Reconstructing Aziz Ghefaili's Cognitive Apprenticeship Model: An Instructional Systems Architecture for Technology-Enhanced Engineering Competence Development

Chris-Abey O.*[1] & **K. R. E. Okoye[2]**

[*]Corresponding Author:abbey@uniben.edu
[1]Department of Geophysical Science Laboratory Technology (Physics/Electronic Tech), Faculty of Science Laboratory Technology, University of Benin, Nigeria

[2]Department of Industrial Technology Education, Faculty of Technology and Vocational Education, Nnamdi Azikiwe University, Nigeria

Abstract

The rapid evolution of digital technologies, artificial intelligence, virtual laboratories, and Industry 4.0/5.0 has reshaped engineering education, creating renewed demand for instructional systems capable of supporting authentic competence development within technology-enhanced learning environments. Although Cognitive Apprenticeship remains one of the most influential instructional approaches for developing professional expertise, existing implementations often reflect traditional apprenticeship contexts and provide limited guidance for digitally mediated engineering education. This study reconstructs Aziz Ghefaili's Cognitive Apprenticeship Model into a contemporary instructional systems architecture for technology-enhanced engineering competence development. Adopting a qualitative design-oriented theoretical reconstruction methodology, the study systematically reinterprets Ghefaili's original model through the complementary lenses of Skills Acquisition Theory, Cognitive Apprenticeship Theory, and recent scholarship on instructional systems and technology-enhanced learning. The reconstruction preserves the model's pedagogical foundations while reorganising its instructional processes into an integrated architecture linking teacher guidance, learner participation, technology-supported instructional environments, continuous feedback, and progressive competence development. The resulting architecture extends the original model by incorporating contemporary instructional technologies, systems-level interactions, and competence-oriented learning processes while maintaining authentic practice, guided participation, scaffolding, reflection, articulation, exploration, and progressive learner independence. The study contributes a theoretically grounded instructional framework that bridges classical cognitive apprenticeship with contemporary engineering education and provides a pedagogical foundation for implementing technology-enhanced instructional systems such as the Technology/Vocational Computer-Assisted Training Model. Beyond reconstructing an established instructional model, the study demonstrates how instructional systems thinking preserves enduring pedagogical principles while extending their applicability to digitally mediated engineering education, providing a robust theoretical foundation for future instructional design and empirical validation.

Keywords: Cognitive Apprenticeship, Engineering Competence Development, Skills Acquisition Theory, Technology-Enhanced Learning, Instructional Systems Reconstruction

1. Introduction

The accelerating convergence of digital technologies, artificial intelligence (AI), cyber-physical systems, and renewable energy innovations has transformed the competencies expected of engineering and technology graduates. The transition towards Industry 4.0 and the emerging Industry 5.0 paradigm has shifted educational priorities beyond disciplinary knowledge to encompass adaptive problem-solving, digital fluency, collaborative intelligence, and the application of technical knowledge within increasingly complex, technology-mediated environments (Leng et al., 2024; Pacher et al., 2024). Consequently, higher education institutions face growing pressure to redesign instructional systems that produce graduates whose competencies align with evolving industrial and societal demands.

Despite substantial investments in educational technologies, evidence indicates that technology adoption alone has yielded only modest improvements in learning where instructional design remains rooted in transmissive pedagogies rather than authentic competence development (Kohler et al., 2024; Bray, 2024). Although digital platforms, virtual laboratories, simulations, learning management systems, immersive technologies, and AI-supported instructional tools have expanded opportunities for technology-enhanced learning, their effectiveness depends largely on the pedagogical architecture within which they are implemented. Consequently, scholarly attention has shifted from technology integration to the design of instructional systems that deliberately cultivate higher-order cognitive processes, procedural expertise, and transferable professional competencies.

This challenge is particularly evident in engineering and technology education, where meaningful learning requires not only conceptual understanding but also the development of procedural knowledge, psychomotor competence, diagnostic reasoning, and professional judgement through sustained engagement with authentic tasks. Many institutions, particularly in developing economies, continue to experience shortages of adequately equipped laboratories, industry-based learning opportunities, specialised instructional resources, and qualified technical personnel. These constraints limit opportunities for the guided practice essential to progressive competence development, often producing graduates whose theoretical knowledge exceeds their practical capability.

Technology-enhanced learning environments have increasingly been proposed to mitigate these challenges through virtual laboratories, interactive simulations, digital twins, intelligent tutoring systems, and other forms of computer-mediated instruction (Elmoazen et al., 2023; Frady, 2023). However, their educational effectiveness depends less on technological sophistication than on the instructional principles governing learner interaction, expert guidance, reflection, and progressive independence. Technology therefore functions as an instructional enabler rather than an instructional theory.

Among the theories informing technology-mediated professional education, Cognitive Apprenticeship remains particularly relevant because it explicitly supports expertise development through modelling, coaching, scaffolding, articulation, reflection, and the gradual transfer of responsibility within authentic learning contexts. Although its foundational principles are widely recognised, many contemporary implementations remain conceptual or confined to traditional face-to-face apprenticeship settings. Existing adaptations provide limited guidance for engineering education characterised by virtual learning environments, distributed instructional resources, computer-assisted practice, and infrastructure-constrained contexts. Consequently, Cognitive Apprenticeship requires reinterpretation to reflect contemporary technology-enhanced instructional environments while preserving its emphasis on guided competence development.

Recent developments in engineering education have further underscored the need for instructional models that integrate iterative practice, authentic problem solving, reflective learning, and progressive skills development into coherent instructional architectures rather than treating them as isolated pedagogical techniques (Li & Liang et al., 2024; Pacher et al., 2024). Such architectures are especially important in technology and vocational education, where effective instruction demands the simultaneous development of cognitive understanding, procedural fluency, technical judgement, and workplace readiness. These requirements align closely with Skills Acquisition Theory, which conceptualises competence development as progression from declarative understanding through repeated guided practice to autonomous expert performance. Integrating this perspective with Cognitive Apprenticeship provides a stronger theoretical foundation for designing technology-enhanced instructional systems capable of supporting competence development in resource-constrained engineering education.

This paper addresses this need by reconstructing Ghefaili's Cognitive Apprenticeship Model (Ghefaili, 2003) into a contemporary instructional architecture for technology-enhanced engineering education. Rather than proposing a new learning theory, the study systematically reinterprets the original model through the complementary lens of Skills Acquisition Theory and contemporary technology-enhanced instructional design principles to address present-day engineering education challenges. The reconstructed model integrates guided practice, virtual situated learning, progressive scaffolding, reflective performance, and competence internalisation into a coherent instructional architecture for technology competence development within digitally mediated learning environments.

Accordingly, the study makes three principal contributions. First, it reconstructs Ghefaili's 2003 Cognitive Apprenticeship Model into a framework responsive to contemporary technology-enhanced learning contexts. Second, it provides a theoretically grounded instructional architecture capable of supporting engineering competence development where conventional laboratory and workplace learning opportunities are constrained. Third, it establishes the pedagogical foundation for the Technology/Vocational Computer-Assisted Training Model (TeVCAT-M) as a technology-enhanced instructional system for engineering and technology education. By repositioning Cognitive Apprenticeship within a contemporary instructional systems perspective, the paper contributes to strengthening technology integration through pedagogically informed instructional design rather than technology adoption alone.

Given the historical evolution of the underpinning theories and the study's objective of reconstructing rather than replacing Ghefaili's original model, a comprehensive theoretical treatment is necessary to establish conceptual continuity, justify the reconstruction process, and articulate the instructional systems architecture underpinning the proposed framework.

