THE "DIGITAL LIFECYCLE LAB" AS AN INTERDISCIPLINARY ENGINEERING ENVIRONMENT FOR FUTURE ENGINEERS AND INDUSTRY FOR ENHANCING ENGINEERING EDUCATION

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ABSTRACT
The complexity of mechatronic systems continues to grow due to various technological and organizational factors. This growing complexity contributes to a rising demand for engineers who can comprehend and abstract both system behaviours and structures. Therefore, it is essential to support engineers in developing and maintaining a mindset oriented toward innovative engineering approaches in the field of Systems Engineering (SE). Acquiring these critical skills and attitudes requires a supportive and practice-oriented environment.
This paper presents the Digital Lifecycle Lab (DLL) at the Graz University of Technology (TU Graz), with a focus on engineering education. The DLL provides an industry-oriented, interdisciplinary engineering and management platform, where SE approaches are taught and applied. By seamlessly connecting processes, methods, organizational factors, engineering models, and industry software tools, the DLL demonstrates how complex system development can be supported to enable comprehensive traceability. Furthermore, bidirectional knowledge transfer between industry and academia is highly promoted in the lab, ensuring that students and professionals gain relevant and innovative expertise.

Keywords: Digital lifecycle lab, digital engineering, engineering education, systems engineering, product lifecycle management, industrial education ecosystem

1 INTRODUCTION
The digital transformation and the implementation of digital solutions in engineering require adaptations in existing processes and organizational structures. A unified strategy to address both societal and company-specific challenges is essential to prevent financial burdens, technical obstacles, and a shortage of professionals. [1], [2] Engineering companies that fail to invest in systematic digital solutions risk losing profitability and technical competitiveness. A clear roadmap for applying methods to execute engineering activities is the first step toward a sustainable approach.
In addition to service providers and tool vendors, universities are actively shaping digital transformation and digitalization processes [3]. Given the growing demand for digitally skilled professionals, the shortage of qualified engineers has become a critical concern. Each year, more than 100,000 engineers are missing in the DACH region [4], [5], and 400,000 in the US [6]. As a result, engineering education and training must adapt to these shifts and help increase the attractiveness of the profession.
Alongside the quantitative shortage, there is also a lack of methodological expertise required to support and implement digitalization strategies. In this context, multidisciplinary collaboration and systems thinking are key competencies. Such collaboration is supported by a T-shaped distribution of knowledge in development teams, combining deep expertise in a specific engineering field with basic interdisciplinary understanding. To establish this broad knowledge spectrum, systems engineers are employed to manage system complexity and meet the growing demands of modern development. [7]
To overcome these social and technical challenges, the teaching, life-long training, and practical application of Systems Engineering (SE) are of particular importance. To scale the benefits of SE, more students must be attracted, SE curricula must be aligned, and universities must expand their SE education offerings. [8]

This paper presents an approach that promotes the synergy and knowledge transfer between industrial application and engineering education. Figure 1 illustrates this approach, which includes five steps for transferring engineering solutions, skills, and knowledge, starting from the identification of engineering challenges and educational objectives (step 1) in both academia and industry.
A central element in realizing this approach is the Digital Lifecycle Lab (DLL) at the Graz University of Technology (TU Graz), which is part of the industrial education ecosystem [9]. The DLL offers a practice-oriented, end-to-end engineering education environment aligned with industrial needs for system development processes. While it focuses on digital development using a seamlessly connected software landscape, it remains a physical engineering environment that enables hands-on experience.
Within this combined framework, innovation primarily refers to advancements at the system development level (step 2), encompassing both didactical innovations (such as hybrid educational formats – see Section 3) and technical innovations (such as development and application of novel virtual engineering methods). These innovations, developed and implemented within the DLL, are elevated to a new level of applicability across educational and industrial contexts (step 3). These application opportunities enable targeted knowledge exchange in system development, supporting the identification of new methods, software solutions, and ideas (step 4 – industry view). In turn, this knowledge is transferred to education and training programs to develop the skills (step 4 – academia view) that students and industry professionals need to implement these solutions.
To realize this innovation approach, this paper primarily focuses on engineering education using the DLL Innovation Canvas, complemented by the didactic concepts and environment of the DLL. In addition, examples of knowledge transfer between industry and academia are presented (step 5).

