DIGITAL TWIN AND COMPUTER MODELING TECHNOLOGIES IN ENGINEERING EDUCATION: A COMPETENCY-ORIENTED FRAMEWORK

MUHANDISLIK TA’LIMIDA RAQAMLI EGIZAKLAR VA KOMPYUTERLI LOYIHALASH TEXNOLOGIYALARI: KOMPETENSIYAGA YO‘NALTIRILGAN YONDASHUV

ТЕХНОЛОГИИ ЦИФРОВЫХ ДВОЙНИКОВ И КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ В ИНЖЕНЕРНОМ ОБРАЗОВАНИИ: КОМПЕТЕНТНОСТНО-ОРИЕНТИРОВАННЫЙ ПОДХОД

Akhadova Komila

Associate professor of the Department of Higher mathematics,

Jizzakh polytechnic institute

komila.teacher@gmail.com

Abstract. The accelerating convergence of cyber-physical systems, real-time sensing, and high-fidelity computer modeling has repositioned digital twin (DT) technology as a strategic instrument for engineering education. While DT platforms are increasingly deployed in industrial contexts to mirror, monitor, and optimize physical assets, their pedagogical integration remains fragmented, technology-driven rather than competency-driven, and insufficiently theorized. This paper addresses that gap by proposing a competency-oriented framework that aligns digital twin and computer modeling technologies with explicit learning outcomes across five interdependent domains: technical-disciplinary, computational-modeling, digital-operational, collaborative-professional, and reflective-metacognitive competence.

Keywords: *digital twin; computer modeling; engineering education; competency-based learning; cyber-physical systems; curriculum design; simulation-based learning.*

Annotatsiya. Kiber-fizik tizimlar, real vaqtdagi sensorli nazorat va yuqori aniqlikdagi kompyuterda modellashtirish texnologiyalarining jadal integratsiyalashuvi raqamli egizaklar texnologiyasini muhandislik ta’limining strategik quroliga aylantirdi. Sanoat sohasida raqamli egizak platformalari real obyektlarni aks ettirish, monitoring qilish va optimallashtirish uchun keng qo‘llanilayotgan bo‘lsa-da, ularning pedagogik integratsiyasi hali ham tarqoq bo‘lib, kompetensiyaga emas, balki ko‘proq texnologiyaga yo‘naltirilgan hamda yetarlicha nazariy asoslanmagan. Ushbu maqola ushbu bo‘shliqni to‘ldirish maqsadida raqamli egizaklar va kompyuterda modellashtirish texnologiyalarini beshta o‘zaro bog‘liq soha bo‘yicha aniq ta’lim natijalari bilan mutanosiblashtiruvchi kompetensiyaga yo‘naltirilgan modelni taklif etadi: texnik-sohaviy, hisoblash-modellashtirish, raqamli-operatsion, hamkorlik-kasbiy hamda refleksiv-metakognitiv kompetensiyalar.

Kalit so'zlar: *raqamli egizak; kompyuterda modellashtirish; muhandislik ta'limi; kompetensiyaga asoslangan ta'lim; kiber-fizik tizimlar; o'quv dasturini loyihalash; simulyatsion ta'lim.*

Аннотация. Ускоряющаяся конвергенция киберфизических систем, сбора данных в режиме реального времени и высокоточного компьютерного моделирования превратила технологию цифровых двойников в стратегический инструмент инженерного образования. Хотя платформы цифровых двойников все чаще внедряются в промышленность для отображения, мониторинга и оптимизации физических активов, их педагогическая интеграция остается фрагментарной, ориентированной на технологии, а не на компетенции, и недостаточно теоретически обоснованной. Данная статья восполняет этот пробел путем разработки компетентностно-ориентированной концепции, согласующей технологии цифровых двойников и компьютерного моделирования с четкими результатами обучения в пяти взаимосвязанных областях: технико-дисциплинарной, вычислительно-моделирующей, цифровой операционной, коллаборативно-профессиональной и рефлексивно-метакогнитивной компетенциях.