1.1 The Engineering Competence Imperative in Technology-Enhanced Education

Engineering education is undergoing unprecedented transformation driven by rapid technological advancement, evolving industrial ecosystems, and increasing expectations for graduates capable of operating within digitally connected workplaces. The emergence of intelligent manufacturing, automation, cyber-physical systems, artificial intelligence, digital twins, and sustainable engineering practices has redefined the competencies required of engineering professionals. Consequently, engineering education is expected to produce graduates who demonstrate not only disciplinary knowledge but also practical reasoning, technological adaptability, collaborative problem solving, and lifelong learning capabilities (Pacher et al., 2024; UNESCO, 2021).

These changes present particular challenges for technology and vocational education, where competence extends beyond cognitive achievement to include procedural fluency, technical judgement, workplace readiness, and the application of knowledge in authentic professional contexts. Unlike many disciplines, engineering competence develops progressively through repeated engagement with realistic tasks involving expert observation, guided practice, corrective feedback, reflection, and increasing professional autonomy. Effective engineering education therefore depends as much on instructional design as on curriculum content.

Across many higher education institutions, particularly in resource-constrained settings, opportunities for sustained practical learning remain limited by inadequate laboratory facilities, obsolete equipment, insufficient industry partnerships, growing enrolments, and shortages of qualified technical instructors. These constraints often reduce practical instruction to demonstrations or isolated laboratory exercises, limiting deliberate practice and progressive competence development. Consequently, a persistent gap remains between theoretical instruction and workplace expectations (UNESCO, 2021; World Economic Forum, 2023).

Educational technologies have expanded opportunities to address these challenges through virtual laboratories, immersive simulations, digital twins, remote laboratories, intelligent tutoring systems, augmented and virtual reality, and AI-supported instructional platforms (Li & Liang, 2024; Frady, 2023). These technologies facilitate repeated practice, immediate feedback, collaborative learning, and flexible access beyond conventional laboratory constraints. However, technological sophistication alone does not ensure competence development. Learning outcomes continue to depend on instructional principles governing learner engagement, expert guidance, scaffolded practice, reflection, and progressive independence. Accordingly, the educational value of emerging technologies lies primarily in the pedagogical architectures through which they support authentic professional learning (Bray et al., 2024; Kohler et al., 2024).

This shift from technology-centred innovation to pedagogy-driven instructional design has renewed interest in learning theories capable of supporting authentic competence development within technology-enhanced environments. Among these, Cognitive Apprenticeship remains particularly significant because it models how professional expertise is developed and transferred. However, many implementations continue to reflect face-to-face apprenticeship contexts and provide limited guidance for virtual, distributed, computer-assisted, and resource-constrained learning environments. Addressing this challenge requires more than digitising existing instructional practices; it requires reconstructing the instructional architecture itself to accommodate technology-mediated guidance, iterative skills development, virtual situated learning, and progressively independent performance while preserving the instructional processes underpinning expertise development. This need provides the rationale for revisiting Ghefaili's Cognitive Apprenticeship Model as a foundation for supporting technology competence development within contemporary engineering education.

1.2 Theoretical Foundations for the Reconstruction

Developing engineering competence requires instructional approaches that extend beyond transmitting disciplinary knowledge to support the progressive acquisition, application, and refinement of professional expertise. This requirement has become increasingly important as engineering practice evolves within digitally connected environments characterised by intelligent technologies, virtual collaboration, virtual experimentation, and rapidly changing technical standards. Contemporary engineering education therefore requires theoretical perspectives capable of explaining both how learners acquire knowledge and how instructional environments deliberately facilitate procedural competence, adaptive reasoning, and professional judgement.

Skills Acquisition Theory provides the principal explanation of how expertise develops through successive stages of learning. The origins of skill acquisition research can be traced to Bryan and Harter (1899), whose studies of telegraphic proficiency demonstrated that expertise develops through repeated practice and increasingly integrated behavioural routines. These findings laid the foundation for later theories of professional expertise. Fitts and Posner (1967) subsequently formalised the theory by proposing three stages of competence development: cognitive, associative, and autonomous. During the cognitive stage, learners depend heavily on explicit instruction while developing initial task understanding. Through deliberate practice, guided repetition, and constructive feedback, performance progresses to the associative stage before reaching the autonomous stage, where procedural knowledge becomes internalised and performance increasingly efficient, adaptable, and automatic (Fitts & Posner, 1967).

Subsequent cognitive perspectives further explained this progression. Anderson's (1982) theory of cognitive skill acquisition demonstrated how declarative knowledge becomes procedural through repeated application, while later developments extended Skills Acquisition Theory to increasingly complex domains of professional learning. Contemporary scholarship continues to emphasise deliberate practice, guided repetition, timely feedback, and progressive learner independence as central to expertise development (Williams & Hodges, 2023). Within STEM education, these processes are operationalised through modelling, coaching, guided participation, and scaffolded engagement that support learners' progression from novice to expert performance (Minshew et al., 2021). Although Skills Acquisition Theory explains how competence develops, it provides comparatively limited guidance on the instructional processes required to facilitate that progression within technology-enhanced learning environments.

Cognitive Apprenticeship Theory addresses this limitation by explaining how expertise should be taught. Originally proposed by Collins, Brown, and Newman (1989), the theory argues that expert performance becomes learnable when instructors make invisible cognitive processes explicit through modelling, coaching, scaffolding, articulation, reflection, exploration, and the gradual withdrawal of instructional support. Rather than treating learning as an isolated cognitive activity, Cognitive Apprenticeship situates it within authentic professional practice, enabling learners to assume increasing responsibility through guided participation. Contemporary reviews reaffirm its relevance because these instructional processes support situated learning, reflective practice, authentic problem solving, and adaptive expertise within increasingly complex learning environments (Matsuo, 2021). Recent scholarship further argues that these instructional relationships require reinterpretation to accommodate digitally mediated instruction, distributed learning, and evolving workplace practices (Darling-Hammond et al., 2020; Matsuo, 2024).

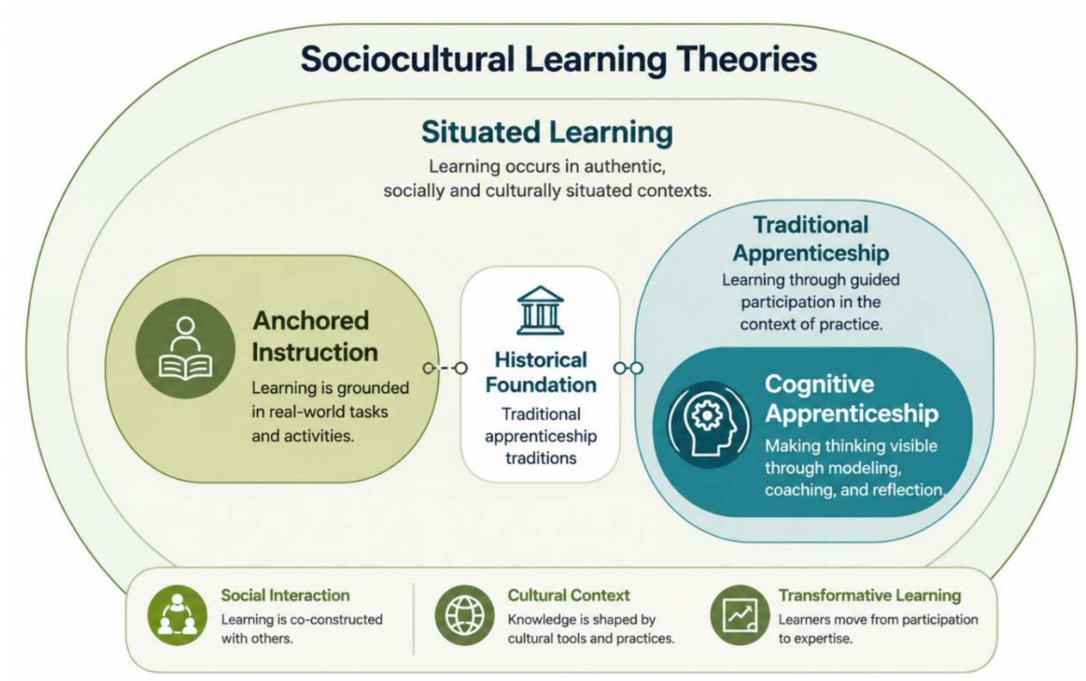


Figure 1: Historical Foundation of Traditional Apprenticeship to Cognitive Apprenticeship adapted from Ghefaili (2003)

Although Cognitive Apprenticeship remains one of the most influential theories for professional competence development, many contemporary implementations continue to reflect traditional apprenticeship environments characterised by face-to-face supervision, stable workplace settings, and limited technology-mediated instruction. Engineering education has since been transformed by virtual laboratories, remote experimentation, immersive simulations, intelligent tutoring systems, artificial intelligence, collaborative online workspaces, and other digitally supported learning environments. These developments have fundamentally reshaped the contexts in which modelling, coaching, scaffolding, guided practice, and reflective learning occur. Consequently, preserving the core pedagogical principles of Cognitive Apprenticeship while reinterpreting their implementation within technology-enhanced instructional systems has become an important scholarly challenge.

