

A STRATEGIC PERSPECTIVE FOR FUTURE-PROOF WORKFORCE DEVELOPMENT: INSIGHTS INTO THE DIGITAL LIFECYCLE LAB

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ABSTRACT

Rapid technological change, digital transformation, and labour shortages are reshaping the requirements placed on the engineering workforce, increasing the need for interdisciplinary and *systems engineering* competencies. The *Digital Lifecycle Lab* (DLL) at *Graz University of Technology* addresses these needs as an educational concept supporting engineering transformation through student training and the upskilling and reskilling of industry professionals. However, effective workforce initiatives also require systematic academia-industry knowledge transfer interfaces to develop future-proof qualifications. Building on research presented at *E&PDE 2024* and *2025*, this study develops strategies to advance the engineering workforce while fostering diversity across educational formats, backgrounds, disciplines, and career stages. It examines how global trends shape workforce orientation and identifies critical future skills. As a key characteristic, the DLL integrates modelling and representation of lifecycle-spanning system phases, enabling learners to recognise interdependencies between disciplines and their contribution to holistic system creation. Moreover, the DLL's structure enables comprehensive system understanding and empowers learners from both academia and industry to identify and apply *artificial intelligence* solutions across development stages. By aligning educational content with technological demands and workforce trends, the DLL provides transferable solutions to close skill gaps and enhance inclusion, positioning itself as a model for building a resilient, future-ready engineering workforce.

Keywords: Digital lifecycle lab, workforce development, academia-industry collaboration, engineering education, systems engineering

1 INTRODUCTION

Rapid technological progress, accelerating digitalisation, and increasing system complexity are fundamentally reshaping the demands placed on the engineering workforce. Beyond technical expertise, engineers must adapt continuously, collaborate across disciplines, and manage complex systems across the lifecycle. At the same time, demographic change, labour shortages, and intensified international competition increase pressure on both engineers and educational institutions. As a result, engineering education is undergoing a profound transformation, requiring interdisciplinary collaboration across diverse teams and career stages. Such collaboration is increasingly recognised as a driver of innovation [1]. This shift moves engineering practice from isolated, sequential activities toward interconnected, model-based, and reusable development approaches. Within this context, *Systems Engineering* (SE) has emerged as an integrative competence, supporting holistic system understanding, tool and data integration, coordination across disciplines, and informed decision-making [2].

Because of these developments, traditional academic credentials alone are increasingly questioned in light of rapidly evolving workforce demands [3]. Engineering education often remains organised around discipline-specific degree programs or isolated training initiatives, thereby limiting flexibility and scalability. In parallel, industrial organisations act as technological drivers and scalars due to substantial research and development investments [4], requiring practice-oriented competencies applicable across organisational and technical boundaries. This misalignment between academic education and industrial needs highlights the necessity for approaches that extend beyond rigid, traditional formats. Prior work presented at *E&PDE 2024* and *2025* provides the background for this study by discussing networked academia-industry structures and bidirectional knowledge exchange [5], as well as an end-to-end SE-

based learning environment covering the system lifecycle [6]. Building on this foundation, the present paper uses this learning environment to examine how concrete educational designs can be scaled toward broader workforce development. It examines how global workforce trends and skill demands (*Section 2*) can be translated into requirements for engineering education (*Section 3*) and operationalised through an educational design (*Section 4*), with particular attention to organisational embedding and broader workforce impact (*Section 5*). Accordingly, this paper provides a methodological foundation for workforce-oriented engineering education through a practical concept study using an educational reference environment, complemented by pilot observations from a system development project.

