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Complementary research and education opportunities—a comparison of learning factory facilities and methodologies at TU Wien and MTA SZTAKI

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Abstract

Typical learning factories are characterized by selective simplification or scaling-down of complex and large-scale production processes, while also safely containing risks in the case of process failures inherent to experimental and didactic activities. The variety of aspects preserved by these scaled-down environments allow different approaches to be taken in research and education. The paper compares two facilities, at TU Wien and at MTA SZTAKI in Budapest, respectively, and highlights differences in their modes of operation, the resulting variations of course-based vs. project-based didactic approaches, as well as their place in technical higher education.

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Keywords: Learning Factory; Smart Factory; Research test-bed; Project-oriented education; Course-oriented education

1. Introduction

Today's socio-technical systems are increasingly marked by complexity, and are subject to accelerating change, growing competitive pressure and tight operating constraints. The increasing intelligence of technical components, as well as new prospectives of process transparency are, in addition, setting the stage for a qualitative change of perspectives and roles of machines and humans involved. Industrial production is one of these areas where the life-cycles of products and production or transportation assets intersect, creating a multitude of situations that require a profound understanding and awareness of one's place and role in the entire system [1,2]. Both technical education (vocational schools and universities) and professional training (typically, but not exclusively, conducted by the industry) appear to lag behind the evolving challenges. While the notion of an academia–industry gap has been around for decades, there is also an increasing need of interdisciplinary skills, abilities of synthesis, autonomous discovery, and transformation of knowledge and adaptivity to a given situation which context-abridged exercises or ex-cathedra teaching approaches of conventional education do not sufficiently address [3,4]. A key source of such shortcomings lies in the nature of currently prevailing educational practice which emphasizes explicit knowledge that fits conveniently into the established—often verbally biased—routine of transferring and testing knowledge. Passing through such education, students have a weak incentive for asking themselves the meaning and relation of explicit knowledge to reality—consequently, they may have facts at hand but remain *unable to apply* them in the real world [5]. Moreover, the subdivision of knowledge into distinct—possibly isolated and poorly harmonized—courses sets obstacles to *synthesizing* a comprehensive "view of the world" which is essential in orientation and practical problem solving in a heavily cross-linked industrial context.

While this situation understandably fuels skepticism towards "academic" expertise in the industry [6,7], the latter also frequently finds itself locked into routines highly focused on day-to-day survival even in disregard of explicit knowledge that could be put to useful work with a minimum of effort and awareness of the application context (a real-life example is the use of measurements and spreadsheets for a hinged actuator where a simple trigonometric calculation would suffice). Similarly, innovation and applied research are often hampered by the constraints and tight human resources, especially in smaller industrial enterprises [7].

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In some cases, the industry has already taken initiative to mitigate such limitations of exploitable knowledge, and created an organizational atmosphere favoring the active exploration, sharing and networking of knowledge [8]—nevertheless, the uptake of such a progressive culture depends very much on the preconditions prevailing in the given organization or locale. Still, even in these cases, the differences in the dynamism and organizational structure of academia and industry will require additional effort in bridging gaps. While this can—and should—be addressed at an organizational level [6], it is also important to bridge disparities on the level of individuals, especially by introducing new education and training concepts for students who are to become professionals in industrial enterprises. It is, e. g., beneficial to gradually shift the control of learning processes over to students in technology-rich environments [9] to develop practical competencies through students-driven activities. As stated by Kobza *et al.* [10], “this is especially true for leaders in industry who need empirical practices rather than theoretical input in order to develop the social context of leadership”.

As mentioned before, fitness for practical work greatly depends on developing an adequate mindset supporting (i) the meaningful combination of explicit and tacit knowledge [8,11], (ii) the willingness to take interdisciplinary perspectives and value other areas of expertise, (iii) developing sound judgment regarding resources, efforts, errors, correction measures, priorities and interdependency structures in the context of teams and complex systems, (iv) social skills, especially of interaction and mutual attention that are indispensible for smooth teamwork, and (v) ability and willingness of creative thinking, explorative solution finding, and autonomous acquisition of new knowledge. While a variety of approaches exists in literature for grouping and identifying the aforementioned skills, previous work frequently points out that both education and industrial practice exhibit mutually disparate imbalance in the set of necessary competencies [3,12].

