EDUCATING FUTURE ENGINEERS IN MATERIAL HANDLING SYSTEMS DESIGN: AN INTEGRATED AND INTERDISCIPLINARY APPROACH

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ABSTRACT

At the Institute of Logistics Engineering at Graz University of Technology, the design, analysis, and optimisation of material handling systems have traditionally been taught in separate courses distributed across multiple semesters throughout the curriculum. The courses can be divided into two categories: Logistics and Mechanical Engineering. Both cover fundamental principles as well as advanced topics. A problem is that the isolated structure limits interdisciplinary learning and systemic understanding of logistics and engineering challenges.

To meet the growing need for engineers with holistic, sustainable, and interdisciplinary systems thinking, a new integrated teaching concept has been developed. This paper presents its design and planned implementation. The approach is inspired by learning factories and aligned with Industry 5.0 principles, which emphasise human-centricity, resilience, and sustainability.

The learning factory represents a parcel hub as a virtual model. It serves as a central didactic tool across multiple courses, enabling students from various disciplines to analyse, design, and optimise processes and system components. The implementation will begin with a pilot phase, in which selected courses are integrated into a cohesive framework. Subsequent iterations will further refine the concept based on continuous evaluation and feedback.

This approach aims to provide students with both theoretical and practical skills, fostering an integrated, systems-based perspective essential for sustainable and efficient design of material handling systems. By embedding real-world applications into the curriculum, this concept ensures that future logistics engineers are prepared to develop technical solutions that align with social and environmental responsibilities, reflected the human-centred vision of Industry 5.0.

Keywords: Material handling systems, Industry 5.0, logistics engineering, sustainable design, human-centric engineering, digital engineering tools, sustainable logistics

1 INTRODUCTION

The increasing complexity and interdisciplinarity in the fields of engineering require an adaptation of academic education. The call for practical and application-oriented teaching of knowledge and skills is becoming more urgent in order to meet the requirements of modern labour markets [1]. In addition to teaching subject-specific fundamentals, the promotion of interdisciplinary skills and a systemic understanding of complex technical challenges is becoming increasingly important. The confident use of digital engineering techniques is also particularly in demand.

Ideally, a consistent teaching concept would span an entire curriculum. While interdisciplinary meta-frameworks or broad pedagogical models may theoretically apply across all subject areas, implementing a concrete and meaningful concept at this scale is rarely feasible within typical university structures. A more practical and effective approach is to meaningfully link multiple courses within a single subject area to promote interdisciplinary thinking and support knowledge transfer.

This paper presents an approach to integrating multiple courses into a unified educational framework. At the Institute of Logistics Engineering (ITL), Graz University of Technology, a formerly isolated teaching concept – initially designed for a single course – was systematically expanded to interconnect up to 17 courses wherever meaningful. The key didactic tool, a virtual learning factory modelled as a parcel hub, fosters interdisciplinary collaboration and develops students' process-oriented and technical competencies.

A central goal of this concept is to enable students to understand how different course contents interact within a real-world system, enhancing practical comprehension and fostering interdisciplinary and cross-domain learning. The focus lies on promoting interdisciplinary thinking, the intensified use of digital engineering tools, the systematic implementation of Industry 5.0, and increasing practical relevance through application-oriented learning and industry insights. These skills are essential for the effective implementation of modern engineering concepts and sustainable design of technical systems.

2 BACKGROUNDS

2.1 New Skill Requirements for Engineers

In recent years, the role of engineers has undergone significant transformation. Their range of responsibilities has steadily expanded, now encompassing a broad spectrum of activities. Engineers are increasingly confronted with interdisciplinary challenges that involve high levels of technical complexity. Moreover, rapid technological progress, driven by the continuous emergence of new technologies, further amplifies these demands [2].

The shift towards industrial concepts such as Industry 5.0 introduces additional challenges for engineers. While Industry 4.0 primarily focused on automation, digitalisation, and data-driven processes, Industry 5.0 builds upon this foundation by emphasising human-centric, resilient, and sustainable principles. Consequently, engineers must not only be proficient in integrating advanced technologies into technical processes but also consider the social and environmental impact of their solutions [3].

This shift is particularly evident in small and medium-sized enterprises (SMEs), which are often characterised by flat hierarchies and limited personnel resources. Engineers in these organisations are increasingly expected to take a holistic approach by considering the entire product life cycle rather than focusing solely on their specific discipline. This demands professionals capable of identifying and managing interfaces between fields, bridging gaps between specialised knowledge areas [4].

