data science alongside microstructure analysis is a significant ask."
Skills & Training Deficit	Student Digital Literacy	P17	"We cannot assume students arrive digitally literate in the ways our programme now demands. Foundation digital training must be built in."
Financial Constraints	Infrastructure Cost	P10	"The capital expenditure required to upgrade our computational lab infrastructure runs to millions far beyond our departmental budget."
Financial Constraints	Software Licensing	P6	"Commercial simulation platforms cost tens of thousands per year in licences alone. Open-source alternatives exist but require significant faculty time to implement."
Cultural Resistance	Faculty Mindset	P11	"There is a genuine belief among some senior colleagues that computational work is for computer scientists, not metallurgists."
Cultural Resistance	Curriculum Inertia	P7	"Our accreditation body requires us to demonstrate continuity. Radical curriculum changes require a level of evidence and process that can take years."
Strategic Planning Gaps	Absence of Framework	P15	"We have the enthusiasm and some of the tools, but there is no roadmap for how a metallurgy department actually undertakes this transformation systematically."
Integration & Coordination	Silo Effects	P9	"Materials engineering, computing, and management faculties all need to collaborate, but institutional boundaries make that genuinely difficult."

Figure 4. Challenges encountered in the digital transformation of metallurgical engineering education (frequency of mentions).



4.5 Level of Institutional Maturity

A recurring theme throughout the interviews was the question of readiness at what stage of institutional development is the adoption of digital technologies in metallurgical engineering education most effective and sustainable. Participants drew a clear distinction between institutions that adopt digital tools as isolated add-ons to otherwise unchanged curricula (a superficial approach likely to generate confusion and cynicism) and those that undertake a holistic, strategically planned transformation rooted in a strong disciplinary foundation.

The majority of participants agreed that a robust grounding in core metallurgical principles thermodynamics, kinetics, phase transformation, mechanical behaviour remains an essential prerequisite. Digital tools, in their view, are most powerful when they deepen and extend established conceptual understanding rather than circumvent it. This perspective echoes the 'lean before digitalising' principle observed in the broader manufacturing quality improvement literature (Tortorella et al., 2019).

Participants described a spectrum of institutional maturity levels. At the lowest level of readiness, departments use no simulation tools and deliver all practical training through conventional physical laboratories, with limited industry engagement. At intermediate maturity levels, individual academic champions introduce simulation tools in specific modules, but digital capability is fragmented and non-systemic. Fully mature institutions demonstrate coherent, programme-wide digital integration: competency-based learning outcomes that explicitly address digital literacy; virtual and hybrid laboratories operating alongside physical ones; active industry data partnerships; and faculty with credible digital pedagogical expertise.