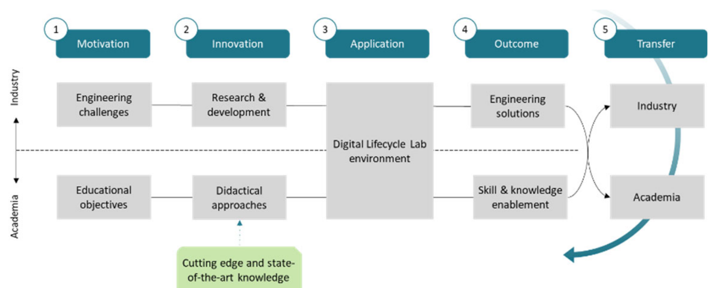

Figure 1. Combined approach to enable innovations for industry and academia

2 SCOPE OF ENGINEERING EDUCATION & TRAINING

As discussed, this section focuses on the educational aspects of the DLL, illustrated by the DLL Innovation Canvas in Figure 2. Based on the University Innovation Canvas [10], this framework was chosen for its ability to clearly align the challenges addressed by the DLL in engineering education and training with actionable innovative strategies in a structured manner. The content of the DLL Innovation Canvas was developed collaboratively by the main stakeholder groups - students, research personnel (including lecturers), and professionals from industry. Based on insights from research projects within the DLL, expert input from researchers, and intensive coordination and feedback loops, the Canvas was iteratively refined to reflect challenges and value propositions in SE education. The value propositions of the DLL are directly derived from the identified challenges in SE education, such as the lack of engineering experience and insufficient SE understanding. Each value proposition is aligned with specific stakeholder groups. Their effectiveness is evaluated through measurable outcomes such as examination results, student project performance, and industry feedback.
Building on these foundations, one key innovation implemented in the DLL to address major challenges in engineering education is the integration of SE with Product Lifecycle Management (PLM) and Artificial Intelligence (AI) technologies. In doing so, the focus lies on understanding system architecture and interfaces rather than deepening expertise in specific engineering disciplines, enabling engineers to collaborate from a higher-level systems perspective. For AI integration in the DLL, use cases include enhanced search functionalities, context-aware question answering, and automation of engineering activities, all of which are continuously being refined. In the context of this innovation, key research gaps in SE education are addressed, including the lack of integration across disciplines, tools, and technologies, as well as limited hands-on experience in generating comprehensive product structures and traceability within PLM systems. While existing SE software solutions offer partial support, they

lack comprehensive traceability integration across the whole development process. The DLL overcomes these gaps by providing an end-to-end configured environment with industrial PLM software, enabling students and professionals to build both theoretical knowledge and practical skills.

In general, SE serves as a basis for applying development principles and best practices through processes, methods, organizational aspects, and software tools, also referred to as the Four Interlocking Pillars. These pillars represent the major perspectives for the application of SE in industry. [7] Within the DLL, the pillars are not isolated, but are integrated through a connected software landscape that seamlessly supports all key activities across the system development process.

For the purpose of realizing interconnectedness within the DLL, the formal application of Model-Based Systems Engineering (MBSE) is of particular importance, as it enables the digital embedding of development artifacts in a scalable, reusable, consistent, and linkable manner according to the corresponding methodical procedures. Effectively transferring this formal application to the discipline-specific engineers requires different approaches depending on the connectivity and scope of the MBSE approach. These approaches include model-based design practices, comprehensive traceability between artifacts, and hierarchical decomposition.

Overall, the combined application of SE and MBSE represents a key strength in driving innovation, making it an essential part of modern engineering education and training. The DLL provides an engineering environment that is ideally suited for their practical implementation.

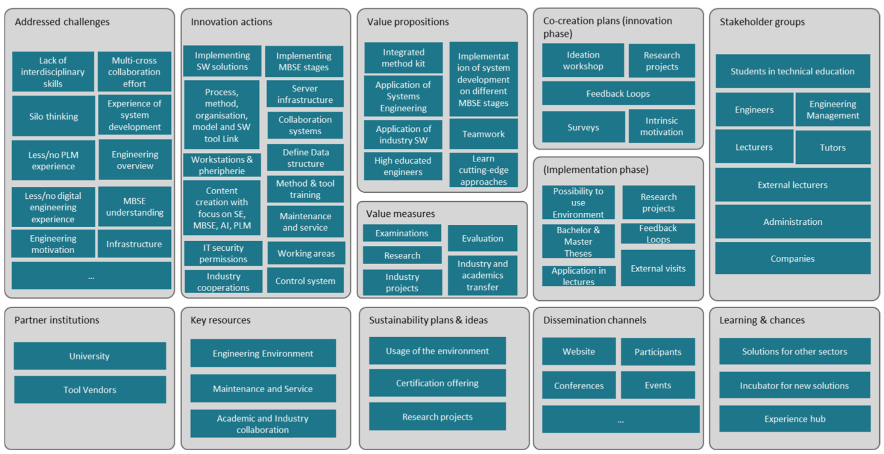

Figure 2. DLL Innovation Canvas

3 DIDACTICAL APPROACHES

The didactical strategies implemented within the DLL are designed to support engineering education through a structured, practice-oriented learning environment. A central element of the didactical strategy of the DLL is a hybrid learning concept, which combines physical and digital spaces to integrate in-person lessons, hands-on project work, on-demand online training, and self-study opportunities. This hybrid concept is aligned with the fact that the past few years have demonstrated the significant potential of digital teaching formats for knowledge transfer and skill development [11] and that they are considered central to the future orientation of education [12]. The blend of both digital and face-to-face formats, applied with students within the DLL is designed to leverage the advantages of both while compensating for their individual weaknesses. In addition, the DLL's hybrid learning strategy is coordinated with Bloom and Engelhart's Taxonomy Stages [13], supporting the stepwise development of cognitive abilities in the context of complex engineering tasks.