Learning factories are currently being introduced in several regions of the world with the goal of (i) counteracting the imbalance perceived in higher education and vocational training, (ii) bringing together groups who would otherwise undergo entirely different courses of education but will have to work together as professionals on different points of a corporate structure, and (iii) facilitate collaboration bridging the academia–industry gap both in education and R&D [12,13]. Learning factories are facilities that realistically replicate certain aspects of a real factory—possibly including the small-scale production of commercial goods—while removing risks and constraints that would present a burden to students engaging in *active* receiving of both explicit and tacit knowledge, and gaining experience related to product planning, production, logistics and management processes [1,2,14]. Abele *et al.* recently presented a systematic overview of characteristics and types of learning factories relying on experience gathered in the CIRP Collaborative Working Group of Learning Factories [12], highlighting which aspects are commonly implemented in such facilities, and which of these exemplify the paradigm “in the narrow sense”. In this paper, we compare two facilities with complementary characteristics—one of them being a “typical” learning factory built primarily for the purpose of educating numerous student groups on a regular basis, with an outlook on incorporating R&D aspects (*TU Wien Learning and Innovation Factory*), the other one (the *Smart Factory* laboratory at MTA SZTAKI) focusing on research and demonstration, with ties to technical higher education in project-oriented and explorative ways the majority of learning factories has not yet covered.

In further parts, the paper is organized as follows. The facilities and current operating practices of both locations are presented separately (the *TU Wien Learning and Innovation Factory* in Section 2, and the *Smart Factory* laboratory at MTA SZTAKI in Section 3, respectively). Next, a comparison is given in Section 4, highlighting the areas in which both types of facilities can complement each other in various ways, followed by concluding remarks also addressing future possibilities.

2. The TU Wien Learning and Innovation Factory

2.1. *Facility composition*

The *TU Wien Learning and Innovation Factory* was founded in 2011 by a consortium of three institutes of the Faculty of Mechanical and Industrial Engineering ath the Vienna University of Technology, namely, (i) the Institute for Management Science / Industrial and Systems Engineering (IMW) in cooperation with Fraunhofer Austria Research GmbH; (ii) the Institute for Production Engineering and Laser Technology (IFT); and (iii) the Institute for Engineering Design and Logistics Engineering (MIVP). With all founding partners dealing with areas of industrial production, the facility was set up with a focus on development, production and logistics. To this end, the facility in its current 140-m^2 area comprises (i) a design compartment with workstations supporting product design (CAD) and process planning, (ii) an area for manufacturing product components (CNC stations, milling and turning machines, laser cutting machines, an automated production cell, coordinate measuring equipment, rapid prototyping equipment, as well as a number of work benches with hand tools), and an assembly section with flexibly configurable work stations consisting of parts dispensers, assembly tools and work surfaces needed for manual product assembly. The facility also has resources for a simplified representation of logistics operations as well as an automated guided vehicle system. Nonetheless, most of such operations as picking and supply of material are carried out by human workforce, providing students with the possibility of firsthand experience by acting out manufacturing and processes themselves [15].

2.2. *Goals of operation*

The main goal of the facility in its current configuration is the infrastructural support for a complex course titled *integrative Product Emergence Process* (*i-PEP*). In this course, initial instructions and explicit knowledge are passed to the students via conventional lectures and tested by conventional means, so that subsequent hands-on activities can commence with sufficient theoretical background knowledge [16].