At the same time, the use of digital engineering tools has become a crucial factor in supporting engineers. Proficiency in methods such as discrete event simulation (DES), finite element analysis (FEA), and multi-body simulation (MBS) is indispensable in modern engineering practice, enabling professionals to analyse, optimise, and implement innovative solutions more effectively [4].

These evolving requirements challenge engineers and must be addressed from the foundation of their education. Universities play a key role in preparing future engineers by integrating these aspects into engineering curricula. The challenge is to maintain subject-specific depth while fostering interdisciplinary connections and incorporating emerging technological trends into academic programmes.

2.2 Learning Factories as a Bridge Between Theory and Practice

A learning factory is a learning environment that closely resembles a real value chain, incorporating authentic technical and organisational processes [5]. Unlike rigid forms of teaching, the didactic concept of learning factories emphasises a combination of formal, informal, and non-formal learning, fostering independent action by participants in a practical setting [6].

Learning factories serve as a platform for bridging theoretical knowledge with practical experience, employing hands-on learning approaches [7]. They align with current and future-oriented developments in the market environment, forming a flexible framework that adapts to the evolving demands of modern workplaces [8]. Depending on their design, learning factories enhance preparation for interdisciplinary teamwork and group projects. They also integrate social aspects of the working environment, fostering the development of professional competencies that extend beyond purely technical qualifications [9].

While applications in product management, LEAN, and automation are widely established, their use in logistics remains relatively limited [10]. Challenges include the risk of oversimplifying subject depth and potentially underrepresenting domain-specific expertise, particularly in early study phases.

However, learning factories do not necessarily have to produce physical products as the term "factory" suggests. They can also be process-oriented learning environments in which value chains are mapped virtually, controlled remotely, or geared towards service processes [11].

2.3 Courses at ITL

Teaching at the Institute of Logistics Engineering is divided into two main areas: “Logistics” and “Mechanical Engineering” (Figure 1). Both areas offer basic and in-depth courses for Bachelor's and Master’s students.

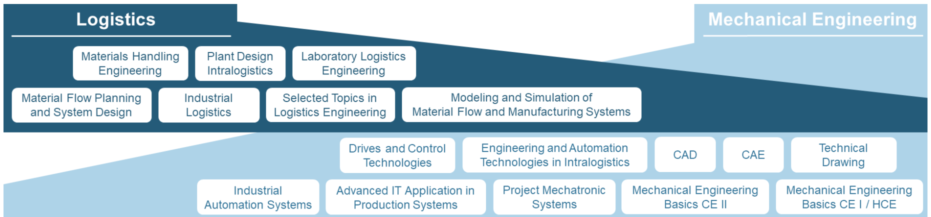

Figure 1. Courses at the Institute of Logistics Engineering[1]

3 DEVELOPMENTS OF THE NEW TEACHING CONCEPT

The new teaching concept is developed by systematically addressing key didactic questions to ensure effective and sustainable knowledge transfer. The first step is to define the content and skills to be taught, followed by the selection of suitable teaching methods and a systematic evaluation concept.

3.1 Content and Skills

The content of the existing courses is already established and covers central engineering subject areas. Basic learning objectives of the individual courses are also defined. The new teaching concept does not focus on redesigning the content, but rather on an overarching structure and methodological expansion in order to link the existing content in a more targeted manner and to enable holistic skills development. The focus is on four overarching objectives (o): (1) the promotion of interdisciplinary thinking, (2) the intensified use of digital engineering tools, (3) the systematic implementation of Industry 5.0 principles, and (4) enhancing practical relevance through application-driven learning and industry-related insights.

3.2 Integration of a Learning Factory as a Central Component

The new teaching concept leverages the didactic benefits of the learning factory as a methodological framework through two main approaches: First, it serves as an interactive learning environment that integrates theoretical knowledge with practice-oriented applications (o4). A virtual learning factory is specifically chosen for its scalability and flexibility, allowing for digital tool integration and enhanced practical relevance (o2) without dependence on physical resources.

Secondly, the learning factory functions as an overarching concept that combines several subject-specific courses. Instead of students learning isolated content in separate courses, the learning factory is used as a common methodological foundation to make interdisciplinary connections visible. In particular, this promotes the networking of content from logistics and mechanical engineering and thus strengthens interdisciplinary thinking as a central competence of future engineers (o1). In addition, objective (o3) serves as a framework condition to which all tasks are oriented. Within the learning factory, concepts are developed that focus on sustainable processes and system design.