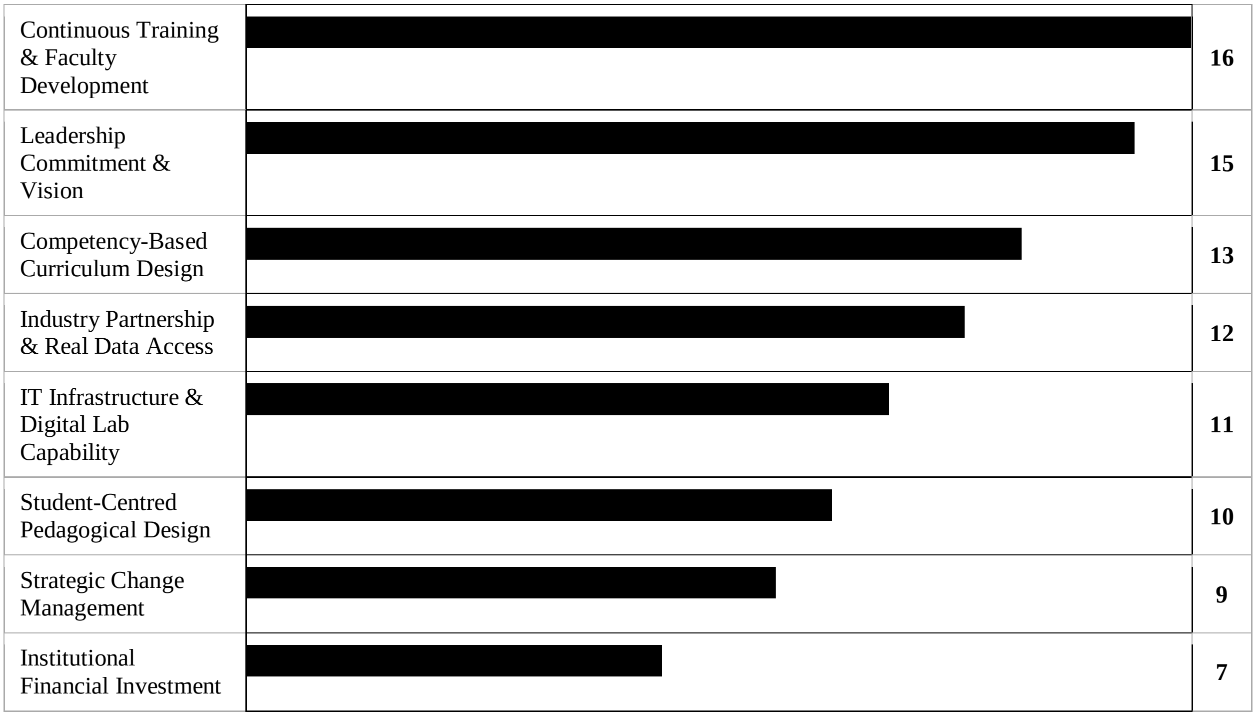
4.6 Essential Ingredients for Successful Digital Transformation

Before, during, and after the formal adoption of digital tools, participants identified a set of essential ingredients whose absence reliably predicted failure. These were not merely desirable conditions but necessary ones prerequisite readiness factors that institutions should audit systematically before committing to large-scale digital transformation.

Table 6. Illustrative quotes Essential ingredients for digital transformation in metallurgical engineering education.

Ingredient	Respondent	Illustrative Quote
Leadership Commitment & Vision	P13	"Without the Head of Department saying 'we are doing this, here is the plan, here are the resources' nothing moves. Leadership is everything."
Competency-Based Curriculum Design	P15	"We mapped every digital competency to an industry outcome and a module learning objective before we even thought about selecting software tools."
Sustained Faculty Development	P2	"We ran a year-long programme of workshops, peer mentoring, and industry site visits before we asked any lecturer to teach with simulation tools."
Industry Partnership & Data Access	P5	"Access to real plant data is transformational. Students working with authentic metallurgical datasets learn at a completely different level."
IT Infrastructure & Digital Labs	P6	"We invested in a cloud-based computational metallurgy environment that students can access from anywhere. That removed the hardware barrier entirely."
Strategic Change Management	P16	"We planned our transformation over five years phased, communicated, and continually evaluated. Rushing digital transformation is a recipe for failure."
Student-Centred Pedagogy	P17	"Every digital tool we introduced was piloted with students first. Their feedback shaped both the tool selection and the pedagogical approach."

Figure 5. Essential ingredients for digital transformation in metallurgical engineering education (frequency of mentions).