Hereafter, the course continues with a multi-phase project-oriented hands-on process that leads the students step-by-step through several phases of a product life-cycle. The product to be designed, procured on the prototype level, finally produced and tested is a functional 1:24-scale slot car with a fabricated metal underframe and a DC motor. The activities of the hands-

Fig. 1. General view of the *TU Wien Learning and Innovation Factory*

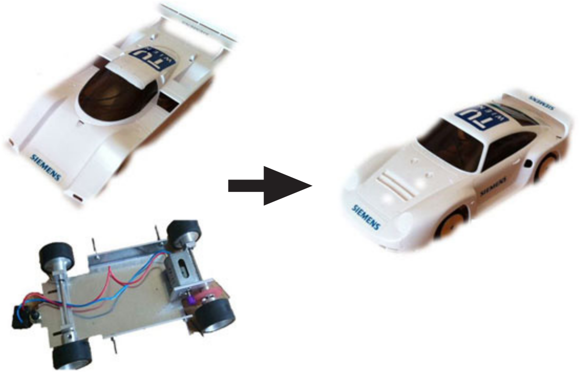


Fig. 2. Example of products designed and built during an i-PEP course in the *TU Wien Learning and Innovation Factory*—product variability by in-house manufacturing of custom parts was already introduced upon student feedback

on phase include (i) setting up a project time plan and allocating human resources, (ii) analysis of an existing prototype as well as product and process requirements, (iii) design of the team's own prototype product, planning of related processes and their implications on resource usage, followed by prototype procurement, analysis and re-design to address the issues surfacing in the process, and (iv) manufacturing of components and assembly of the finalized product which is tested for functionality on an in-house test track [17].

The project-oriented teamwork in the course is laid out so that students can enrich their tacit knowledge, and experience the nature of cross-links in technical domains related to product design and industrial production. Aside from gaining interdisciplinary perspectives on various knowledge areas, students acquire experience in autonomous, collaborative and creative problem solving, social skills necessary for functioning in the context of a larger socio-technical system, as well as management skills needed for structured problem solving and responsible usage of technical and human resources. Students conclude the course with a presentation of their results including a test race of the vehicle produced, whereupon their performance and their own findings are discussed.

2.3. Extension possibilities

While the initial *i-PEP* course was integrated into the bachelor program of the university, positive feedback encouraged the participating institutes to set up a similar (elective) course for the master program in mechanical engineering as well. Meanwhile, the original bachelor course is also undergoing fine-tuning in response to student feedback regarding perceived difficulties or work intensity imbalances. Aside from supporting courses that strengthen interdisciplinary skills and competencies poorly covered by traditional subject-oriented, ex-cathedra education, the facility is also intended to find further use as an infrastructure for open experiments, individual student projects, as well as research. As a project work, students are engaged in the continuous improvement of the facilities. In the next round of the course, students will, e. g., be able to create their own chassis for the slot car by utilizing a 3D-printed model for a deep-drawing process, replacing pre-purchased components used in previous rounds.

In the near future, the TU Wien Learning and Innovation Factory will be integrated into the TU Wien Demonstrationsfabrik. In this context, the facilities will be enhanced in order to transfer Industrie 4.0/CPPS use cases into the curriculum.

3. The Smart Factory laboratory at MTA SZTAKI

3.1. Facility composition

The design process of the *Smart Factory* laboratory at MTA SZTAKI was initiated in 2011, and is managed by the Research Laboratory on Engineering and Management Intelligence (EMI), and the Fraunhofer Project Center PMI at MTA SZTAKI. The current form of the facility is being gradually built up since 2013.

Intended to comprise a small-scale (socio-)cyber-physical system [18–20], the facility models a production site where material handling, resource management and agent interaction aspects are represented by physical components. The layout of equipment is organized around a circle of four conveyor belts of 45 mm width, accessible to four, structurally identical, PLC-controlled workstations, a high bay warehouse, a set of 2–3 mobile robots, and two 6-DOF manipulators. Workpieces are represented by RFID-equipped resin castings which receive blank paper inlays that undergo processing steps at the workstations. The latter include drilling/punching with resources permanently allocated to each workstation, and stamping with ink dispensers implemented as a movable resource that is delivered to the workstations as demanded by pending operations. Individual control units are connected via an architecture of CAN and LAN connections, while the mobile robots use WLAN. Functional units are individually accessible and represented as agents in an agent container running on a central host which can be connected to further virtual subsystems and receive commands and data from other higher-level sources, such as scheduling algorithms. Interaction with human operators is supported by a rich assortment of interfaces, including 3D imaging, a large touch screen, local pendants, etc.

