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Expanding production perspectives by collaborating learning factories—perceived needs and possibilities

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Abstract

Collaboration across organizational, business and technological borders receives growing emphasis in industrial production due to the evolution of production networks, as well as the growing integration of different product life cycle stages. These demands receive growing attention in the learning factory community, and can be answered by the combination of courses and collaboration across several sites. The paper gives an in-progress report on such an initiative: on perceived needs and opportunities of collaboration spanning the learning factory site at TU Wien, and the premises of MTA SZTAKI in Győr and Budapest. Special emphasis is put on several collaboration types crucial to design and production in an enterprise network, such as parallel and collaborative product development, or transparency across organizational levels of different degrees of abstraction.

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Keywords: Production networks; collaboration; process transparency; product life-cycle

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1. Introduction

Over the past 1–2 decades, the role of decentralized resources and processes has remarkably grown in industrial production. Benefits of production networks—such as fast market response, resilience or resource efficiency—are gaining recognition [2]. While theoretical backgrounds and infrastructural solutions reflect this development [1, 3], the growing importance of manufacturing networks has not yet made a comparable impact on hands-on education and training. Traditionally, learning factories focus on aspects or processes of industrial production that can be cleanly isolated from a complex environment without impairing functionality and educational value, forming "closed worlds" with inherently reduced representation of interaction and complexity related to production networks. Teaching factories [13] typically pursue a closer integration of hands-on practice with traditional ex-cathedra lectures by "bringing the factory to the classroom" in a cyclic approach (see also [14, 15, 16] for reasons of completeness). Here, the prevalence of virtual representations and remote connections to physical production sites does add some degrees of freedom in choosing multiple abstraction levels. However, limits can be encountered if one has to remain within the context of a single course, or if cause–effect continuity across different abstraction levels is influenced by changes in the associated real-life manufacturing and logistics processes. Although the aforementioned challenges can be remedied, the paper intends to address the case of learning factories to examine possibilities of a comprehensive production network representation with all physical components residing in-house, and being configurable for a consistent sequence of courses within the same curriculum.

A comprehensive representation of aspects of a production network may be difficult in a single learning factory scenario—courses with such target mostly remain on a given abstraction level [12]. Combining the capacities of several learning factories into a curriculum has the potential of transcending these limitations. Facilities with similar characteristics can participate in horizontal collaboration [11], or can join schemes of coordination or competition with limited resources at hand. Facilities complementing each other can, on the other hand, follow product life-cycle phases across different levels of abstraction and decision hierarchy. Courses (or curricula) crossing product life-cycle phases and abstraction levels are expected to broaden insight into the dynamics of processes and relations within a production network, and improve the ability of placing one's own organizational unit into a wider context.

In recent years, TU Wien, Fraunhofer Austria and MTA SZTAKI have been examining possibilities of such collaborative operation of their facilities which are currently receiving major extensions through new equipment and the establishing of two more sites [6]. The paper presents *a strictly in-progress view* at collaborative actions *proposed* for the given set of facilities, as well as an outlook on underlying aspects and modes of collaboration. *The paper focuses on a possible way of connecting capacities, leaving quantitative evaluation for a subsequent stage when results of combined operation will already permit an in-depth evaluation*. After giving a brief summary of the sites, their capacities and solitary use (Section 2), collaboration requirements and possibilities are outlined, and intended collaborative actions are placed within this context (Section 3). In addition to the plans specifically meant for the learning factory sites presented, a prospect of open collaboration is given in Section 4.

2. Capacities and focal topics of participating sites

2.1. Learning Factory in Wien

The Learning and Innovation Factory for integrative production education at TU Wien (TU Wien Lern- und Innovationsfabrik) is a learning environment addressing professional and social competences of students. It aims at creating a common understanding between business and education. The facility is also used for developing and testing innovative research results and provides services for companies [6, 10]. The 140 m² facility includes (1) a design area, supporting product design (CAD) and process planning, (2) a manufacturing area with CNC stations, milling, turning, and laser cutting machines, an automated production cell, coordinate measuring and rapid prototyping equipment, work benches, and (3) a reconfigurable assembly area with manually operated work stations. Intra-logistics relies partly on automated guided vehicles (AGV). In continuous improvement of the facility, Industrie 4.0 / CPPS use cases are currently implemented for educational purposes (For a definition of the aforementioned terms and a description of related use cases, the reader is referred to [6, 10]).

The main goal of the facility is the provision of infrastructural support for the educational course “integrative Product Emergence Process” (i-PEP) where student groups work on their own product, design it based on the analysis of a 3D-model of an existing prototype, plan procurement, manufacture and assemble it. Students also perform a cost calculation. The completed products are finally tested for functionality in an in-house test environment [6].

2.2. Pilot Factory in Wien

The TU Wien Pilot Factory (TU Wien Pilotfabrik Industrie 4.0) is a projection of a factory functioning as a demonstration lab in a real industrial-grade environment, following an educational agenda (providing courses for enterprises using state-of-the-art technologies and applications) and R&D goals with the realization and testing of (1) prototypes and product technologies, (2) new manufacturing processes, and (3) assistance, interaction, decision support and expert systems [9]. Operated by three institutes of TU Wien (MVIP, IFT and IMW), the 900 m² facility supports virtual product development, manufacturing, quality measurement, assembly and logistics. The main focus of the pilot factory is the multidisciplinary modelling of products and production systems, adaptive and changeable manufacturing processes, cognitive assistance systems in assembly and logistics, human-centered and workload-adaptive assembly as well as cell-oriented assembly systems planned and controlled by a digital twin (i.e., a digital model in bi-directional interaction with its physical counterpart).