Within the DLL's didactic strategy, SE and MBSE provide the methodological foundation for collaborative, model-based development across disciplines. These virtual approaches promote structured systems thinking and support cognitive accessibility. To prepare students for future engineering challenges, the DLL integrates recommender systems and AI-based assistance tools into the curriculum. This is based on SE, MBSE, and PLM as an interconnected framework that enables efficient application of AI in product development [14], [15].

The DLL's didactic concept for the master's curriculum in mechanical engineering follows a stepwise structure to build knowledge from theory to practice. It begins with fundamental SE lectures supported by a hands-on modeling approach designed to lower the entry barrier to MBSE tools, introduce systems thinking, and familiarizes them with the DLL environment. This is followed by lectures on system modeling and PLM, where students apply MBSE and PLM software in a controlled lab setting. In a subsequent project work, students build a mechatronic system from scratch using SE principles for discipline-specific and interdisciplinary engineering (see Section 5 - first dimension). During this project support is provided through exclusive access to *Antemia's mindary* platform [16], offering practical, application-oriented training content outside of live sessions. These on-demand courses include SE methodologies and tool guides (SE and MBSE in combination with PLM), originally designed for engineers from industry for immediate SE application. In addition, as part of an academic cooperation with Siemens, access to the *Xcelerator academy* [17] platform is provided for tool-specific training in Siemens software.

The didactic concept is complemented by a fully developed reference system in the DLL (see Section 5 – second dimension), which is accessible at every stage of the learning path and provides comprehensive digital engineering models for demonstration and advanced training. This enables students to quickly grasp and apply the core principles of SE, MBSE, and PLM through immediate, practice-oriented engagement. Their understanding, competencies, and acquired knowledge are continuously assessed throughout the lectures via interactive exchange, as well as a combination of presentations, oral examinations, written reports, and functional system tests.

This comprehensive educational and training approach in the DLL equips students with the theoretical knowledge and practical expertise needed to address complex engineering challenges. Upon completion of the program, students are well prepared to pursue a final thesis in this field, contribute to state-of-the-art (SoTA) engineering methodologies, or apply their interdisciplinary systems understanding in complex industrial projects.

4 THE DLL ENVIRONMENT

As stated, the DLL has been designed to support diverse engineering activities along the product development process. For this purpose, different workspaces have been implemented, reflecting common disciplines in teams for collaborative development. Each workspace is equipped with different industrial software applications, which are managed and seamlessly connected by a PLM system.

The core of the DLL in terms of information technology (IT) infrastructure is a scalable, high-performance server that acts as a hypervisor that manages and executes engineering IT processes. The server enables the operation of multiple instances of configured PLM, process management, and model management technologies. Supported by an innovative visualization and control system, different views on engineering management and engineering processes can be utilized for coordinating, orchestrating and evaluating projects. A prerequisite in the design of the DLL is the implementation of the VDI 2221, VDI/VDE 2206 guidelines, along with the comprehensive coverage of MBSE activities, to enable an industry-oriented environment for research and the application of SoTA engineering.

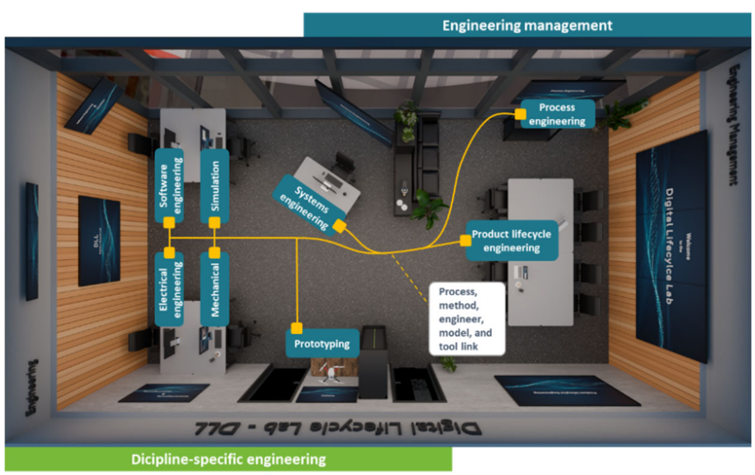

Figure 3. Areas in the DLL © Antemia

5 TRANSFERS BETWEEN ACADEMIA AND INDUSTRY

This section presents selected examples of the bidirectional knowledge transfer within the DLL, covering three dimensions: university education, scientific work combined with engineering solutions, and industry workshops. This transfer bridges the gap between knowledge generation and application, and between optimizing engineering approaches and developing new solutions.