As an example, a parcel hub is chosen as learning factory. A parcel hub is a central component of parcel logistics in which consignments are sorted and prepared for onward transportation. Its structure and the processes involved have already been described by the authors in several scientific publications [12] [13]. Figure 2 shows the parcel hub as a virtual learning factory developed by the ITL, which aligns with the objectives outlined in section 3.1, supported by the studies mentioned above:

- **Interdisciplinary thinking:** The inherent complexity of a parcel hub – encompassing material handling, mechanical engineering, and IT – makes it an ideal setting for interdisciplinary training.
- **Use of digital engineering tools:** Digital engineering plays a fundamental role in the design, simulation, and optimisation of parcel hubs. The virtual parcel hub functions as a Digital Twin, enabling students to experiment with real-world logistics systems in a virtual environment.
- **Industry 5.0:** The parcel hub is an ideal application example for teaching Industry 5.0 principles, as it combines complex, networked and highly dynamic processes that present both technical and socio-economic challenges.

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[1] Details can be found here: https://online.tugraz.at/tug_online/wblvangebot.wbshowlvoffer?porgnr=9189

- **Practical relevance and industry cooperation:** Beyond applying methods and tools, students gain direct insight into industrial processes. Collaboration with Austrian Post provides opportunities to visit a real parcel hub in the region.

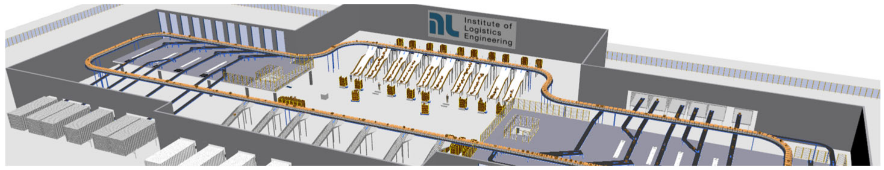

Figure 2. Virtual Parcel Hub

3.3 Teaching Format and Integration of Digital Engineering Tools

Courses are structured into lectures, which focus on theoretical knowledge, and integrated exercises that bridge theory with practical applications. The virtual parcel hub serves as the central didactic model which illustrates theoretical principles such as material handling technology in the lectures and at the same time provides a simulation-based learning environment for analytical calculations, digital engineering tools and the development of process optimisations.

Digital engineering tools play an integral role in the teaching concept. Students will use methods like Discrete Event Simulation (DES) to analyse and optimise logistical processes and mechanical systems. Additionally, XR technologies create interactive learning environments, enabling realistic layout designs and virtual walkthroughs, enhancing students' understanding of material handling processes.

The examination formats include both theoretical and practical assessments. In addition to written exams to test theoretical background, project-based exercises are integrated where students have to apply their knowledge practically (e.g. by running simulations to adjust layouts or optimise processes).

3.4 Evaluation and Continuous Improvement

Systematic and continuous evaluation is required to ensure the effectiveness of the new teaching concept. A key component of this approach is the Start-Stop-Continue method, a structured evaluation technique for optimising teaching formats. In this method, students anonymously evaluate three key aspects: Start covers new content, methods or tools to integrate into the course; Stop identifies ineffective or obstructive elements which should be revised or removed; Continue identifies proven components that should be retained and further strengthened.

This qualitative feedback is supplemented by a quantitative analysis of grade distribution before and after introducing the learning factory. Key statistical measures – including the arithmetic mean, standard deviation, and distribution of extreme grades – serve as comparative indicators. However, observed grade shifts are always interpreted in conjunction with broader evaluation results.

The evaluation is systematically conducted using a standard tool from TU Graz, ensuring a unified methodological framework for student feedback. This tool enables structured data collection and allows for additional course-specific questions to facilitate a more differentiated analysis[2]

4 IMPLEMENTATIONS OF THE NEW CONCEPT

Adapting all relevant courses at once is not a realistic approach. Therefore, the new teaching concept will be implemented in two stages. The first stage is currently being implemented and is therefore described in more detail below. The second stage will follow after successful implementation and initial evaluation of the first stage, which is why it will only be explained in broad terms for the time being.

4.1 Stage 1 – Logistics-Focused Implementation

The overarching goal of this stage is for students to understand and practically design material handling systems, focusing on layout and process optimisation. A core component is the integration of Industry 5.0 principles, ensuring that students not only optimise logistics efficiency but also consider resilience, sustainability, and human-centric design. For this purpose, five courses were chosen which are shown in Table 1. The table provides an overview of the learning objectives of each course, the practical application within the virtual parcel hub and the use of digital engineering (DE) tools. In this case, the focus is solely on providing an overview of the course content. Insights into methods, scope, and

[2] Details can be found here: https://mibla-archiv.tugraz.at/09_10/Stk_1/Lehrveranstaltungs_Evaluierung.pdf

participants are specific to each course and are therefore not covered here. The shown implementation of Industry 5.0 principles applies comprehensively across all courses. However, it is important to note that the courses do not focus exclusively on the parcel hub.