Responding to this challenge, Ghefaili (2003) contextualised Cognitive Apprenticeship for technology and vocational education, particularly in environments with limited instructional resources and constrained workplace learning opportunities. Ghefaili's Cognitive Apprenticeship Model demonstrated that computer-assisted learning environments could complement traditional laboratory experiences by providing structured opportunities for modelling, coaching, guided practice, reflection, and progressive skills development. In doing so, the model extended guided expertise development beyond conventional master–apprentice relationships while preserving the central goal of developing authentic professional competence through situated participation and progressively independent performance (Ghefaili, 2003).

To establish the conceptual foundation for the present study, Figure 2 presents Ghefaili's (2003) original Cognitive Apprenticeship Model. The figure illustrates the instructional relationships among the foundational building blocks of cognitive apprenticeship, teachers' instructional interventions, and students' corresponding learning responses that informed the present reconstruction.

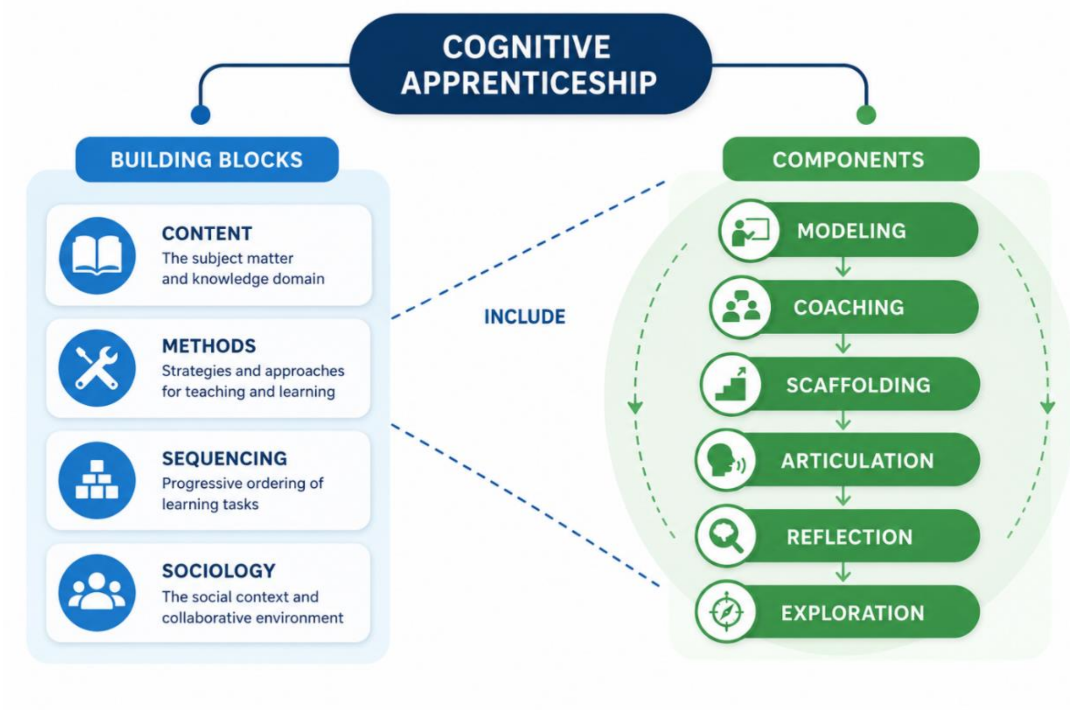


Figure 2: Aziz Ghefaili's (2003) Cognitive Apprenticeship Model

As illustrated in Figure 2, Ghefaili's model successfully contextualised cognitive apprenticeship for computer-assisted vocational education by explicitly linking instructional processes with learner responses. However, the model predates many of the technological and instructional developments that now characterise contemporary engineering education, thereby motivating its theoretical reconstruction.

Nevertheless, substantial advances in educational technology, engineering practice, and digital learning ecosystems have occurred since the development of Ghefaili's model. Contemporary engineering instruction increasingly incorporates multimedia learning environments, virtual and remote laboratories, digital simulations, artificial intelligence-supported instructional systems, collaborative cloud-based workspaces, learning analytics, and immersive technologies that reshape professional competence development. The effectiveness of these technologies depends not simply on their availability but on instructional designs that align their affordances with established principles of human cognitive processing and meaningful learning (Mayer, 2024). Consequently, although the pedagogical principles underpinning Ghefaili's model remain highly relevant, their implementation requires reinterpretation within a broader instructional systems perspective capable of supporting distributed, technology-enhanced, and competence-oriented engineering education.

The complementary relationship between Skills Acquisition Theory and Cognitive Apprenticeship provides the theoretical foundation for this reinterpretation. Skills Acquisition Theory explains the progressive development and internalisation of professional expertise, whereas Cognitive Apprenticeship specifies the instructional processes that facilitate this progression. Ghefaili's Cognitive Apprenticeship Model provides the contextual bridge between these complementary perspectives by adapting cognitive apprenticeship principles to technology-oriented vocational education (Ghefaili, 2003). However, the instructional architecture required to operationalise these principles within contemporary technology-enhanced engineering education remains insufficiently articulated.

Addressing this theoretical and instructional gap provides the rationale for reconstructing Ghefaili's Cognitive Apprenticeship Model into a contemporary instructional systems architecture for technology competence development within virtual, computer-assisted, and digitally mediated engineering learning environments.

Table 1 summarises the complementary roles of Skills Acquisition Theory, Cognitive Apprenticeship Theory, Ghefaili's Cognitive Apprenticeship Model, and the present reconstruction..

Table 1: Theoretical Foundations of the Reconstructed Cognitive Apprenticeship Instructional Systems Architecture

Dimension	**Skills Acquisition Theory**	**Cognitive Apprenticeship Theory**	**Ghefaili's Cognitive Apprenticeship Model (2003)**	**Authors' Present Reconstruction**
Primary purpose	Explains how professional expertise develops through progressive skill acquisition.	Explains how expertise should be taught through guided participation.	Contextualises Cognitive Apprenticeship for technology and vocational education using computer-assisted learning.	Reconstructs Ghefaili's model as a contemporary instructional systems architecture for technology-enhanced engineering education.
Principal proponents	Bryan & Harter (1899); Fitts & Posner (1967); Anderson (1982).	Allan Collins, John Seely Brown, and Susan E. Newman (1989).	A. Ghefaili (2003).	Researcher's reconstruction informed by contemporary theory and instructional systems principles.
Central question addressed	How do learners progress from novice to expert?	How can instructors facilitate that progression?	How can Cognitive Apprenticeship be adapted to technology and vocational education?	How can Ghefaili's model be reinterpreted for digitally mediated engineering competence development?
Core concepts	Cognitive → Associative → Autonomous stages; deliberate practice; proceduralisation; automaticity.	Modelling, coaching, scaffolding, articulation, reflection, exploration, fading.	Computer-assisted modelling, guided practice, reflection, progressive skills development in vocational settings.	Technology-mediated modelling, virtual laboratories, AI-supported guidance, digital simulations, collaborative learning, reflective practice, progressive competence development.
Role of the learner	Progressively internalises procedural knowledge through repeated practice.	Learner participates in authentic professional activities with decreasing instructional support.	Learner develops competence through structured computer-assisted guidance.	Learner develops technology competence through virtual, distributed, and authentic engineering learning experiences.
Role of the instructor	Provides feedback and opportunities for deliberate practice.	Makes expert thinking visible through modelling and coaching before gradually withdrawing support.	Facilitates technology-supported learning and structured guidance.	Designs and orchestrates technology-enhanced instructional systems integrating pedagogy, technology, and authentic engineering practice.