The first dimension focuses on university education, aiming to prepare students and postgraduates for advanced engineering activities. As an example, a student project from the mechanical engineering master's program (see Section 3) is presented. In this project, students developed a mechatronic system from end to end – a fully traceable, structured, and physically realized 3-axis logistics robot (see Figure 4.a). By working within the interconnected DLL environment, students gain a holistic understanding of engineering methods, system architecture, and complex interactions. The project includes hands-on SE, discipline-specific engineering, simulation, and testing, supported by software tools, hardware components, and interactive visualization tools. To acknowledge these achievements, students receive customized digital badges as verifiable credentials, highlighting their advanced competencies and positioning them as competitive candidates for industry careers. This demonstrates the in-depth transfer of SoTA knowledge to industry.

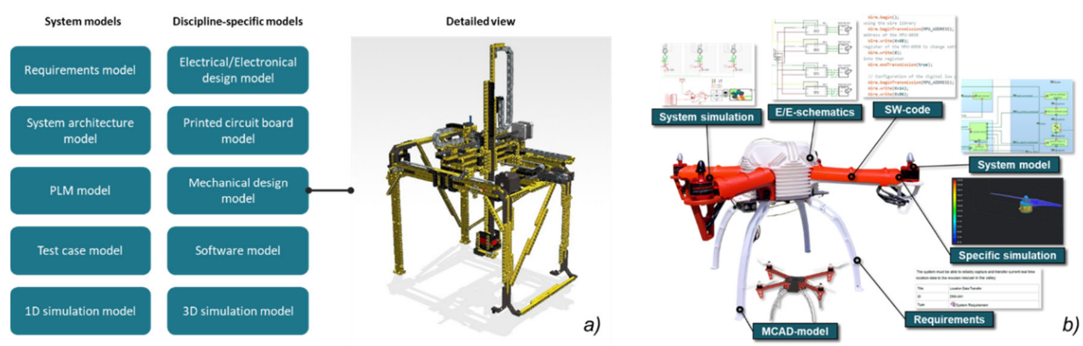

Figure 4. a) Outcomes of the PMS student group 24/25 and b) an ongoing Ph.D. work

The second dimension focuses on scientific work and the development of innovative engineering solutions for industrial application. One example is an ongoing Ph.D. project that demonstrates the potential of interrelated technical models to ensure traceability, centralized data availability, and standardized data structuring throughout the development process. Current efforts concentrate on integrating the Four Interlocking Pillars within a centrally managed database to enable full engineering traceability by connecting and orchestrating various software tools. The DLL supports this approach through its interactive visualization capabilities. The resulting holistic engineering solution is applied within the connected tool landscape onto a radio-controlled drone system, involving several engineering models (see Figure 4.b). Around the DLL's PLM system, relevant engineering data are captured and interlinked to ensure traceability and facilitate cross-disciplinary communication. This structured, transparent implementation represents a novel SE solution that combines system modeling methods, an adaptable PLM framework, and iterative approaches for structuring and detailing systems and data.

The third dimension focuses on enablement and strategy workshops that leverage digital engineering methods. Utilizing the DLL, *Antemia GmbH* offers workshops for industry professionals, providing training in virtual methods and guidance on implementing SE and MBSE strategies in conjunction with PLM to meet specific industrial needs. The workshops are tailored to participants' expertise and are aligned with the value-creation perspective of system development. They incorporate detailed and realistic use cases to demonstrate the practical value of the presented solutions, supporting first-time-right implementation strategies. Within these workshops, the DLL environment enables clear and accessible presentation of complex, interconnected engineering concepts, helping participants understand system interactions and development structures effectively. By actively contributing to the ongoing evolution of the DLL, these workshops ensure its alignment with current and future challenges and promote continuous progression of this learning infrastructure as a real-world engineering platform.

6 OUTLOOK

The future development of the DLL aims to strengthen its role in education, training, research, and industry collaboration by addressing emerging challenges and leveraging innovative technologies. Current efforts focus on expanding the use of AI in system development to derive specific technical solutions within the DLL environment. As part of this strategy, digital learning experiences such as on-demand training and interactive simulations are being implemented to support flexible, practice-oriented knowledge transfer. These innovations create an environment where engineering strategies and development activities can be orchestrated in new, integrated ways, enabling students and industry professionals to gain a deeper, more practical understanding of SE, MBSE, and PLM. By maintaining a strong feedback loop between academia and industry, the DLL will remain responsive to practical needs and emerging trends – solidifying its role as a hub for innovation, education, and research in digital engineering.

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