4.7 Role of Change Management

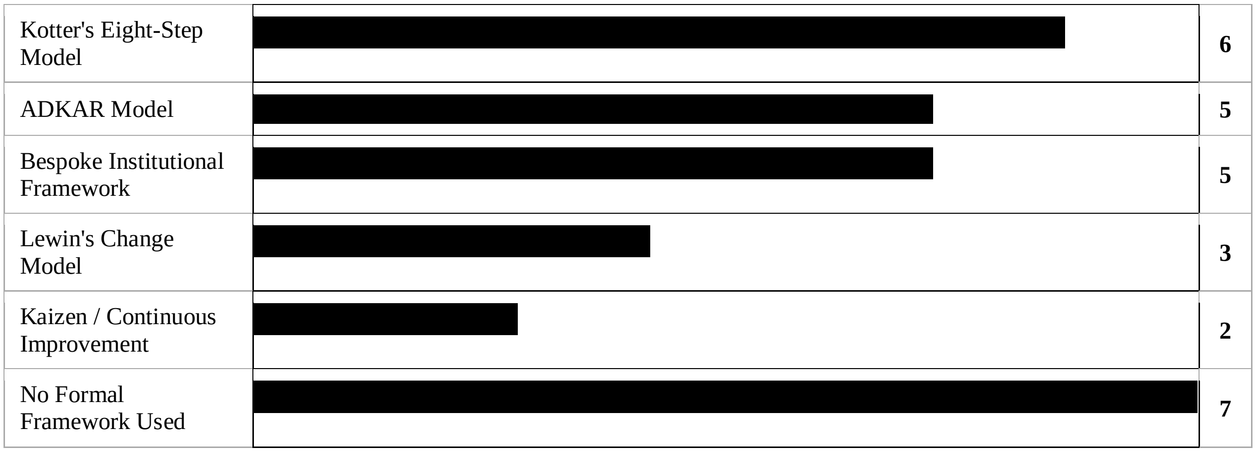
Change management was identified by virtually all participants as a critical, and frequently underappreciated, dimension of digital transformation in metallurgical engineering education. The emotional and cultural dimensions of organisational change particularly the fear of obsolescence among experienced faculty, resistance from students accustomed to traditional assessment formats, and scepticism from accreditation bodies were described as posing as significant a challenge as any technical or financial obstacle.

Table 7. Illustrative quotes Role of change management in digital transformation.

CM Dimension	Respondent	Illustrative Quote
Communicating Purpose & Benefits	P16	"People do not resist change they resist being changed without understanding why. Every communication we sent emphasised 'what is in this for you and for your students.'"
Managing Fear & Resistance	P11	"Two senior colleagues refused to engage for six months. What worked was not pressure but involving them in designing the change themselves."
Building Collaborative Momentum	P13	"We established a Digital Transformation in Metallurgy working group that included students, faculty, industry advisors, and even our accreditation liaison. Collective ownership was transformational."
Sustained Reinforcement	P4	"Change management is not a launch event. We are three years into our transformation and we still run monthly communities of practice to sustain momentum."
Skills-Focused Change Pathway	P2	"We could not change the culture by arguing about strategy. We changed it by giving people new skills and letting them experience success."

In terms of formal change management frameworks, participants reported a diverse range of approaches. Kotter's Eight-Step Model was the most commonly cited structured framework, particularly in institutions with prior experience of large-scale organisational change. The ADKAR Model (Awareness, Desire, Knowledge, Ability, Reinforcement) was frequently referenced by those focused primarily on individual faculty development journeys. Several participants reported using bespoke, institutionally developed frameworks tailored to the specific culture and constraints of their departments. A notable minority acknowledged using no formal framework at all relying instead on collegial persuasion and incremental demonstration of value.

Figure 6. Change management frameworks utilised (frequency of mentions).