Dimension	Skills Acquisition Theory	Cognitive Apprenticeship Theory	Ghefaili's Cognitive Apprenticeship Model (2003)	Authors' Present Reconstruction
Instructional emphasis	Practice, repetition, feedback, procedural fluency.	Guided participation and situated learning.	Computer-assisted vocational instruction.	Integrated instructional systems supporting virtual, AI-assisted, and competence-oriented engineering education.
Contribution to this study	Explains the cognitive progression of competence development.	Explains the instructional mechanisms facilitating competence development.	Provides the contextual bridge between Cognitive Apprenticeship and technology-oriented education.	Provides the theoretical basis for reconstructing Ghefaili's model into a contemporary instructional systems architecture.

Rather than representing competing perspectives, these frameworks provide complementary explanations of competence development, instructional support, contextual adaptation, and instructional systems reconstruction

The remainder of this paper is organised as follows. Section 2 describes the design-oriented theoretical reconstruction methodology adopted in the study. Section 3 presents the reconstructed Cognitive Apprenticeship instructional architecture and explains its internal instructional structure. The subsequent discussion examines the theoretical and instructional implications of the reconstruction for technology-enhanced engineering education, while the concluding section summarises the study's contributions, limitations, and directions for future empirical validation

2. Research Design and Reconstruction Methodology

2.1 Research Design

This study adopted a qualitative design-oriented theoretical reconstruction approach to reinterpret Ghefaili's Cognitive Apprenticeship Model for contemporary technology-enhanced engineering education. Unlike empirical studies that test hypotheses or evaluate instructional interventions, theoretical reconstruction re-examines an existing conceptual model in response to theoretical developments, technological advances, and changing educational contexts to produce a more coherent and instructionally relevant framework (Matsuo, 2024).

The reconstruction focused exclusively on Ghefaili's Cognitive Apprenticeship Model. Skills Acquisition Theory and Cognitive Apprenticeship Theory were not reconstructed; rather, they served as complementary theoretical lenses through which Ghefaili's model was analysed and reinterpreted. As established in the theoretical foundation, Skills Acquisition Theory explains the progressive development of expertise, whereas Cognitive Apprenticeship Theory explains the instructional processes through which that progression is facilitated. Ghefaili's model therefore constituted the unit of reconstruction, while the two theories informed the reinterpretation and reorganisation of its instructional architecture.

The reconstruction was undertaken from an instructional systems perspective that views engineering competence as the product of coherent interactions among pedagogy, guided practice, technology-mediated learning environments, and progressive skills development. Accordingly, the study sought to preserve the pedagogical integrity of Ghefaili's original model while adapting its instructional processes to advances in educational technology, virtual learning environments, artificial intelligence-supported instruction, and digitally mediated engineering practice.

2.2 Sources Informing the Reconstruction

The reconstruction drew upon four complementary sources of theoretical and conceptual evidence.

First, Ghefaili's original Cognitive Apprenticeship Model served as the primary object of reconstruction. Its instructional principles, pedagogical assumptions, and learning processes provided the conceptual foundation for the reconstructed instructional architecture.

Second, the study drew upon the researcher's doctoral investigation, during which Ghefaili's model was critically analysed, conceptually extended, and reconstructed as part of a broader instructional model development process. The present manuscript isolates the reconstructed Cognitive Apprenticeship Model as an independent theoretical contribution without reporting the associated model development procedures, validation activities, or empirical findings.

Third, contemporary scholarship published between 2020 and 2025 on cognitive apprenticeship, skills acquisition, engineering education, instructional systems design, technology-enhanced learning, virtual laboratories, intelligent tutoring systems, and digital learning environments was synthesised to identify theoretical developments, emerging instructional practices, and persistent gaps relevant to engineering competence development.

Fourth, the reconstruction was informed by evidence generated during the conceptual development of the Technology/Vocational Computer-Assisted Training Model (TeVCAT-M). The conceptual analyses, instructional design decisions, and iterative model development undertaken during its development provided additional evidence for evaluating the coherence, completeness, and practical applicability of the reconstructed instructional architecture. Detailed procedures and empirical findings relating to the development and validation of TeVCAT-M are beyond the scope of this manuscript and are reported separately.

Rather than aggregating empirical findings through systematic review procedures, these complementary sources were synthesised to establish theoretical continuity, conceptual coherence, instructional complementarity, and instructional systems alignment.

2.3 Reconstruction Protocol

The reconstruction followed four sequential stages (Figure 2).

The first stage involved critically examining Ghefaili's original model to distinguish its enduring pedagogical principles from instructional components requiring reinterpretation within digitally mediated engineering education. Particular attention was given to modelling, coaching, scaffolding, articulation, reflection, exploration, guided participation, and progressive learner independence.

The second stage involved theoretical integration, during which Skills Acquisition Theory and Cognitive Apprenticeship Theory were synthesised to establish explicit relationships between progressive competence development and the instructional mechanisms supporting movement from guided participation to autonomous professional performance. The complementary relationships summarised in Table 1 provided the conceptual foundation for this stage.

The third stage involved instructional systems reconstruction. Guided by the integrated theoretical framework, Ghefaili's instructional components were reorganised into a contemporary architecture supporting technology-mediated guidance, virtual situated learning, collaborative engagement, iterative practice, reflective performance, and progressive engineering competence development.

The fourth stage involved conceptual verification through iterative comparison of the reconstructed architecture with contemporary theoretical perspectives and the instructional systems principles underpinning the developed electronic-assisted model. This process ensured that the reconstructed architecture preserved the pedagogical integrity of Ghefaili's original framework while improving its applicability to technology-enhanced engineering education.

2.4 Ensuring Theoretical Rigour

The credibility of the reconstructed architecture was strengthened through four complementary strategies.

First, theoretical continuity was maintained by preserving the core pedagogical principles of Ghefaili's original Cognitive Apprenticeship Model while avoiding unnecessary modification of established instructional constructs.

Second, theoretical triangulation was achieved through the complementary integration of Skills Acquisition Theory, Cognitive Apprenticeship Theory, contemporary cognitive apprenticeship scholarship, instructional systems design principles, and recent developments in engineering education, thereby strengthening the theoretical consistency of the reconstruction.

Third, conceptual coherence was ensured by maintaining logical relationships among instructional processes, learner progression, and competence outcomes, with every reconstructed component contributing directly to the progressive acquisition, application, and refinement of engineering competence.

Finally, instructional systems alignment was established by evaluating the reconstructed architecture against the pedagogical assumptions underpinning the Technology/Vocational Computer-Assisted Training Model. This ensured internal consistency while supporting its intended implementation within contemporary technology-enhanced engineering learning environments.