2 WORKFORCE DEVELOPMENT AND FUTURE ENGINEERING SKILLS

To frame workforce-oriented engineering education, it is necessary to clarify this evolving context. In engineering, workforce development is increasingly understood as a continuous process spanning formal education and professional practice [2], requiring not only university training but also ongoing upskilling and reskilling of professionals in response to technological and organisational change [7], [8]. As highlighted by *Graham* [9], conventional engineering education often remains characterised by siloed disciplinary structures and fragmented curricula that limit cross-disciplinary learning and flexibility. This constrains heterogeneous learner groups and results in isolated educational initiatives. *Figure 1 a)* illustrates the scope of engineering education and the impact of global trends on educational pathways, ranging from student training to industrial upskilling and reskilling. Workforce development thus emerges as a shared responsibility across institutional actors. The trends outlined below provide the basis for the future-oriented competencies identified in *Section 2.2*.

2.1 Global trends shaping the engineering workforce

The engineering workforce is influenced by interrelated megatrends, including digital transformation, smart systems, *artificial intelligence* (AI), globalisation, and sustainability [10], [2], which reshape competence requirements and educational pathways. These trends alter how engineered systems are created and how engineering teams operate, while increasing complexity and expanding lifecycle integration. As engineering tasks span multiple domains and technologies, interdisciplinary and diverse teams become essential for addressing complex challenges. Research highlights the importance of heterogeneous teams for multidisciplinary problem-solving and sustained performance [11], [1], thereby extending required competencies beyond technical expertise.

Demographic decline in many industrial societies [12], combined with a persistent shortage of qualified engineers [13], intensifies pressure on educational systems and organisations to develop competencies earlier in the educational lifecycle, referred to as knowledge frontloading, as illustrated in *Figure 1 b)*. In addition, accelerating technological change reinforces the importance of structured academia-industry cooperation to align educational content with industrial needs [14], [2]. Together, these trends underscore the necessity of integrated and systematic approaches to workforce development.

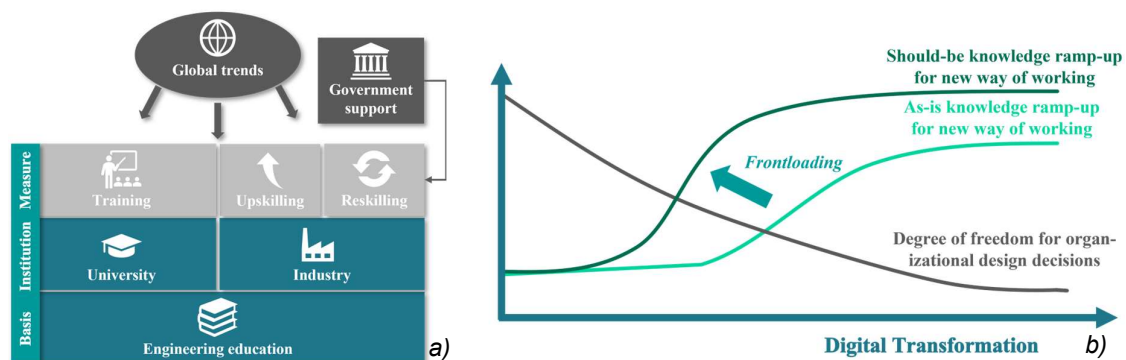


Figure 1. a) Impact of global trends on education pathways and b) Knowledge frontloading
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2.2 Future-oriented engineering competencies

The trends described in *Section 2.1* broaden the required engineering competence profile. Recent studies on engineering skills emphasise systems thinking, AI and digital fluency, complexity handling, flexibility, adaptability, lifelong learning, teamwork and leadership, and diversity awareness [15], [3].

At its core, this profile combines technical-methodological competencies that enable engineers to manage complex systems with collaborative competencies for working in heterogeneous teams. SE, *Model-Based Systems Engineering* (MBSE), and *Product Lifecycle Management* (PLM) support this integration by enabling abstraction, cross-disciplinary coordination, and lifecycle coherence. Within such approaches, AI competencies and digital fluency are central to automated and data-driven processes. Additionally, diversity-aware competencies strengthen innovation and resilience in heterogeneous teams. Across competence dimensions, lifelong learning is a major pillar of future-oriented engineers.