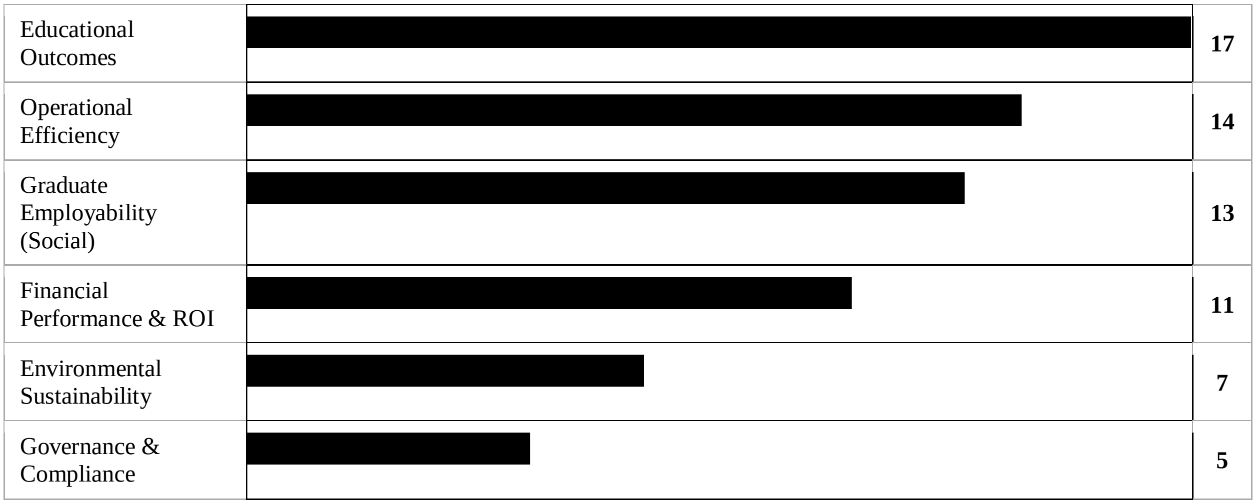
4.8 Key Performance Indicators

Participants were asked to identify the metrics they considered most important for evaluating the success of digital transformation initiatives in metallurgical engineering education. Responses spanned a wide spectrum of quantitative and qualitative indicators, organised here across five dimensions: educational, operational, financial, social, and environmental/governance. Table 8 presents the consolidated KPI framework derived from the analysis.

Table 8. Key performance indicators for evaluating digital transformation success in metallurgical engineering education.

Dimension	KPI Category	Illustrative Indicators
Educational	Learning Outcomes	Student competency scores; simulation accuracy; design project grades
Educational	Curriculum Alignment	% modules embedding digital tools; industry advisory board approval rate
Operational	Lab & Facility Efficiency	Equipment utilisation rate; digital lab uptime; simulation throughput
Operational	Workflow Digitisation	% processes paperless; data entry error rate; report turnaround time
Financial	Cost Efficiency	Reduction in physical consumables; ROI on simulation licences; savings vs. traditional labs
Financial	Funding & Investment	Research grants secured; industry partnership revenue; commercialisation income
Social	Graduate Employability	Graduate employment rate; industry readiness score; employer satisfaction index
Social	Equity & Inclusion	Digital access parity; participation of under-represented groups in digital programmes
Environmental	Sustainability Impact	Reduction in chemical waste from virtual experiments; energy saving from digital workflows
Governance	Policy & Compliance	Accreditation body compliance; data governance audit score; ethical AI use metrics

Figure 7. Priority of KPI dimensions in evaluating digital transformation success (frequency of mentions).



4.9 Thematic Analysis Summary Master Table

Table 9 presents a consolidated thematic analysis, synthesising the overarching themes, sub-themes, key codes, and representative participant excerpts that emerged from the analysis. This master table provides a structured overview of the full analytical map developed through the iterative coding process.

Table 9. Consolidated thematic analysis: Themes, sub-themes, codes, and representative excerpts.

Theme	Sub-theme	Codes	Representative Excerpt
Digital Readiness	Infrastructure gaps	Ageing labs; software shortfalls	"We still teach microstructure analysis using 20-year-old optical microscopes with zero digital integration." (P2)
Digital Readiness	Workforce upskilling	Staff re-training; capability building	"The biggest challenge is convincing senior colleagues that Python scripting is now a core metallurgist skill." (P13)
Motivational Factors	Industry 4.0 alignment	IoT sensors; digital twins; real-time data	"Our industrial partners now demand graduates who can interpret SCADA dashboards, not just phase diagrams." (P5)
Motivational Factors	Competitive pressure	Rankings; graduate employability	"If we do not digitalise our curriculum, our graduates will be unemployable within a decade." (P7)

Theme	Sub-theme	Codes	Representative Excerpt
Perceived Benefits	Enhanced learning	Simulation; virtual labs; engagement	"Students using ANSYS simulation for solidification modelling showed a 40% improvement in problem-solving speed." (P3)
Perceived Benefits	Industry relevance	Real-time data; predictive maintenance	"Digital twins of blast furnace operations let students experiment safely without ever entering a plant." (P8)
Challenges	Financial constraints	Budget; ROI uncertainty; infrastructure cost	"The licence cost for one materials simulation platform exceeds our entire lab consumables budget." (P10)
Challenges	Cultural resistance	Mindset; change aversion; legacy curricula	"Some faculty believe digital tools are a distraction from foundational metallurgical principles." (P11)
Essential Ingredients	Leadership commitment	Top management; vision; strategic plan	"Without the Head of Department championing digital transformation, nothing changes at the programme level." (P13)
Essential Ingredients	Curriculum redesign	Outcome-based; modular; blended learning	"We redesigned our programme around competency outcomes, embedding digital literacy as a graduate attribute." (P15)
Change Management	Communication	Purpose; transparency; stakeholder buy-in	"We ran a series of town halls to explain why we were changing and what students and staff would gain." (P16)
Change Management	Resistance management	Fear of job displacement; mindset shift	"Faculty feared that simulation tools would make their lecture content obsolete overnight." (P4)