The reconstruction methodology provided a systematic procedure for preserving the pedagogical integrity of Ghefaili's Cognitive Apprenticeship Model while extending its applicability to digitally mediated engineering education. The reconstructed instructional architecture presented in the following section constitutes the principal theoretical contribution of this study and provides the pedagogical foundation upon which technology-enhanced instructional systems such as TeVCAT-M may be understood and implemented.

3. Reconstructed Cognitive Apprenticeship Instructional Systems Architecture

3.1 Design Principles Guiding the Reconstruction

The reconstruction of Ghefaili's Cognitive Apprenticeship Model sought to preserve its enduring pedagogical principles while enhancing its applicability to contemporary technology-enhanced engineering education. Rather than replacing the original model, the reconstruction reinterpreted its instructional architecture in response to advances in engineering practice, educational technology, and instructional systems theory.

Five complementary principles guided the reconstruction. First, authentic learning, guided participation, progressive learner independence, and reflective professional practice were retained as the core mechanisms of engineering competence development. Second, the reconstructed architecture was aligned with Skills Acquisition Theory by supporting learners' progression from cognitive understanding through guided practice to autonomous professional performance. Third, the architecture accommodated digitally mediated learning through virtual laboratories, simulations, multimedia resources, intelligent instructional support, collaborative online environments, and other technologies that extend authentic engineering experiences. Fourth, an instructional systems perspective was adopted by integrating instructional strategies, learner activities, technological resources, learning environments, and competence outcomes into a coherent framework. Finally, while instructional technologies have evolved, the core cognitive apprenticeship processes of modelling, coaching, scaffolding, articulation, reflection, exploration, and progressive withdrawal of instructional support were retained and reinterpreted for contemporary engineering education.

3.2 Reconstructed Cognitive Apprenticeship Instructional Systems Architecture

The reconstructed instructional systems architecture extends Ghefaili's Cognitive Apprenticeship Model by integrating Skills Acquisition Theory, Cognitive Apprenticeship Theory, and contemporary instructional systems design into a unified framework for technology-enhanced engineering competence development. Whereas Ghefaili's model contextualised cognitive apprenticeship for computer-assisted vocational instruction, the reconstructed architecture conceptualises competence development as an integrated instructional system in which authentic engineering activities are supported through technology-mediated instructional processes.

The architecture retains the core instructional processes of modelling, coaching, scaffolding, articulation, reflection, and exploration while embedding them within technology-enhanced environments that support virtual experimentation, collaborative problem solving, iterative practice, and progressively independent professional performance.

Figure 3 reconstructs Ghefaili's original Cognitive Apprenticeship Model by preserving its foundational building blocks and instructional components while introducing explicit teacher intervention and student response dimensions. This reconstruction operationalises the original conceptual framework by making visible the instructional interactions through which cognitive apprenticeship principles are enacted during teaching and learning.

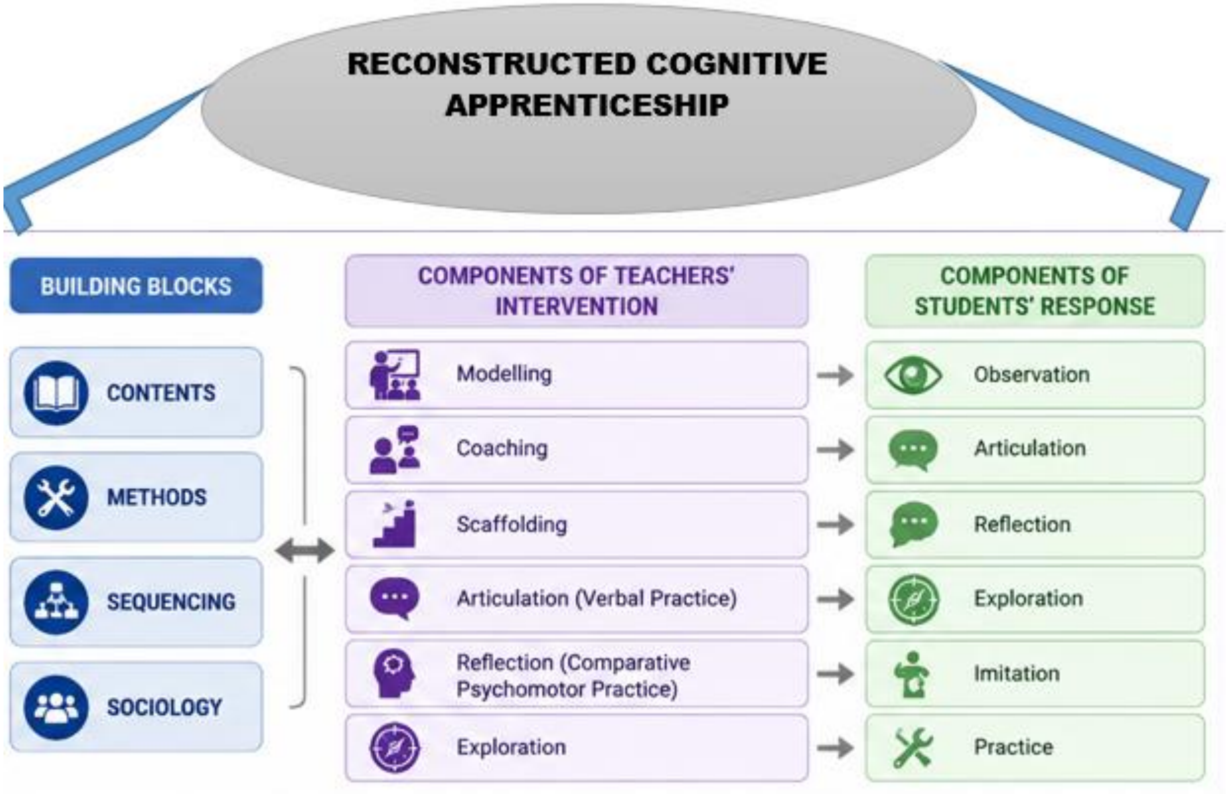


Figure 3: Authors' Reconstruction of Ghefaili's Cognitive Apprenticeship Model Showing Teacher Intervention and Student Response Processes

The above figure illustrates the reconstructed model at a conceptual level, highlighting the preserved instructional relationships inherited from Ghefaili's original framework. The internal organisation and systems interactions through which these instructional processes collectively facilitate engineering competence development are presented in Figure 4.

3.3 Components and Internal Structure of the Reconstructed Architecture

The reconstructed architecture functions as an integrated instructional system in which the instructional components operate interdependently rather than as isolated pedagogical techniques. As illustrated in Figure 3, the architecture preserves Ghefaili's original instructional relationships while extending them into a technology-enhanced systems framework. The four foundational building blocks—content, method, sequencing, and sociology—provide the instructional foundation upon which teachers organise modelling, coaching, scaffolding, articulation, reflection, and exploration. These instructional interventions, in turn, elicit corresponding learner responses, including observation, imitation, articulation, reflection, exploration, and repeated practice, thereby supporting the progressive internalisation of engineering competence.

Unlike linear instructional models, the reconstructed architecture emphasises continuous interaction among instructional guidance, learner participation, technology-enhanced learning environments, and competence development. Teacher interventions and learner responses are therefore viewed as reciprocal processes that continuously influence one another through guided participation, iterative practice, and formative feedback. As learners acquire increasing competence, instructional support is progressively reduced, enabling movement from highly guided participation towards autonomous professional performance consistent with the principles of Skills Acquisition Theory.

Technology-enhanced learning environments surround and strengthen these instructional interactions rather than replacing them. Virtual laboratories, remote experimentation, multimedia learning resources, intelligent tutoring systems, collaborative digital workspaces, learning analytics, and artificial intelligence-supported instructional tools function as instructional enablers that extend opportunities for authentic practice, coaching, collaboration, and reflective learning beyond conventional laboratory settings. Their educational value therefore derives from supporting the pedagogical processes of Cognitive Apprenticeship rather than from technological sophistication alone.