3 DIDACTIC REQUIREMENTS FOR MICRO-LEVEL EDUCATIONAL DESIGN

The future-oriented engineering competencies identified in *Section 2* expose a growing mismatch between traditional educational structures and emerging workforce demands. While engineering practice increasingly requires systems thinking, teamwork, and adaptability, many educational formats remain shaped by static curricula and disciplinary silos. This limits flexibility, scalability, and the ability to address heterogeneous learner groups across career stages. Workforce-oriented engineering education must therefore move beyond isolated courses or rigid degree programs. To achieve this, labour market demands must be translated into actionable educational design requirements. These requirements should support continuous competence development, accommodate diverse prior knowledge among both students and industry professionals, and provide realistic, system-oriented learning environments. Within this context, five core *didactic requirements* (DR) are derived and summarised in *Table 1*. They form the basis for the educational design introduced in *Section 4*.

Table 1. Didactic requirements for workforce-oriented engineering education

DR1	Modularity: Educational formats must be modular to enable flexible learning paths and targeted competence development for diverse learner groups.
DR2	Scalability and transferability: Didactic concepts must be scalable beyond individual courses and transferable across institutional and organisational contexts, supported by structured academia-industry transfer interfaces for broader workforce impact.
DR3	Practice orientation: Learning environments must reflect real-world complexity and lifecycle considerations, enabling the application of methods and tools in realistic engineering contexts.
DR4	Collaborative learning: Educational design must foster interdisciplinary collaboration, teamwork, and diversity-aware interaction within heterogeneous learning groups.
DR5	Support for lifelong learning: Educational formats must enable continuous upskilling and reskilling beyond formal degree programs through flexible and adaptable learning structures.

4 MICRO-LEVEL EDUCATIONAL DESIGN AND TRANSFER

To operationalise *DR1-DR5* from *Section 3*, this section translates the workforce-oriented requirements into architectural, didactic, and organisational elements. Located at *Graz University of Technology* (TU Graz), the *Digital Lifecycle Lab* (DLL) serves as a reference implementation for a concrete educational design, referred to as a micro-level educational design. While prior work introduced its technical-didactic setup in detail [6], the following sections summarise its structure, practical use, and observed outcomes as the basis for examining its scalability beyond a single institutional setting.

4.1 Concept of the Digital Lifecycle Lab

The DLL is realised as a hybrid digital-physical learning environment developed through collaboration between TU Graz, *Antemia GmbH*, and *Siemens Digital Industries Software*. As illustrated in *Figure 2 a)*, it provides an end-to-end engineering environment in which learners explore complete system lifecycles through SE, MBSE, and PLM-based data integration. In practice, learners work on connected engineering models and artifacts such as requirements, system models, simulations, and test results, which are connected through a PLM backbone and managed across role-specific workspaces. By embedding lifecycle-spanning system creation within real-world complexity, the DLL directly addresses *DR3* while fostering systems and lifecycle thinking, AI competencies, and digital fluency.

The DLL primarily serves learners across different career stages, while educators, DLL coordinators, and industry partners act as facilitators who develop and maintain the environment and infrastructure. Bachelor students are addressed mainly through introductory modules, Master students through project-based system development courses, PhD students through research-oriented method development, and industry professionals through upskilling and reskilling formats such as workshops, micro credentials,

and online training. These flexible learning paths operationalise *DR1* and *DR5* by enabling competence development across career stages. A central element is the DLL knowledge transfer triad, depicted in *Figure 2 b)*, which integrates university education, scientific work and solutions, and industry workshops into a continuous exchange between education, research, and application. This structure establishes the basis for scalability and transferability in line with *DR2*.