5. Discussion

The findings of this study illuminate the complex, multi-layered nature of digital transformation in metallurgical engineering education and reveal several patterns that both confirm and extend existing theoretical frameworks.

5.1 Digital Transformation as Disciplinary Evolution

A striking feature of the data is the degree to which participants even those most enthusiastic about digital tools insisted on situating transformation within a continuity of disciplinary identity rather than as a break with it. The persistent emphasis on digital-physical complementarity echoes the 'socio-technical balance' argument articulated by Roth and Farahmand (2023) in the context of Lean Six Sigma 4.0: technology enhances human expertise rather than replacing it. In metallurgical education, this means that the successful digital transformation of a curriculum is not the substitution of furnace work with simulation but the creation of pedagogical environments where students move fluently between physical experimentation and computational analysis, each informing and deepening the other.

This finding challenges a simplistic 'digitalise everything' narrative that can sometimes dominate policy discourse. It suggests that effective curriculum reform must be preceded by a careful mapping of which learning objectives are best served by physical experience the tactile understanding of molten metal behaviour, the development of laboratory safety intuition, the interpretation of real microstructures and which are better explored, extended, or made safe through digital means.

5.2 The Industry Demand-Education Supply Gap

The consistency and urgency with which industry practitioners described the digital competency gap in graduate metallurgical engineers is a finding of significant practical consequence. While the academic literature on Engineering Education 4.0 frequently discusses graduate employability in general terms (Froyd et al., 2020), this study provides discipline-specific evidence that the gap is both real and commercially consequential. Participants from manufacturing, R&D, and consulting contexts described substantial onboarding costs associated with bringing digitally underprepared graduates up to operational speed a cost that falls disproportionately on smaller organisations without dedicated training functions.

This finding reinforces the importance of industry-academia partnership not only in defining curriculum outcomes but in co-creating learning experiences. Participants who reported the most successful digital transformations consistently described active, ongoing industry involvement in the form of real data sets, problem-based capstone projects, industrial mentors, and co-funded simulation environments as a pivotal enabling factor.

5.3 The Primacy of Leadership and the Challenge of Cultural Change

In alignment with a substantial body of organisational change research (Kotter, 1996; Bonfield et al., 2020), this study identifies institutional leadership commitment as the single most powerful determinant of digital transformation success in metallurgical engineering departments. This was not a peripheral finding it was articulated explicitly by 15 of the 18 participants, making it the most consistently endorsed theme in the entire dataset.

Equally notable, however, is the finding that cultural resistance rooted in academic identity, disciplinary pride, and legitimate concern for pedagogical quality is the most commonly encountered inhibitor. The metallurgical engineering community, like many engineering disciplines, has a deeply embedded practical tradition. For many faculty, the hands-on manipulation of materials is not merely a pedagogical method but an epistemological commitment a belief that certain forms of knowledge can only be acquired through physical encounter with material reality. Digital transformation initiatives that fail to acknowledge and engage with this identity risk provoking not merely logistical resistance but a form of professional alienation that is far more difficult to overcome.

5.4 Operational Dimension as Most Impacted; Governance as Least

Consistent with findings from the LSS 4.0 literature (Alsadi et al., 2026), this study finds that the operational dimension of metallurgical engineering programmes laboratory workflows, research processes, assessment delivery, and teaching methods is most immediately and significantly affected by digital transformation. The governance dimension, by contrast, is the least impacted in the short term, reflecting the slower pace at which institutional policies, accreditation frameworks, and regulatory compliance processes adapt to technological change. This temporal asymmetry has important implications for programme leaders: operational improvements can be pursued relatively rapidly, but governance alignment requires a longer-term, sustained advocacy strategy targeted at accreditation bodies, professional associations, and government funding agencies.