Fig. 3. Partial view of the *Smart Factory* at MTA SZTAKI, showing 3 of the 4 workstations (left), one of the mobile robots (center), and the two manipulators (right)

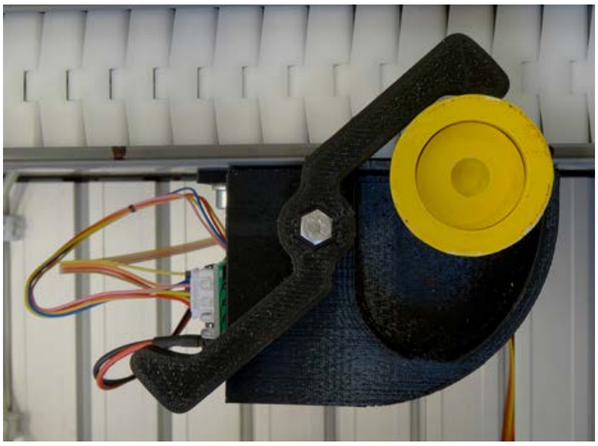


Fig. 4. One of the successful student projects: a bypass unit printed out on a 3D printer designed and constructed in an earlier student project

3.2. Goals of operation

The original incentive of the *Smart Factory* was the provision of a flexibly configurable infrastructure for research within the scientific community, and for demonstration to the industry and the general public. Nevertheless, the growing involvement of students in the design, implementation and functional integration of extensions to the original equipment quickly opened up the prospective of its use in technical higher education, focusing on aspects of automation, human–machine interaction, as well as the paradigms of *(Socio-)Cyber-Physical Systems* and closely related *Industry 4.0* [19], some of which are not yet commonly represented in the mainstream of learning factories.

Currently, most student activities related to the *Smart Factory* are not based on repeatable courses with stable content, but are individual projects in preparation for a BSc [21–23] or MSc thesis [24]. While the particular problems to be solved with the guidance of a supervisor are highly individual, the projects and their outcomes are interlinked due to being parts of the same production system. While elaborating solutions, students gain experience in the analysis of problems and available means of solution, conduct design and make decisions in the presence of cross-links with other equipment that may represent other (possibly legacy) standards, or have to reach trade-offs with conflicting solution preferences. Students are also carrying out much of the physical implementation of solutions, gaining hands-on experience in adding new components to an automated production system, and properly handling existing ones. The ongoing extension of the *Smart Factory* involves active community work with regular discussions within the laboratory team and consultation with external suppliers, in which the students are fully included to the benefit of their social skills.

Previous experience in education showed that students may be deterred from hands-on work by (i) the known cost of equipment involved, (ii) the apparent complexity of an interlinked system or barriers to breaking down a major development to smaller steps, and (iii) the possibility of knock-on effects of wrong decisions spreading through the system. The configuration of the *Smart Factory* lowers these barriers by employing low-cost components, many of which can be taken off-site for convenient “first steps”, and by the subdivision of functional component groups into safely containable “sand boxes” that allow gradual testing and integration of new solutions.