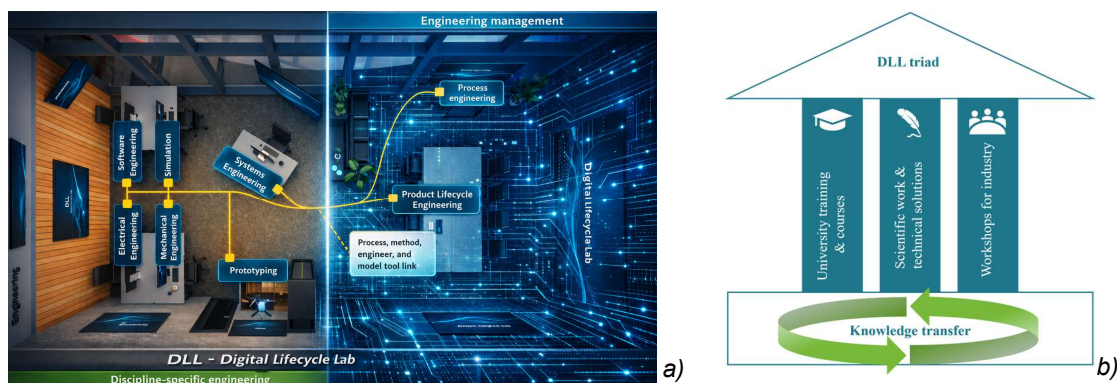


Figure 2. a) Overview of the DLL © Antemia GmbH [adapted from an original illustration with AI assistance] and b) DLL triad transfer model

4.2 Didactic design principles of the Digital Lifecycle Lab

The educational design of the DLL builds on learning-by-doing and project-based learning in hybrid formats for diverse learner profiles. Interdisciplinary project settings address realistic system challenges and operationalise *DR4* through structured collaboration and diversity-aware interaction. To ensure reproducibility and scalability, the DLL prioritises team roles, flexible learning paths, and engineering methodologies over specific software tools. Derived from *DR2* and *DR4*, these principles support transferability across institutional contexts while keeping systems thinking and lifecycle-oriented methods at the core. The DLL knowledge transfer triad reinforces feedback between education, research, and industrial application.

To illustrate these principles, the master-level *Project of Mechatronic Systems* (PMS) course serves as a blueprint, in which groups of 5-10 students physically and digitally develop a mechatronic system over one semester with an effort of 150 hours per student, as discussed in [6]. The course applies role-based collaboration, formalised MBSE, and documented system architectures as reusable artifacts. In initial implementations, SE-related activities accounted for approximately 25-30% of total project effort, as captured in detailed time and task recording. In subsequent PMS courses, reuse of formalised models and artifacts reduced overall effort by up to 15%, indicating the transferability of the model-based methodology. However, these figures are reported as limited pilot observations rather than statistically generalisable results from systematic learner evaluation. Beyond measurable efficiency gains, the availability of reference models improved system understanding, traceability awareness, and interdisciplinary coordination, as reflected in learner and instructor feedback.

4.3 Organisational embedding and academia-industry transfer interfaces

For the DLL to function as a scalable template, it is embedded in academia-industry transfer interfaces connecting academic education with industrial competence development, as required by *DR2*. These structures extend micro-level educational design beyond isolated learning environments and enable diffusion toward broader workforce contexts.

Within industrial organisations, exemplified by Siemens' *Science, Academics & Transfer* unit, boundary-spanning teams – meaning teams connected across different organisational units, disciplines, and institutions – operate at universities, where embedded PhD candidates and researchers act as translators between education, research, and application. These teams support universities and industrial partners in adapting the DLL concept to new institutional settings by aligning educational objectives, technical constraints, and workforce needs while preserving its didactic and methodological principles. In practice, they moderate alignment between academic instructors and industry representatives by translating industry needs into academic learning objectives while feeding innovative impulses back

into industrial practice. Industry partners provide relevant use cases, while academic instructors remain responsible for curricular coherence and assessment.