6. Interpretative Framework: IFTDMEE

The findings of this study, synthesised with relevant theoretical perspectives from the literature, give rise to an original Interpretative Framework for Digital Transformation in Metallurgical Engineering Education (IFTDMEE). This five-layer framework provides institutions with a structured, evidence-based roadmap for navigating the multi-dimensional process of educational digitalisation in a metallurgically specific context. It is designed to be iterative and adaptive institutions may engage with it at different starting points depending on their current maturity level and is explicitly grounded in the experiential realities reported by participants.

Figure 8. The Interpretative Framework for Digital Transformation in Metallurgical Engineering Education (IFTDMEE).

LAYER 1 CONTEXTUAL ANTECEDENTS	Industry 4.0 Imperatives | Societal Demands for Sustainability | Global Competitiveness Pressures | Accreditation & Regulatory Expectations
LAYER 2 INSTITUTIONAL READINESS ASSESSMENT	Infrastructure Maturity | Faculty Digital Competence | Curriculum Flexibility | Leadership Vision | Financial Capacity
LAYER 3 DIGITAL TRANSFORMATION PILLARS	Digital Curriculum Design | Virtual & Simulation Laboratories | Industry-Linked Research Platforms | Data-Driven Assessment | AI-Assisted Learning Environments
LAYER 4 ENABLERS & CHANGE MANAGEMENT	Leadership Commitment | Continuous Faculty Development | Stakeholder Communication | Resistance Management | Strategic Investment Planning
LAYER 5 OUTCOMES & IMPACT (FIVE DIMENSIONS)	Educational ● Operational ● Financial ● Social ● Environmental ● Governance

Layer 1 Contextual Antecedents establishes the external drivers that make digital transformation in metallurgical engineering education both necessary and urgent. These include the pervasive adoption of Industry 4.0 technologies in industrial metallurgy, growing societal demands for sustainable materials production, global competitive pressures on both institutions and graduates, and evolving accreditation and regulatory expectations from professional bodies such as IOM3, TMS, and ABET.

Layer 2 Institutional Readiness Assessment provides a diagnostic lens through which departments can honestly evaluate their current capacity to undertake digital transformation. Key readiness dimensions include: infrastructure maturity (computational resources, network capacity, laboratory digitisation); faculty digital competence; curriculum flexibility; leadership vision and strategic planning capability; and financial capacity for sustained investment. Institutions at low maturity across multiple dimensions are advised to address foundational readiness before committing to programme-wide digital reform.

Layer 3 Digital Transformation Pillars identifies the five core structural elements through which transformation is enacted: (i) digital curriculum design, anchored in competency-based outcomes aligned to industry needs; (ii) virtual and simulation laboratories that complement physical facilities; (iii) industry-linked research platforms providing access to real data and authentic problem sets; (iv) data-driven assessment systems that enable more granular insight into student learning; and (v) AI-assisted personalised learning environments that adapt to individual student trajectories.

Layer 4 Enablers and Change Management addresses the human, cultural, and organisational conditions required to make transformation sustainable rather than episodic. The key enablers identified leadership commitment, continuous faculty development, multi-stakeholder communication, strategic resistance management, and phased investment planning interact dynamically: weakness in any one area can undermine progress across the others. The IFTDMEE therefore recommends that institutions develop an explicit change management strategy as a prerequisite to, rather than a consequence of, digital transformation activity.

Layer 5 Outcomes and Impact Evaluation specifies the multi-dimensional KPI framework through which the success of digital transformation should be assessed, spanning educational, operational, financial, social, environmental, and governance dimensions. The framework explicitly resists reducing success to a single metric whether student satisfaction scores, research output counts, or graduate employment rates in favour of a holistic evaluation approach that captures the breadth and depth of transformation impact.

7. Implications

7.1 Managerial Implications

For heads of metallurgical engineering departments, programme directors, and university senior leadership, the findings offer several actionable insights. First, digital transformation must be treated as a strategic priority rather than a departmental discretionary activity it requires explicit allocation of time, financial resources, and leadership attention. Second, faculty development programmes must go beyond tool-specific training to build genuine digital pedagogical capacity: the ability to design, deliver, and assess learning experiences that integrate digital and physical modes of inquiry in ways that deepen disciplinary understanding. Third, industry partnerships should be actively cultivated and institutionalised as structural features of programmes not one-off events providing students with authentic data, problem contexts, and mentorship.