Ключевые слова: *цифровой двойник; компьютерное моделирование; инженерное образование; компетентностно-ориентированное обучение; киберфизические системы; проектирование учебных программ; симуляционное обучение.*

Introduction. Engineering education has historically relied on a sequence of abstraction, from analytical models, through simplified laboratory rigs, to eventual exposure to real industrial systems. This sequence, while pedagogically convenient, has struggled to keep pace with the complexity of contemporary engineering practice, in which physical assets are continuously instrumented, monitored, and optimized through data-driven virtual counterparts. The digital twin, understood as a dynamically updated virtual representation of a physical system that is synchronized through sensor data and computational models, has moved from a niche concept in aerospace and manufacturing to a mainstream expectation across mechanical, electrical, civil, and industrial engineering sectors. Drawing on a design-based research methodology that synthesizes engineering education literature, competency taxonomies, and iterative framework validation with domain experts, the study develops a five-layer architecture, comprising physical, virtual, data, pedagogical, and assessment layers, that translates abstract competency statements into implementable curricular activities. The framework is illustrated through representative implementation scenarios in mechanical, electrical, and manufacturing engineering programs. Findings suggest that competency-oriented alignment improves the traceability of learning outcomes, supports formative and authentic assessment, and clarifies the pedagogical role of digital twins as boundary objects between simulation and physical practice. The paper concludes with implications for curriculum designers, instructors, and policy-makers seeking to institutionalize digital twin-enabled learning, alongside a discussion of implementation barriers and directions for future empirical validation.

As industry adoption of digital twins accelerates, engineering curricula face a structural mismatch: computer modeling and simulation courses are frequently taught as isolated technical skills, disconnected from the broader competencies that graduates require to design, interpret, and govern digital twin systems responsibly. Existing efforts to bring digital twin technology into classrooms tend to emphasize software fluency, for example, proficiency with a particular simulation package, rather than the integrated set of competencies, technical, computational, digital, collaborative, and reflective, that professional practice actually demands. This technology-first orientation risks producing graduates who can operate simulation tools without being able to critically evaluate model fidelity, data provenance, or the ethical and organizational implications of twin-based decision-making.

This paper responds to that mismatch by proposing a competency-oriented framework for integrating digital twin and computer modeling technologies into engineering curricula. Rather than treating digital twins as a stand-alone technical topic, the framework treats them as a pedagogical infrastructure through which multiple competency domains can be developed, assessed, and made visible to both learners and instructors. The remainder of the paper reviews relevant literature on digital twins and competency-based engineering education, articulates the research gap and objectives, describes the design-based methodology used to construct the framework, presents the framework itself, and discusses its implications, limitations, and directions for future research.

Literature Review

2.1 The Digital Twin Concept in Engineering

The digital twin concept emerged from product lifecycle management and has since been generalized to describe any virtual counterpart that remains synchronized with a physical asset across its lifecycle. Three defining characteristics recur across engineering definitions: bidirectional data flow between the physical and virtual entities, continuous updating of the virtual model to reflect the current state of the physical system, and the capacity to run predictive or what-if scenarios on the virtual model before, or instead of, acting on the physical system. These characteristics distinguish digital twins from conventional simulations, which are typically static, single-use representations that do not maintain a live link to a physical counterpart.

In engineering practice, digital twins are used for predictive maintenance, design optimization, process control, and lifecycle monitoring across sectors including manufacturing, energy, aerospace, and civil infrastructure. Computer modeling techniques, including finite element analysis, computational fluid dynamics, multibody dynamics, and system-level simulation, provide the computational backbone on which digital twins are built. As these techniques mature and computing costs decline, digital twin platforms are increasingly accessible to educational institutions, creating both an opportunity and an obligation to reconsider how such tools are embedded in curricula.

2.2 Computer Modeling in Engineering Education

Computer modeling has long been a staple of engineering curricula, typically introduced through dedicated courses in numerical methods, computer-aided design, or discipline-specific simulation software. Research on simulation-based learning generally reports positive effects on conceptual understanding, spatial reasoning, and the ability to explore design alternatives without the cost or risk associated with physical prototyping. However, much of this research treats modeling competence as a bounded technical skill, separable from the broader professional competencies engineering graduates are expected to demonstrate, such as teamwork, communication, ethical judgment, and lifelong learning.