The DLL also serves as an industrial validation environment in which new engineering approaches and emerging technologies are tested early under realistic conditions before broader application. In parallel, industrial credential ecosystems, such as micro credentials, underline the need to align academic training with industrial upskilling and reskilling. Together, these structures enable the replication and scaling of micro-level educational designs and support their translation into macro-level workforce development.

5 FROM MICRO-LEVEL EDUCATION TO MACRO-LEVEL IMPACT

Building on the didactic design principles, organisational embedding, and transfer mechanisms described in *Section 4*, the DLL shows how concrete learning environments can contribute to broader workforce development goals at the macro-level. Rather than relying on isolated learning interventions, the DLL operationalises workforce-oriented engineering education through modular and adaptable formats that support continuous competence development across learner profiles and career stages. Through its integration into academia-industry transfer interfaces, the DLL functions as a transferable model for workforce development by providing adaptable design principles rather than a fixed technical setup to be replicated one-to-one. As a result, individual learning environments can contribute to broader objectives such as skill-gap reduction, workforce resilience, and lifelong learning in response to accelerating technological and demographic change.

The scalability of such educational concepts depends less on individual learning formats than on enabling framework conditions. Replication of the DLL concept requires qualified personnel, digital infrastructure, faculty training, sustained institutional commitment, long-term financing models, and locally adaptable core elements such as role-based workspaces, lifecycle integration, and academia-industry alignment. Its distinct value lies in integrating project-based SE education with PLM-based lifecycle continuity, reusable engineering artifacts, role-based collaboration, and moderated academia-industry transfer. Potential barriers to adaptation include high setup and maintenance effort, institutional resistance to curriculum change, and the risk that software tool complexity may overshadow didactic objectives. Sustainable financing models that combine academic funding, industrial co-investment, and public support are therefore essential to ensure continuity beyond project-based initiatives. Targeted governmental programs and policy frameworks can further amplify impact by incentivising structured academia-industry collaboration and long-term investment in workforce-oriented educational infrastructures. Central to this scaling process are strategically designed collaborations, in which boundary-spanning teams and intermediary roles, as outlined in *Section 4.3*, coordinate stakeholders, align educational objectives with workforce needs, and adapt the DLL concept to diverse institutional and regional contexts.

By linking project-based SE education, PLM-supported lifecycle continuity, reusable engineering artifacts, role-based collaboration, and moderated academia-industry transfer, the DLL's distinct role lies in demonstrating how engineering education can move beyond isolated interventions toward scalable and sustainable workforce development.

6 CONCLUSION AND OUTLOOK

This paper addresses the growing need for systematic workforce-oriented engineering education in response to accelerating technological change, increasing system complexity, and shifting labour market conditions. Building on prior work presented at *E&PDE 2024* and *2025*, it advances the discussion from isolated educational environments toward a structured linkage between micro-level educational design and macro-level workforce development. The contribution lies in the conceptual and methodological grounding of workforce-oriented engineering education. By deriving requirements from global workforce trends and future-oriented competency demands and operationalising them through the DLL, the paper demonstrates how educational design can be aligned with long-term workforce objectives. Additionally, diversity and inclusion are treated as functional design principles, supporting innovation and resilience in heterogeneous engineering contexts.

Through its organisational embedding and academia-industry transfer interfaces, the DLL illustrates how micro-level educational designs can be transferred beyond isolated institutional settings. At the same time, the approach is subject to limitations related to resource requirements, organisational complexity, faculty training, institutional resistance, and the risk that software tools may overshadow

didactic objectives. This underlines the importance of sustained institutional commitment, industrial co-investment, and supportive governmental frameworks.

Future work should focus on systematic learner evaluation and long-term impact assessment, including perceived learning value, learning effectiveness, competence development over time, and organisational workforce outcomes, building on the initial observations reported in *Section 4.2*. Further research on transferability and policy-driven support mechanisms will be essential to strengthen scalability. In this context, the DLL provides a promising foundation for continued experimentation and collaboration toward resilient and future-ready engineering workforce development.

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