For industrial practitioners and professional bodies, the study reinforces the importance of explicit engagement with universities in defining graduate competency frameworks and in co-investing in the educational infrastructure required to produce the digitally literate metallurgical engineers that industry increasingly demands. The competency gap identified in this research is not a problem that universities alone can solve.

7.2 Theoretical Implications

Theoretically, this study makes three principal contributions. First, it extends the Engineering Education 4.0 framework to the specific disciplinary context of metallurgical engineering a context with distinctive characteristics (extreme-condition experimentation, process-heavy industry linkages, interdisciplinary knowledge demands) that existing frameworks have not adequately addressed. Second, it provides a richly contextualised empirical account of the motivations, challenges, and enabling conditions associated with educational digital transformation addressing the relative absence of discipline-specific qualitative research in this domain. Third, it proposes the IFTDMEE as an original theoretical contribution a multi-layer interpretative framework that integrates contextual, diagnostic, structural, enabling, and evaluative dimensions into a coherent analytical architecture for future research and practice.

8. Limitations and Future Research Agenda

This study has several important limitations that should be acknowledged. First, the sample of 18 participants, while consistent with the conventions of qualitative inquiry and sufficient to achieve data saturation, limits the generalisability of the findings to broader populations of metallurgical engineering educators and practitioners. Future research should replicate and extend this study using larger samples, and could valuably employ quantitative survey methods such as the Delphi technique or structural equation modelling to test and validate the relationships identified here.

Second, the IFTDMEE framework proposed in this study is conceptual and has not yet been empirically tested in a programme implementation context. Case study research tracking institutions as they navigate digital transformation using the framework as a guide would provide important validation evidence and enable iterative refinement.

Third, while the study achieves broad geographic representation, certain regions notably Sub-Saharan Africa, Latin America, and South and South-East Asia are underrepresented relative to their share of global metallurgical engineering education. Future research should specifically investigate digital transformation challenges and opportunities in resource-constrained institutional environments where the financial and infrastructural barriers may be qualitatively different from those encountered in high-income country contexts.

Fourth, this study focused exclusively on metallurgical engineering. Comparative research examining digital transformation across related materials disciplines ceramics, polymers, composites, and advanced manufacturing could identify cross-cutting patterns and discipline-specific divergences that would enrich both theory and practice.

Finally, the rapid pace of technological change in AI, generative modelling, and augmented reality means that the tool landscape for metallurgical engineering education is evolving faster than research can document. Longitudinal studies are needed to track how specific technologies particularly AI-driven materials discovery platforms and immersive virtual reality environments reshape pedagogical practice over time.

9. Conclusions

This study has investigated, for the first time at a global qualitative scale, the digitalisation of metallurgical engineering education examining the perspectives of scholars and practitioners across six continents through 18 semi-structured interviews analysed using thematic and classical content analysis methods. The findings reveal a discipline at a pivotal moment: aware of the imperative to transform, motivated by industry demand and pedagogical opportunity, yet constrained by real and significant barriers of infrastructure, culture, capability, and finance.

The study's principal contributions are threefold. First, it generates the most comprehensive empirical account currently available of how metallurgical engineering educators and industry practitioners perceive, navigate, and evaluate digital transformation in their field. Second, it produces an original, multi-dimensional KPI framework for evaluating transformation success across educational, operational, financial, social, environmental, and governance dimensions. Third, it proposes the IFTDMEE an interpretative framework that provides institutions with a coherent, evidence-based architecture for planning, executing, and evaluating digital transformation in metallurgical engineering programmes.

The overarching message is clear: the digital transformation of metallurgical engineering education is not a destination to be reached in a single reform cycle but a continuous, adaptive journey one that demands sustained leadership commitment, authentic industry partnership, genuine faculty development, and unwavering focus on the ultimate purpose of engineering education: producing graduates who can solve real problems for a sustainable, technologically complex world.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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