The course “Materials Handling Engineering” forms the didactic foundation as the first in the semester sequence. It covers the fundamentals of material handling technology and introduces students to the learning factory, addressing key topics from section 3.1. Subsequent courses build on this foundation, progressing from basic concepts to detailed planning and optimisation of material handling systems.

Table 1. General Overview of Selected Courses for Implementation in the First Stage

Course	Learning Objectives	Application of the Virtual Parcel Hub	Usage of DE Tools
1	Students understand fundamentals of material handling systems and recognise trends such as Industry 5.0.	Introduction as a cross-cutting use case to illustrate material handling concepts and components.	XR virtual tours to visualise material handling processes and components.
2	Students acquire the ability to integrate commercial and technical requirements into factory planning and layout design.	Strategic planning process for designing an optimised parcel hub layout for logistical efficiency.	XR-based layout planning for developing different configurations.
3	Students can analyse material handling systems, collect data, and perform analytical calculations for material flow planning.	Analytical calculation of material flow within a parcel hub using real-world data and computational methods.	MS Excel for data analysis and material flow calculations.
4	Students understand digital twins and can simulate and interpret scenarios.	Simulation of parcel hub processes to identify optimisation potential.	DES for modelling material handling systems.
5	Students develop strategies for optimising material handling systems to enhance efficiency, sustainability, and resilience.	Optimisation of parcel hub processes through simulations and AI-supported methodologies.	DES for process optimisation.
1 … Materials Handling Engineering 2 … Plant Design Intralogistics 3 … Material Flow Planning & System Design 4 … Modelling and Simulation of Material Flow & Manufacturing systems 5 … Selected Topics in Logistics Engineering			

While Table 1 outlines course-specific objectives and tool usage, integration is achieved through the continuous use of the virtual parcel hub as a shared case study across all courses. For example, a layout designed in course 2 may later be tested for resilience in course 4 or optimised in course 5. In addition, the courses collectively address key principles of Industry 5.0:

- Sustainability through energy-efficient layout planning and material flow analysis
- Resilience via disruption scenarios and recovery simulations
- Human-centric design through ergonomic considerations supported by XR and digital twins

4.2 Stage 2 – Integration of Mechanical Engineering Courses

After successful evaluation of the first stage, the second stage – integrating mechanical engineering – will follow. A key element is the expansion of the virtual parcel hub to include not only logistics processes but also technical components. The specific courses will be selected in coordination with the findings from the first stage and will be determined in the final implementation phase. A key focus will be on strengthening interdisciplinary connections between logistics and mechanical engineering. For example, energy consumption in material handling systems can be analysed by coupling mechanical design aspects (e.g., drive systems) with process-related factors from logistics (e.g., layout planning).

Since this paper presents an ongoing implementation rather than a retrospective analysis, no empirical validation data is yet available. However, the evaluation strategy outlined in section 3.4 ensures a structured approach to assessing the effectiveness of the new teaching concept. The authors acknowledge the importance of empirical validation and will report results in subsequent research.

5 CONCLUSION AND OUTLOOK

This paper presents an interdisciplinary teaching concept for material handling systems that fosters a systems-based perspective on logistics and engineering. By integrating a virtual learning factory, modelled as a parcel hub, the concept aims to link previously fragmented courses into a practice-oriented educational framework, enabling students to apply theoretical knowledge to real-world challenges. The approach aligns with the increasing demand for engineers who possess technical expertise, interdisciplinary thinking, and a sustainability-driven mindset. Through the systematic implementation of Industry 5.0 principles, students develop skills in digital engineering, resilient logistics design, and human-centred system optimization. As implementation has not yet been completed, no empirical data is yet available to confirm its effectiveness.

At this stage, the focus lies primarily on the rollout of the integrated teaching concept and the associated challenges. Initial efforts are aimed at aligning teaching content, ensuring coherence between modules, and integrating digital tools. However, this process also involves several risks, including the challenge of maintaining subject-specific depth while fostering interdisciplinary learning. Overcoming these challenges will be supported by structured student feedback and internal evaluation mechanisms.
Future work will concentrate on the systematic assessment of learning outcomes, student engagement, and skill development in order to evaluate the actual impact of the teaching approach. These findings will inform the ongoing refinement of course integration, tool usage, and the potential extension of the learning factory framework to other engineering domains. In this way, the concept will be developed into a robust and transferable model for interdisciplinary, sustainability-oriented engineering education.

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