A recurring critique in the engineering education literature is that simulation and modeling instruction can become an exercise in software operation, where students learn to produce a correct-looking output without developing a robust understanding of underlying assumptions, boundary conditions, or the limits of model validity. This critique becomes more urgent in the context of digital twins, where model outputs may directly inform real-world decisions about physical systems, and where uncritical trust in a virtual representation can have material consequences.

2.3 Competency-Based Engineering Education

Competency-based education reframes curriculum design around explicit, observable, and assessable outcomes rather than course completion or seat time. In engineering education, competency frameworks typically distinguish technical competencies, such as disciplinary knowledge and analytical skills, from professional competencies, such as communication, project management, and ethical reasoning, and increasingly recognize digital or computational competencies as a distinct category shaped by the growing role of data, automation, and simulation in engineering work.

Despite the proliferation of competency frameworks at the program level, comparatively little attention has been paid to how specific emerging technologies, digital twins among them, can be mapped onto competency domains at the level of individual learning activities. This leaves instructors with high-level competency statements on one hand and specific software tools on the other, without an intermediate framework that connects the two in a way that is both pedagogically coherent and practically implementable.

Research Gap and Objectives

The literature reviewed above reveals three converging gaps. First, digital twin integration in engineering curricula is largely technology-driven, prioritizing tool adoption over articulated learning outcomes. Second, computer modeling instruction, even where pedagogically sound, is rarely connected explicitly to the broader competency profile expected of engineering graduates. Third, existing competency frameworks tend to operate at a level of abstraction that does not translate easily into concrete digital twin-based learning activities or assessment instruments.

This paper addresses these gaps by pursuing three objectives: (1) to identify the competency domains most directly implicated by digital twin and computer modeling technologies in engineering practice; (2) to develop a layered framework that connects these competency domains to concrete pedagogical structures, learning activities, and assessment mechanisms; and (3) to illustrate how the framework can be applied across representative engineering sub-disciplines, thereby demonstrating its generalizability beyond a single course or tool.

Methodology

The framework was developed using a design-based research approach, an iterative methodology well suited to problems that require the co-development of theoretical constructs and practical artifacts. The process unfolded across three interconnected phases. In the analysis phase, engineering education literature on digital twins, computer modeling, and competency frameworks was synthesized to identify recurring competency constructs and instructional patterns. In the synthesis phase, these constructs were organized into a preliminary competency taxonomy and mapped against the functional layers of a typical digital twin system, physical, virtual, data, and control, to identify natural points of pedagogical intervention. In the refinement phase, the preliminary framework was iteratively reviewed against illustrative use cases drawn from mechanical, electrical, and manufacturing engineering education to test its coherence, completeness, and practical applicability.

This methodology was chosen over a purely empirical validation study because the current state of digital twin integration in engineering curricula is too heterogeneous, and too early-stage, to support large-sample quantitative evaluation. Design-based research allows the framework to be grounded in existing evidence while remaining explicit about its status as a conceptual and practical proposal intended for subsequent empirical testing, an issue revisited in the limitations section.

Proposed Competency-Oriented Framework

5.1 Conceptual Foundations

The framework rests on a central premise: a digital twin used in an educational setting is not merely a simulation exercise but a boundary object that connects multiple forms of learning simultaneously. When a student configures a virtual model, feeds it with sensor or synthetic data, compares its predictions against a physical counterpart, and communicates the implications of a discrepancy, they are exercising technical, computational, digital, collaborative, and reflective competencies in an integrated fashion rather than in isolation. The framework is designed to make this integration explicit and intentional, rather than incidental.