The architecture is further regulated by overarching instructional systems principles that maintain coherence across all instructional processes. Authentic practice ensures that learning remains grounded in realistic engineering activities; situated learning contextualises competence within professional practice; progressive independence guides the gradual withdrawal of instructional support; iterative feedback supports continuous performance improvement; integration of cognition and practice links conceptual understanding with procedural performance; and technology functions as an instructional enabler that extends rather than replaces expert guidance. These principles collectively sustain the interaction among instructional processes, learning environments, and competence development throughout the learning cycle.

Within this instructional system, the traditional Cognitive Apprenticeship processes retain their distinct pedagogical roles while operating as mutually reinforcing components. Modelling initiates learning by making expert reasoning visible; coaching provides guidance during initial performance; scaffolding regulates instructional support according to learner progress; guided practice enables repeated application of engineering procedures; articulation encourages learners to explain and justify their reasoning; reflection promotes metacognitive evaluation of performance; and exploration supports increasingly independent application of acquired competencies to unfamiliar engineering problems. Collectively, these processes transform declarative understanding into procedural competence through repeated cycles of guided participation and progressively independent performance.

The intended outcome of these interacting instructional processes is engineering technology competence characterised by procedural fluency, adaptive reasoning, authentic problem-solving ability, reflective professional practice, collaborative capability, and autonomous workplace performance. The reconstructed architecture therefore conceptualises competence development not as the product of individual instructional techniques but as the cumulative outcome of coordinated interactions among pedagogical processes, learner engagement, technological affordances, and continuous instructional feedback.

3.3.1 Reconstructed Cognitive Apprenticeship Instructional Systems Architecture for Technology-Enhanced Engineering Education

The micro internal structure of this study's reconstructed cognitive apprenticeship model shown in Figure 4, demonstrates how the reconstructed model is operationalised within a comprehensive instructional system incorporating foundational instructional inputs, technology-enhanced learning environments, systems principles, continuous feedback, and engineering competence outcomes.

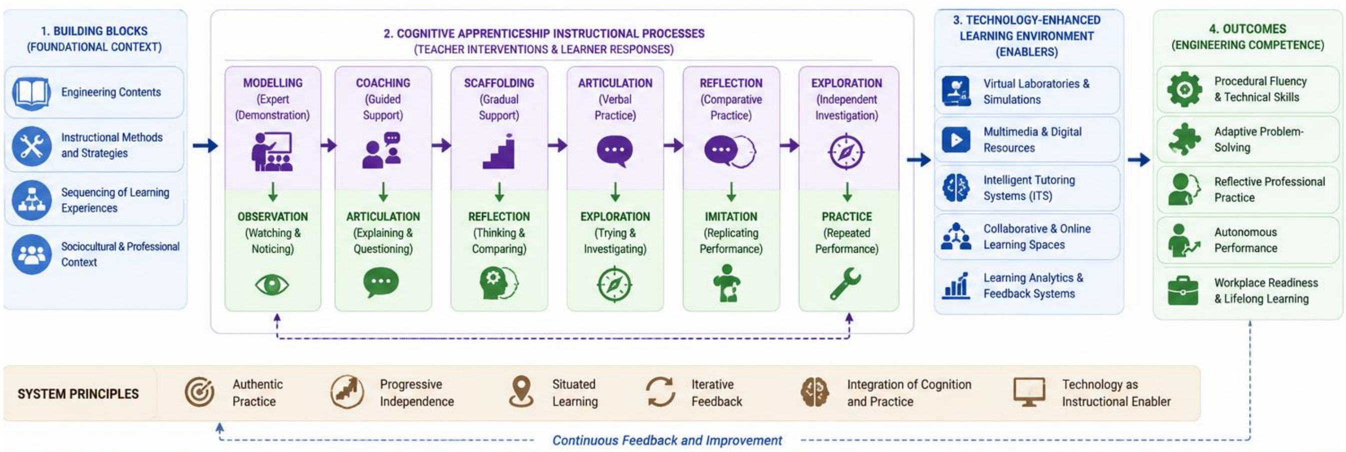
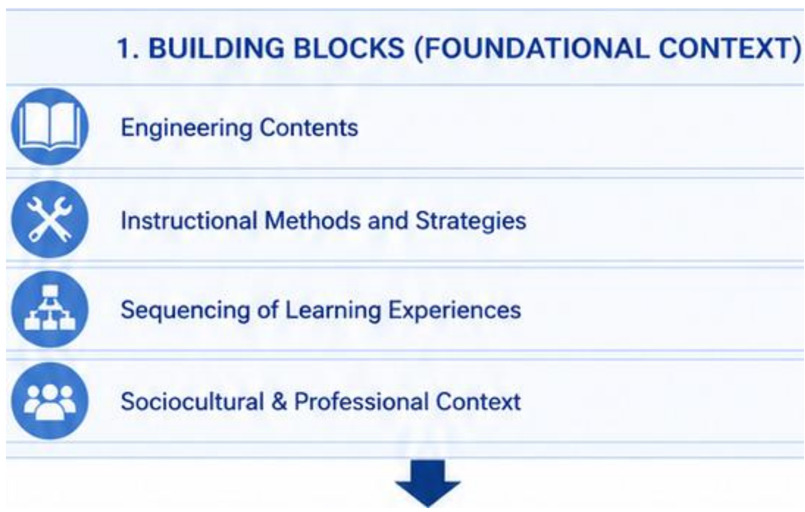


Figure 4: Contemporary Cognitive Apprenticeship Instructional Systems Architecture for Technology-enhanced Engineering Competence Development

For clarity and legibility, the different sections of the internal structure is decoupled and represented below



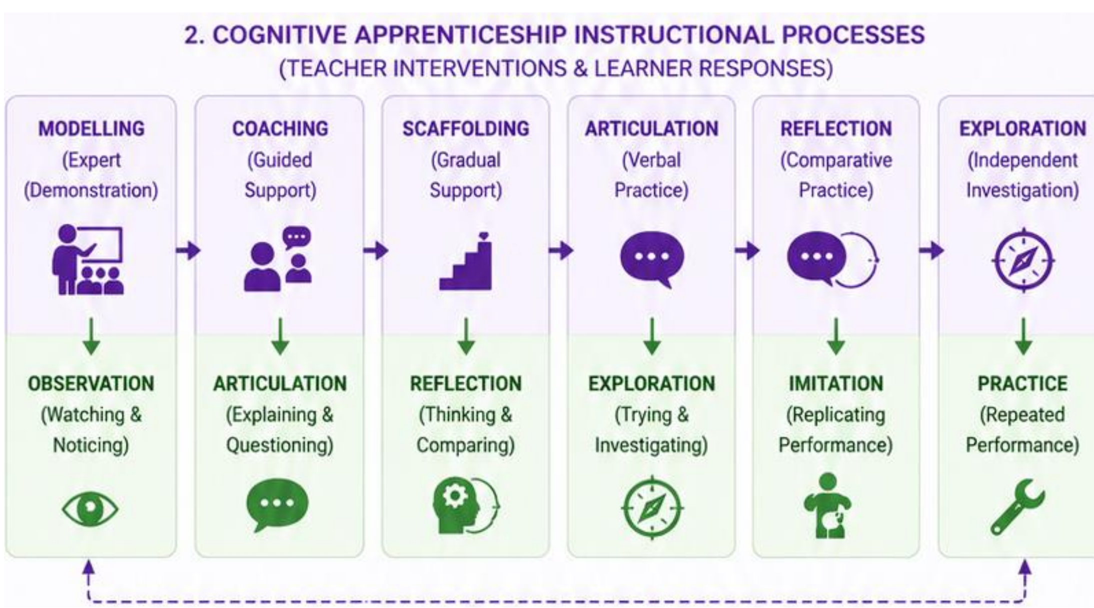


Figure 5: Decoupled Contemporary Cognitive Apprenticeship Instructional Systems Architecture for Technology-enhanced Engineering Competence Development

The reconstructed model operates as a coherent instructional system. Building blocks provide the instructional foundation upon which teachers organise modelling, coaching, scaffolding, articulation, reflection and exploration. Each instructional intervention deliberately elicits a corresponding learner response—observation, articulation, reflection, exploration, imitation and repeated practice—which collectively represent the learner's progressive internalisation of engineering competence. Rather than functioning independently, teacher interventions and learner responses operate as mutually reinforcing processes mediated by technology-enhanced learning environments. Virtual laboratories, intelligent tutoring systems, simulations, collaborative platforms and multimedia resources strengthen each instructional process by extending opportunities for guided practice, authentic participation and iterative feedback beyond traditional laboratory settings. Continuous feedback links all instructional processes, enabling progressive refinement of learner performance while gradually reducing instructional support. Through repeated cycles of guided participation, reflection and increasingly independent performance, learners progressively develop procedural fluency, adaptive problem solving, reflective professional practice and workplace readiness.

