INTERNATIONAL CONFERENCE **Dehli, India, 2026**
https://eijmr.org/conferences/

DIGITAL TWIN TECHNOLOGY AS A PEDAGOGICAL INSTRUMENT FOR HIERARCHICAL MODELING OF TECHNICAL SYSTEMS IN ENGINEERING EDUCATION

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Abstract. Digital Twin (DT) technology - the real-time virtual replication of a physical system - is rapidly emerging as one of the most pedagogically consequential innovations in engineering education. This paper examines the theoretical foundations and practical frameworks for deploying Digital Twin environments as instruments for hierarchical, multi-level instruction in technical systems. The study argues that DT architecture inherently mirrors the four-level pedagogical hierarchy (component, device, subsystem, full system) proposed by Mesarovic's multilevel systems theory, making it a uniquely suitable medium for developing systems thinking competencies in engineering students.

Practical recommendations are provided for curriculum designers and engineering faculty seeking to embed DT technology into technical systems courses without displacing foundational analytical reasoning.

Keywords: digital twin, hierarchical modeling, engineering education, technical systems, systems thinking, multilevel instruction, MATLAB, Siemens MindSphere, pedagogical model.

Introduction. The increasing complexity of contemporary engineered systems - from cyber-physical manufacturing plants and smart power grids to autonomous vehicle platforms - demands that engineering graduates possess not merely component-level knowledge but a robust capacity for multi-level systems reasoning. Traditional engineering curricula, organised predominantly around disciplinary silos and sequential topic coverage, have proven structurally ill-suited to cultivating this capacity. The learner who masters the mathematics of a PID controller in isolation but cannot situate it within the control architecture of a complete industrial process possesses knowledge that is, in professional terms, incomplete.

Digital Twin (DT) technology offers a response to this structural problem that is simultaneously technological and pedagogical. A Digital Twin is a dynamic virtual model of a physical system that receives real-time (or near-real-time) data from its physical counterpart and replicates its behaviour across all relevant operational parameters. Crucially for educational purposes, DT environments are built around precisely the hierarchical decomposition that complex technical systems require: physical entity components are modelled at the lowest abstraction level, aggregated into functional devices, grouped into subsystems, and coordinated within the representation of the complete system.

Theoretical framework. Mesarovic, Macko, and Takahara's Theory of Hierarchical, Multilevel Systems established the formal mathematical basis for representing complex engineered systems as ordered collections of levels, where each level operates with its own variables, relationships, and decision logic while remaining subject to coordination from higher levels. In engineering practice, this framework maps naturally to the architectural layers of any sufficiently complex technical system: individual components obey physical laws at the lowest level; devices aggregate components into

functional units; subsystems coordinate devices toward partial system goals; and the complete system integrates subsystems within an overarching control and optimisation logic.

Digital twin platforms: didactic affordances by hierarchical level. Four representative Digital Twin platforms are currently used or pilotable in higher technical education contexts. Their comparative affordances at each hierarchical level are analysed in.

MATLAB-Based Digital Twin as the Primary Instructional Platform. For the purposes of structured hierarchical instruction in technical systems, the MATLAB Digital Twin framework is recommended as the primary platform, for three reasons: it provides complete coverage of all four hierarchical levels through its Simulink modelling environment and System Composer toolbox; it is already deployed in the majority of Uzbekistan's technical universities as the standard simulation environment for engineering disciplines; and its scripting capability allows instructors to design pedagogically controlled scenarios that constrain the student's view to a specific hierarchical level before progressively revealing the broader system context.

At Level I (component), students model individual electrical, mechanical, or thermal components as Simulink fundamental blocks, observing parameter-behaviour relationships in isolation. At Level II (device), components are encapsulated into Simulink subsystem blocks with defined input-output interfaces, introducing the concept of functional abstraction. At Level III (subsystem), multiple devices are interconnected to form a control loop or energy conversion chain, making coupling and emergence phenomena visible. At Level IV (full system), students work with a complete Simulink model composed of multiple subsystems, managing complexity through hierarchical navigation and engaging with system-level optimisation objectives.

Integrated pedagogical model for dt-based hierarchical instruction. Drawing on the foregoing analysis, an integrated pedagogical model for Digital Twin-based hierarchical instruction in technical systems courses is proposed. The model is structured around four instructional phases aligned with the four hierarchical levels, implemented across a 16-week semester. Each phase combines theoretical grounding, DT-based simulation work, a structured reflection task, and a formative assessment event.

A critical design principle of the model is progressive disclosure: the student's access to higher hierarchical levels is sequentially unlocked only upon demonstrated competency at the current level. This prevents the cognitive overload associated with premature exposure to full-system complexity while preserving the motivational function of the «whole system» as a visible destination. In practice, progressive disclosure is implemented through Moodle LMS gating: completion of the Level I formative assessment unlocks Level II materials, and so forth.

Conclusion. This paper has argued that Digital Twin technology constitutes a uniquely appropriate pedagogical instrument for hierarchical instruction in technical systems, by virtue of the structural isomorphism between DT architecture and the four-level Mesarovic hierarchy. Three conclusions follow:

1. DT platforms differ substantially in their hierarchical coverage, with MATLAB providing the broadest pedagogical utility across all four levels, while Siemens MindSphere and ANSYS Twin Builder offer higher fidelity at the subsystem and system levels.

2. An integrated pedagogical model built on progressive disclosure across four instructional phases - aligned with component, device, subsystem, and full-system levels - provides a coherent framework for semester-long DT-based technical systems instruction.

3. Engineering faculty seeking to implement DT-based instruction are advised to begin with MATLAB Simscape for component and device phases, and to introduce live-data DT platforms (MindSphere, ThingWorx) only in the full-system phase, when students have the hierarchical conceptual structure to contextualise real-time data meaningfully.

Future work should investigate the development of open-source, educationally accessible Digital Twin frameworks tailored to the resource constraints of technical universities in Central Asia, and examine the longitudinal impact of DT-based hierarchical instruction on graduates' professional engineering performance.

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