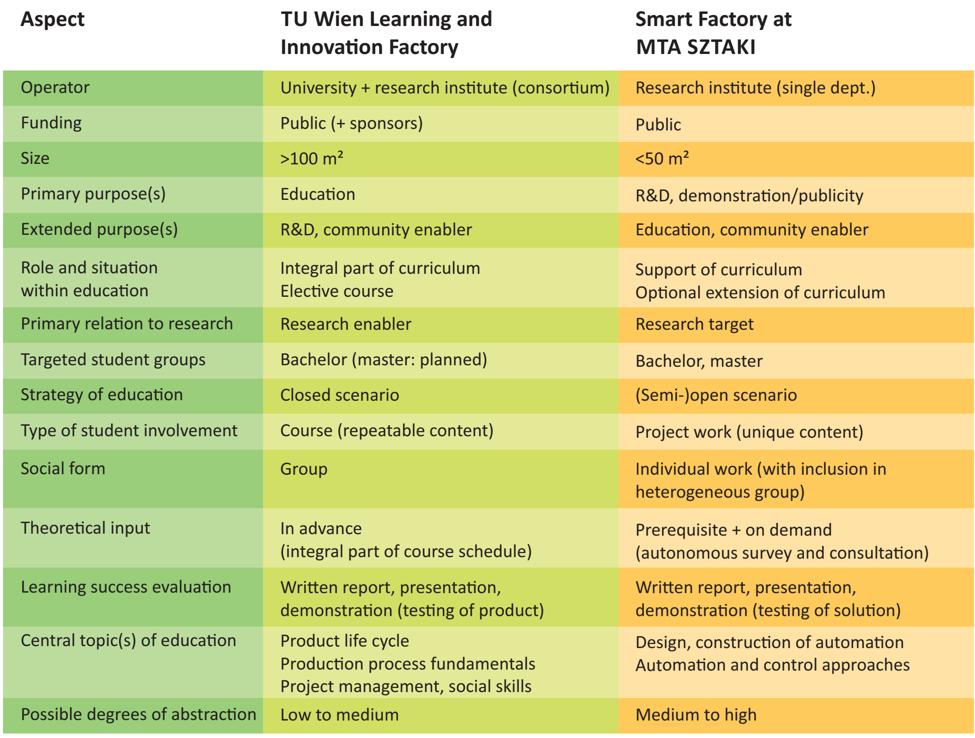
3.3. Extension possibilities

The infrastructure and functionalities of the *Smart Factory* are still under development with regard to hardware and control (completion of workstation and logistics functionalities and agent representation), human–machine interaction (high-level integration of existing components, access points for NFC-enabled smart phones for direct interaction with workpiece tags), and remote coupling with virtual subsystems.

Meanwhile, increasing inclusion in education is planned in collaboration with the Department of Manufacturing Science and Engineering (DMSE) of the Budapest University of Technology and Economics. Individual student projects remain an important part of the development of the *Smart Factory*. While the capacities and dimensions of the facility do not favor full support for entire courses, the facility has become one of several possible sites supporting the “Mechatronics Project” course at DMSE. “Offshoots” in the form of replicated devices or further resource-limited services (e. g., physical test environment for production planning problems) will be included at a later time in mechatronics education courses.

4. Discussion of selected aspects

The facilities presented in Sections 2–3 show substantial differences, and a closer examination of selected aspects is worthwhile to see how facilties of such diverse characteristics could meaningfully complement each other in technical higher education. To this end, relevant aspects of the learning factory morphology in [12] were selected and augmented by further characteristics (see also Figure 5). The latter was necessary to properly reflect the fact that the *Smart Factory* facility at MTA SZTAKI is not a classical learning factory built specifically for education, but a research and demonstration tool with opportunities of enriching technical higher education.



Aspect	TU Wien Learning and Innovation Factory	Smart Factory at MTA SZTAKI
Operator	University + research institute (consortium)	Research institute (single dept.)
Funding	Public (+ sponsors)	Public
Size	>100 m²	<50 m²
Primary purpose(s)	Education	R&D, demonstration/publicity
Extended purpose(s)	R&D, community enabler	Education, community enabler
Role and situation within education	Integral part of curriculum Elective course	Support of curriculum Optional extension of curriculum
Primary relation to research	Research enabler	Research target
Targeted student groups	Bachelor (master: planned)	Bachelor, master
Strategy of education	Closed scenario	(Semi-)open scenario
Type of student involvement	Course (repeatable content)	Project work (unique content)
Social form	Group	Individual work (with inclusion in heterogeneous group)
Theoretical input	In advance (integral part of course schedule)	Prerequisite + on demand (autonomous survey and consultation)
Learning success evaluation	Written report, presentation, demonstration (testing of product)	Written report, presentation, demonstration (testing of solution)
Central topic(s) of education	Product life cycle Production process fundamentals Project management, social skills	Design, construction of automation Automation and control approaches
Possible degrees of abstraction	Low to medium	Medium to high