3.4 Relationship Between Ghefaili's Original Model and the Reconstructed Architecture

The reconstructed instructional architecture preserves the pedagogical philosophy of Ghefaili's Cognitive Apprenticeship Model while substantially extending its conceptual scope, instructional organisation, and applicability to contemporary technology-enhanced engineering education. Rather than replacing Ghefaili's model, the reconstruction retains its foundational assumption that engineering competence develops through guided participation in authentic learning activities supported by modelling, coaching, scaffolding, articulation, reflection, and exploration. These instructional processes therefore remain the pedagogical core of the reconstructed architecture.

However, Ghefaili's original model primarily represented cognitive apprenticeship as a sequence of instructional components linking four foundational building blocks (contents, methods, sequencing, and sociology) with teachers' instructional interventions and corresponding student learning responses. Although this structure successfully contextualised Cognitive Apprenticeship for computer-assisted vocational education, it largely reflected instructional environments in which technology functioned principally as a delivery medium supporting conventional teaching and learning processes (Ghefaili, 2003). Consequently, the model provided limited explanation of how emerging digital learning ecosystems, intelligent instructional technologies, and instructional systems thinking interact to facilitate engineering competence development.

The reconstructed architecture therefore reorganises Aziz Ghefaili's instructional model into an integrated instructional systems framework while preserving its original pedagogical logic. At its core remains the instructional interaction originally articulated by Ghefaili, namely the reciprocal relationship between teachers' instructional interventions and students' cognitive and behavioural responses. As illustrated in Figure 3, the foundational building blocks continue to provide the instructional context from which modelling, coaching, scaffolding, articulation, reflection, and exploration are organised. These instructional interventions continue to elicit corresponding learner responses, observation, articulation, reflection, exploration, imitation, and practice, which collectively support the progressive acquisition of engineering competence. This internal instructional structure therefore represents the preserved pedagogical core inherited directly from Ghefaili's original model.

Building upon this preserved instructional core, the reconstruction extends the model beyond its original boundaries by embedding the instructional processes within a broader instructional systems architecture. As illustrated in Figure 4, the teacher–student instructional interactions are no longer viewed as isolated pedagogical events but as interconnected processes supported by technology-enhanced learning environments incorporating virtual laboratories, digital simulations, multimedia learning resources, intelligent tutoring systems, collaborative online workspaces, learning analytics, and artificial intelligence-supported instructional tools. These technological components do not replace the instructional processes inherited from Ghefaili's model; rather, they function as instructional enablers that strengthen modelling, guided practice, coaching, reflection, collaboration, and progressive learner independence across both physical and virtual engineering learning environments.

The reconstruction also introduces an explicit systems layer absent from the original model. Authentic practice, situated learning, progressive independence, iterative feedback, integration of cognition and practice, and technology as an instructional enabler operate as overarching instructional principles that continuously regulate the interaction among instructional components, learning environments, and competence outcomes. Continuous feedback and instructional improvement further reinforce the dynamic nature of competence development by supporting iterative refinement of both learner performance and instructional practice.

Another important extension concerns the intended instructional outcome. Whereas Ghefaili's model primarily emphasised instructional interactions within computer-assisted vocational learning, the reconstructed architecture explicitly positions those interactions within a competence-oriented instructional systems perspective. Engineering competence is conceptualised as the cumulative outcome of sustained interaction among authentic engineering problems, structured instructional guidance, learner participation, technology-enhanced learning environments, and continuous feedback. Consequently, competence development extends beyond procedural proficiency to include adaptive problem solving, reflective professional practice, autonomous workplace performance, and lifelong learning capabilities required within contemporary engineering practice.

Accordingly, the relationship between Ghefaili's original model and the reconstructed architecture is best understood as one of instructional preservation and systems expansion. The internal instructional structure proposed by Ghefaili remains intact and continues to explain how teachers' interventions stimulate progressive learner responses. The reconstruction preserves this pedagogical mechanism while situating it within a broader instructional systems architecture that integrates Skills Acquisition Theory, contemporary technology-enhanced learning environments, engineering competence outcomes, and systems-level instructional principles. In doing so, the reconstructed model transforms Ghefaili's computer-assisted instructional model into a comprehensive instructional systems architecture capable of supporting technology-enhanced engineering competence development within digitally mediated learning environments. A comparison that highlights this transformation is presented in Table 2.

Table 2: Comparison between Ghefaili's Original Model and the Reconstructed Architecture

Dimension	Ghefaili's Original Model	Reconstructed Model
Learning environment	Computer-assisted learning	Technology-enhanced ecosystems
Technologies	Computer-based instruction	AI, virtual labs, simulations, digital twins, ITS
Pedagogical basis	Cognitive Apprenticeship	Cognitive Apprenticeship + Skills Acquisition
Learning context	Technology/vocational education	Engineering education

Dimension	Ghefaili's Original Model	Reconstructed Model
Learner progression	Guided participation	Progressive competence development
Instruction	Coaching and modelling	Full instructional systems architecture
Reflection	Limited	Continuous reflective performance
Independence	Exploration	Adaptive professional competence
Outcome	Technology-assisted learning	Engineering competence development

3.5 Theoretical Alignment of the Reconstruction

The reconstructed instructional systems architecture demonstrates the complementary relationship among the theoretical perspectives underpinning this study.

Skills Acquisition Theory explains the developmental progression through which learners acquire increasingly sophisticated levels of professional competence. Cognitive Apprenticeship Theory specifies the instructional processes required to facilitate that progression through guided participation in authentic professional practice. Ghefaili's original model contextualised these instructional processes for technology-supported vocational education by demonstrating the educational value of computer-assisted apprenticeship environments.

The present reconstruction extends this contextualisation by integrating contemporary instructional systems principles with advances in educational technology while preserving the pedagogical integrity of cognitive apprenticeship. Consequently, the reconstructed architecture provides a coherent instructional systems framework through which engineering technology competence can be progressively developed within virtual, computer-assisted, and digitally mediated learning environments.

The reconstructed Cognitive Apprenticeship Instructional Systems Architecture therefore constitutes the principal conceptual contribution of this study and provides the theoretical foundation for its subsequent operationalisation within the Technology/Vocational Computer-Assisted Training Model (TeVCAT-M), the detailed development and validation of which are reported separately.