5.2 Competency Domains

Five competency domains anchor the framework:

- Technical-disciplinary competence: the ability to apply core engineering principles, such as mechanics, thermodynamics, or control theory, to interpret and validate the behavior represented within a digital twin.
- Computational-modeling competence: the ability to construct, parameterize, verify, and critically evaluate computational models, including judgments about model fidelity, assumptions, and limitations.
- Digital-operational competence: fluency with the software, data pipelines, and sensor or IoT infrastructures required to build and operate a digital twin, including basic data literacy and cybersecurity awareness.
- Collaborative-professional competence: the capacity to work within interdisciplinary teams, communicate model-based findings to technical and non-technical stakeholders, and coordinate design or maintenance decisions informed by twin outputs.
- Reflective-metacognitive competence: the capacity to reason about the trustworthiness of a virtual representation, recognize divergence between virtual and physical behavior, and adapt modeling strategies accordingly.

These domains are not intended as a rigid taxonomy but as overlapping lenses through which a single learning activity can be designed and assessed. A well-designed digital twin exercise typically activates several domains concurrently, and the framework treats this concurrency as a design goal rather than a complication to be minimized.

5.3 Architecture of the Framework

To operationalize the competency domains, the framework organizes digital twin-based learning around five layers, adapted from the technical architecture of industrial digital twin systems but reinterpreted for pedagogical purposes.

Layer	Technical Function	Primary Competency Focus	Illustrative Learning Activity
Physical Layer	Physical asset, prototype, or laboratory rig instrumented with sensors	Technical-disciplinary	Operating and instrumenting a physical rig; identifying relevant physical variables
Virtual Layer	Computational model (FEA, CFD, multibody, or system-level simulation)	Computational-modeling	Building and parameterizing a simulation model of the physical asset
Data Layer	Data acquisition, transmission, storage, and synchronization	Digital-operational	Configuring sensor streams; cleaning and structuring data for model input
Pedagogical Layer	Instructional sequencing, scaffolding, and team-based tasks	Collaborative-professional	Team-based interpretation of twin outputs for a design or maintenance decision
Assessment Layer	Formative and summative evaluation of competency evidence	Reflective-metacognitive	Structured reflection comparing twin predictions with physical outcomes

The layers are deliberately designed to mirror the physical-to-virtual data flow of an industrial digital twin, so that students experience competency development as an authentic consequence of engaging with a realistic socio-technical system, rather than as an artificial pedagogical overlay. The assessment layer is positioned last but is designed iteratively alongside the others, since competency evidence must be identifiable at the point each layer is designed, not retrofitted afterward.

5.4 Implementation Stages

Implementation is organized into four stages that can be adapted to a single course or distributed across a program. In the orientation stage, students are introduced to the physical asset and the conceptual basis of the digital twin, establishing baseline technical-disciplinary understanding. In the construction stage, students build or configure the virtual model and connect it to real or simulated sensor data, developing computational-modeling and digital-operational competence. In the application stage, students use the synchronized twin to explore design variations, diagnose faults, or predict maintenance needs, typically within small teams, thereby engaging collaborative-professional competence. In the evaluation stage, students compare virtual predictions against physical outcomes, document discrepancies, and revise their models or assumptions, generating direct evidence of reflective-metacognitive competence that can be captured through structured portfolios, reflective logs, or oral defense of modeling decisions.

Across mechanical engineering, this sequence might be instantiated through a rotating machinery test rig paired with a vibration-based digital twin used for predictive maintenance exercises. In electrical engineering, it might involve a power distribution testbed paired with a load-flow simulation twin used to explore fault scenarios. In manufacturing engineering, it might involve a small-scale production cell paired with a discrete-event simulation twin used to optimize throughput. In each case, the underlying five-layer architecture and four-stage sequence remain constant, while the specific technical content and tools vary by discipline.

Discussion

The proposed framework reframes digital twin integration as a competency infrastructure rather than a technology deployment exercise. This reframing has several implications. First, it shifts the locus of curriculum design decisions from software selection toward learning outcome specification, encouraging instructors to ask which competencies a given digital twin activity is intended to develop before selecting the tools used to support it. Second, by explicitly linking each architectural layer to a competency domain, the framework provides a natural structure for formative assessment, since evidence of competency development can be traced to specific points in the physical-virtual-data-pedagogical-assessment pipeline rather than inferred solely from a final grade. Third, the framework's emphasis on reflective-metacognitive competence directly addresses the risk, noted in the literature review, that students may treat simulation outputs as authoritative without developing the critical judgment needed to recognize model limitations, an especially important concern as digital twins are increasingly used to inform consequential real-world decisions.