Fig. 5. Comparison of both facilities with regard to selected aspects

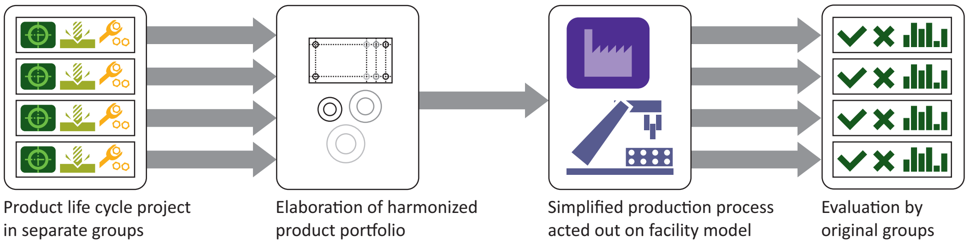


Fig. 6. A possible extension of the i-PEP course by high-level processes acted out in a Smart Factory-like facility

Aside from differences in size, targeted aspects of industrial production and corresponding abstraction level, the key difference of both facilities lies in the way students perform their learning activities with the equipment. The *TU Wien Learning and Innovation Factory* is laid out for repeated runs of the i-PEP course centered around a product life-cycle and related design, manufacturing and logistics operations. Meant for a larger contingent of students, the course is performed by separate student groups as project work—upon its completion, the outcomes (i. e., completed products) do not remain in the facility, while feedback will still effect a gradual evolution of the course material. The *Smart Factory* at MTA SZTAKI, on the other hand, offers learning opportunities to individual students who actively take part in building up the equipment, or are attending courses related to automation solutions. Consequently, their problem scenarios are often unique, requiring a higher degree of independent analysis and problem solving. Also, results of successful student projects will become parts of the production equipment—this is, naturally, more in line with the characteristics of automation engineering jobs where problems are often very diverse, and possibly not transferable right away on other production sites or assets. Both approaches to student involvement do have a justified place in technical higher education, and can very well be parts of the same curriculum.

A tighter combination of both types of facilities can arise when the re-usable “service” character of the *Smart Factory* (i. e., customized process planning and scheduling, reconfigurable logistics and material handling processes) is exploited. A possible scenario of combined use is proposed in Figure 6. In this example, student groups—having already completed their i-PEP courses—agree on a harmonized product portfolio based on their existing product designs, and act out production processes with a given degree of product diversity at a facility similar to the *Smart Factory*. Given the high abstraction level, actual production will not necessarily take place, but students can still gain experience with higher-level production and material handling processes—possibly involving suppliers, fluctuation of stock, demands and resources, various kinds of disturbances, etc.—which they can relate to their own past scenarios. Product variability, production cell capabilities, etc. can be logically mapped onto the facility's resources (simply formulated, on the level of unique identities and classes of entities), and planning, scheduling, process control, etc. can be acted out on the physical system which also delivers data for subsequent analysis. It is important to note that acting out the production processes can also occur remotely via network connection—this is an important aspect *per se* to experience, saving travel time and expenses as well. The evaluation of findings can finally take place group-by-group, or in the same "consortium" where they agreed on the common product portfolio. Due to its resource constraints, the *Smart Factory* at MTA SZTAKI would face limitations in fulfilling such a role, but its approaches in system architecture, construction and function can make it a prototype for larger and specifically education-oriented facilities of similar character.

5. Conclusion and outlook

The paper briefly presented two different facilities that have their place in technical higher education in the *learning factory* context—the *TU Wien Learning and Innovation Factory*, and the *Smart Factory* at MTA SZTAKI in Budapest. While the former of the two was built specifically for educational purpose, the latter is a compact research and demonstration tool with opportunities for students in design and construction projects whose outcomes remain integrated in the equipment. The paper presented a comparison of the two facility models with regard to relevant characteristics and proposed two cases of combination: (i) side-by-side use of the facilities for widening the students' knowledge both in process/product engineering and automation, and (ii) interlinked use organized around different aspects and abstraction levels of the same product design and production cycle. By a digital network, it is possible to interlink both—or several—learning factories and facilitate a learning environment spanning several locations—such plans are already present in the enhancement plans of both facilities.

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