Table 3: Complementarity of Skills Acquisition Theory and Cognitive Apprenticeship

Skills Acquisition Theory	Cognitive Apprenticeship	Contribution to Reconstruction
Cognitive Stage	Modelling	Initial understanding
Cognitive Stage	Coaching	Guided execution
Associative Stage	Scaffolding	Performance refinement
Associative Stage	Guided Practice	Procedural fluency
Associative Stage	Articulation	Knowledge externalisation
Associative Stage	Reflection	Metacognition

Skills Acquisition Theory	Cognitive Apprenticeship	Contribution to Reconstruction
Autonomous Stage	Exploration	Independent performance
Autonomous Stage	Authentic Engineering Practice	Adaptive expertise

4. Discussion and Implications

4.1 Advancing Cognitive Apprenticeship for Contemporary Engineering Education

The present study reconstructed Ghefaili's Cognitive Apprenticeship Model to address the evolving instructional demands of contemporary engineering education. While Ghefaili's original model successfully contextualised cognitive apprenticeship for technology and vocational education through computer-assisted learning environments, significant developments in educational technology, engineering practice, and instructional systems design have since transformed the contexts within which professional competence is developed. The reconstructed instructional systems architecture responds to these developments by preserving the pedagogical integrity of cognitive apprenticeship while extending its operationalisation to contemporary technology-enhanced learning environments.

Unlike traditional applications of cognitive apprenticeship, which frequently assume face-to-face supervision within relatively stable learning environments, the reconstructed architecture recognises that engineering education increasingly occurs within virtual laboratories, intelligent tutoring systems, collaborative online workspaces, remote experimentation platforms, multimedia learning environments, and artificial intelligence-supported instructional systems. Consequently, the reconstruction shifts the emphasis from computer-assisted instruction as an isolated technological intervention towards technology-enhanced instructional systems in which digital technologies function as integrated pedagogical enablers supporting authentic competence development.

4.2 Integrating Skills Acquisition Theory and Cognitive Apprenticeship

One of the principal theoretical contributions of the reconstructed architecture lies in its explicit integration of Skills Acquisition Theory with Cognitive Apprenticeship Theory. Although these perspectives have frequently been discussed independently within engineering and professional education, the present reconstruction demonstrates their complementary relationship within a unified instructional systems framework.

Skills Acquisition Theory explains how learners progressively internalise procedural knowledge through deliberate practice, guided repetition, and increasingly autonomous performance, whereas Cognitive Apprenticeship specifies the instructional processes required to facilitate that developmental progression through modelling, coaching, scaffolding, articulation, reflection, and exploration. By integrating these complementary perspectives, the reconstructed architecture establishes explicit theoretical relationships between learner development and instructional support, thereby providing a more coherent explanation of technology competence development than either theoretical perspective offers independently.

This theoretical integration also strengthens the instructional coherence of the architecture by ensuring that every instructional process contributes directly to progressive competence development. Consequently, instructional support is neither arbitrary nor technology-driven but systematically aligned with learners' evolving levels of expertise.

4.3 Contribution to Technology-Enhanced Engineering Education

The reconstructed architecture contributes to technology-enhanced engineering education by repositioning technology as an instructional resource that strengthens authentic learning rather than replacing established pedagogical principles. Virtual laboratories, multimedia environments, intelligent tutoring systems, collaborative digital platforms, remote experimentation facilities, and artificial intelligence-supported instructional tools are conceptualised as mechanisms for enhancing modelling, coaching, guided practice, reflection, and learner independence rather than as instructional objectives in themselves.

This perspective aligns with contemporary instructional systems thinking, which recognises that educational technologies produce meaningful learning outcomes only when their affordances are systematically aligned with sound pedagogical principles. Accordingly, the reconstructed architecture provides engineering educators with a theoretically grounded instructional framework capable of supporting competence development across both physical and digitally mediated learning environments.

Furthermore, by explicitly incorporating instructional systems principles into the architecture, the reconstruction provides a more comprehensive conceptual foundation for designing technology-enhanced engineering learning environments than models that focus primarily on individual instructional techniques or isolated technological tools.

4.4 Scholarly Contribution of the Reconstruction

The principal contribution of this study is not the introduction of an entirely new instructional theory but the systematic reconstruction of an established conceptual model in response to contemporary educational contexts. By preserving the enduring pedagogical strengths of Ghefaili’s Cognitive Apprenticeship Model while reinterpreting its instructional architecture through complementary theoretical perspectives and recent developments in educational technology, the study demonstrates how established instructional theories can remain relevant despite changing technological and professional environments.

The reconstructed architecture therefore contributes to scholarship in three important ways. First, it provides a contemporary reinterpretation of Cognitive Apprenticeship for technology-enhanced engineering education. Second, it establishes explicit theoretical relationships among Skills Acquisition Theory, Cognitive Apprenticeship Theory, and instructional systems design. Third, it provides a coherent conceptual architecture capable of informing the subsequent development, implementation, and evaluation of technology-enhanced instructional models, which aided the development of Technology/Vocational Computer-Assisted Training Model.

4.5 Limitations and Future Research

The present study is conceptual in nature and therefore focuses on theoretical reconstruction rather than empirical validation. Although the reconstructed architecture was developed through systematic theoretical integration and conceptual analysis, its instructional effectiveness requires further investigation through implementation within authentic engineering learning environments.

Future research should therefore examine the practical application of the reconstructed architecture across diverse engineering disciplines, technology-enhanced instructional settings, and professional training contexts. In particular, empirical studies should evaluate how the reconstructed instructional processes influence learners' technology competence, procedural knowledge, adaptive expertise, and workplace readiness.

The subsequent development and validation of the Technology/Vocational Computer-Assisted Training Model (TeVCAT-M) provide one such avenue for examining the practical applicability of the reconstructed architecture within computer-assisted engineering education and are reported separately.

5. Conclusion

The continued evolution of engineering practice and technology-enhanced learning environments necessitates instructional frameworks capable of supporting the progressive development of professional competence beyond the transmission of disciplinary knowledge. Although Cognitive Apprenticeship remains one of the most influential theories for developing expertise through guided participation, its traditional implementation reflects instructional contexts that have been substantially transformed by advances in educational technology, virtual learning environments, artificial intelligence, and digitally mediated engineering practice. This study therefore reconstructed Ghefaili's Cognitive Apprenticeship Model to enhance its relevance and applicability within contemporary technology-enhanced engineering education.

The reconstruction was undertaken through a qualitative design-oriented theoretical reconstruction approach that preserved the pedagogical integrity of Ghefaili's original model while systematically reinterpreting its instructional architecture through the complementary perspectives of Skills Acquisition Theory, Cognitive Apprenticeship Theory, and contemporary instructional systems principles. The resulting instructional systems architecture extends Ghefaili's contextualisation of cognitive apprenticeship by integrating authentic engineering practice, progressive skills acquisition, technology-mediated instructional support, and learner-centred competence development into a coherent framework suitable for contemporary engineering education.

A principal contribution of the study lies in demonstrating the complementary relationship between Skills Acquisition Theory and Cognitive Apprenticeship Theory within a unified instructional systems perspective. Whereas Skills Acquisition Theory explains the progressive cognitive development of expertise, Cognitive Apprenticeship specifies the instructional processes through which such development can be deliberately facilitated. By reconstructing Ghefaili's model through the integration of these complementary theoretical perspectives, the study provides a contemporary instructional architecture capable of supporting engineering technology competence within virtual, computer-assisted, and digitally mediated learning environments.

The reconstructed architecture contributes to engineering education scholarship by providing a theoretically grounded framework that may guide the design of technology-enhanced instructional systems, virtual laboratories, intelligent tutoring environments, and other digitally supported engineering learning contexts. Beyond engineering education, the reconstruction also demonstrates the continuing value of theoretically informed instructional model reconstruction as an approach for adapting established educational models to rapidly evolving technological and professional environments while preserving their foundational pedagogical principles.

The present study is conceptual and therefore does not report empirical evaluation of the reconstructed architecture. Future research should examine its implementation and effectiveness across diverse engineering disciplines and technology-enhanced instructional settings. The operationalisation, implementation, and validation of the reconstructed instructional architecture through the Technology/Vocational Computer-Assisted Training Model (TeVCAT-M) constitute the next phase of this programme of research and are presented separately.

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