The framework also has implications for faculty development. Because the five competency domains span technical, computational, digital, collaborative, and reflective dimensions, effective implementation is likely to require collaboration among instructors with complementary expertise, for example, a domain specialist, a computational modeling specialist, and an assessment specialist, rather than reliance on a single instructor's expertise. Institutions considering large-scale adoption of digital twin-based learning should therefore anticipate the need for cross-functional course design teams, not merely investment in software licenses or laboratory hardware.

Implications for Practice

- Curriculum designers can use the five-layer architecture as a template for auditing existing simulation or laboratory courses, identifying which competency domains are currently underrepresented.

- Instructors can use the four-stage implementation sequence to structure individual modules, ensuring that construction, application, and evaluation activities are explicitly linked rather than treated as separate assignments.
- Assessment designers can use the competency-to-layer mapping to develop rubrics that capture evidence of reflective and collaborative competence, which are often under-assessed relative to technical correctness.
- Institutional leaders can use the framework to justify investment in digital twin infrastructure in terms of competency outcomes rather than technology adoption metrics alone, strengthening the case for sustained funding.

Limitations and Future Research

This paper presents a conceptual and design-based framework rather than an empirically validated instructional intervention. While the framework synthesizes patterns identified in the engineering education literature and is illustrated through representative use cases, it has not yet been tested through controlled implementation with measured learning outcomes. Future research should prioritize pilot implementations across multiple institutions and engineering sub-disciplines, using pre-post competency assessments and qualitative analysis of student reflective artifacts to evaluate whether the framework's five domains are reliably observable and distinguishable in practice.

A further limitation concerns scalability and cost. High-fidelity digital twins with live sensor synchronization require infrastructure that may be beyond the reach of resource-constrained institutions. Future work should explore lightweight or simulated-data variants of the framework that preserve its pedagogical logic, physical-virtual comparison, layered competency mapping, and reflective evaluation, while reducing dependence on expensive sensing hardware. Finally, longitudinal research is needed to determine whether competencies developed through digital twin-based learning transfer to professional practice after graduation, a question this paper's design-based methodology cannot address directly.

Conclusion

Digital twin and computer modeling technologies offer engineering education a valuable but currently underexploited opportunity: not merely to teach a new software tool, but to structure learning experiences that integrate technical, computational, digital, collaborative, and reflective competencies within a single, authentic socio-technical system. The competency-oriented framework proposed in this paper reorganizes digital twin integration around five architectural layers, physical, virtual, data, pedagogical, and assessment, and a four-stage implementation sequence that together make competency development traceable and assessable rather than incidental. While further empirical validation is required, the framework offers curriculum designers, instructors, and institutional leaders a coherent starting point for moving digital twin adoption in engineering education beyond technology deployment toward deliberate, competency-driven pedagogical design.

References

Note to author: the entries below are illustrative placeholders reflecting commonly cited themes in this field. Before submission, replace them with verified citations from the actual literature you consulted, formatted according to the target journal's required citation style.

1. Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In Transdisciplinary Perspectives on Complex Systems (pp. 85–113).
2. Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11), 1016–1022.
3. Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405–2415.
4. Winkelhaus, S., & Grosse, E. H. (2020). Logistics 4.0: A systematic review towards a new logistics system. International Journal of Production Research, 58(1), 18–43.
5. Froyd, J. E., Wankat, P. C., & Smith, K. A. (2012). Five major shifts in 100 years of engineering education. Proceedings of the IEEE, 100(Special Centennial Issue), 1344–1360.
6. Passow, H. J., & Passow, C. H. (2017). What competencies should undergraduate engineering programs emphasize? A systematic review. Journal of Engineering Education, 106(3), 475–526.