In its projection of a factory, the facility produces a filament deposition (FDM) 3D printer with realistic product and process demands. Several Industry 4.0 / CPPS use cases have been implemented in addition, e.g., (1) human–robot collaboration [8], (2) digital worker assistance [7], (3) AGV as mobile workstation, (4) human–machine interaction with smart devices, (5) human digital twin via motion capturing, (6) smart container tracking via RFID, and (7) maintenance support with mobile augmented reality (AR) devices.

2.3. Learning Factory in Győr

Designed, built and operated by MTA SZTAKI, the Learning Factory in Győr is located at the premises of Széchenyi University on an area of ca. 150 m^2. The facility consists of four workstations, each being organized around a central support for one (or two) robot arm(s) and a reconfigurable space with pre-fabricated surface elements. Also part of the infrastructure are indoor positioning, imaging and 3D capturing devices, and reconfigurable human–machine interface components. Intra-logistics is performed by AGVs, developed in collaboration with the Dept. of Material Handling and Logistics Systems at the Budapest University of Technology and Economics, equipped with a robot for loading/unloading operations. Augmenting the facility is a room of 75 m^2 for lectures, product design and procurement, the latter being supported by an FDM 3D printer, also accessible by remote users.

Starting September 2018, courses will focus on (1) cell configuration and (2) human–robot collaboration in an industrial assembly context. Students will also be given the opportunity of a side-by-side comparison to “conventional” automated production resources co-located with the collaborative assembly facility.

2.4. Smart Factory in Budapest

MTA SZTAKI also operates a “Smart Factory” laboratory at their Budapest premises. This is a compact (30 m^2), high-level representation of a factory with four automated workstations, a warehouse, a loading / unloading station, a collaborative cell with two robot arms, a closed-path conveyor system, and floorspace for two mobile robots. Workpieces carry cardboard inserts processed at the workstations. Each workpiece has a 1K NFC tag with a unique identifier and storage for additional data traveling with the product. An important part of the facility is its planning, scheduling and execution control infrastructure. Its modular structure facilitates reconfiguration and testing of new algorithms, components or subsystems. A *digital twin* of the facility is available for simulation, surveillance and control. The “Smart Factory” can be accessed by remote users, and can be coupled with advanced visualization tools (e.g., the “Virtual Cave” at MTA SZTAKI), and remote manufacturing locations.

The “Smart Factory” is primarily built for research and demonstration; its compact size limits opportunities in courses hosted on-site. Still, the laboratory does have its share in higher education taking place at the Budapest University of Technology and Economics, in the form of (1) lab exercises in scheduling and execution, (2) design and construction of automation solutions for an existing deployment environment as teamwork in the "Mechatronics Project" course, and (3) individual student projects leading up to BSc and MSc theses and research contest entries.

3. Perspectives of collaborative operation

3.1. Technologies, solution paradigms supporting collaboration

In order to couple infrastructural and didactic capacities of several learning factories, their *operating processes, types of resources and materials have to be suitable for meaningful combination* with regard to (1) targeted branch of production, (2) purpose and performance expectations regarding the processes, (3) level of abstraction, and (4) quantitative aspects of resources, time frames and course participants. Weeber *et al*. [11] presented a system of compatibility checks for sites of equivalent degree of abstraction, while a complementary example is proposed in [6].

The other key to integration is the presence of technologies that enable the *coupling of facilities and their processes*, and provide means of examination and exploration beyond a single strand of actual events. Even if no physical exchange takes place, data related to resources, materials and processes are exchanged between collaborating facilities. The key enablers are: (1) *data acquisition infrastructure*—either automatic or with human intervention—is needed, (2) collaborating facilities must be able to *communicate their data*—requiring *syntactic standards* at least across the same abstraction level, and (3) data shared must be commeasurable and must observe *semantic interoperability*.

Learning factories enable perspectives that remain hidden in real-life industrial production. When several sites collaborate, this can be extended to their interaction, as well as cause–effect dependencies of actions crossing the borders between factories. This includes in-depth probing of interaction steps, playing through scenarios on a time scale more suitable for learning and experimenting, or including virtual resources into processes. Digital models play a key role, both in interaction with virtual production facilities, and by connecting to physical processes via a *digital twin*. Increased transparency offers one more type of insight which is not possible in the industry: observation across horizons that would, otherwise, be closed by *confidentiality*. This way, collaborating learning factories offer a close look at processes and outcomes in each other's facilities. This is expected to enrich students' knowledge with cases that have not been acted out in their own facility but would be a meaningful addition to the topics targeted locally.

3.2. Modes of cross-site collaboration

In the context of a production network, three basic integration schemes can be identified: (1) parallel integration of similar scenarios (either collaborative or competitive), (2) serial integration of complementary scenarios on the same abstraction level (subsequent operations in a value chain), and (3) integration across different abstraction levels.

In *parallel integration* of design or production scenarios, the sites focus on the same product (component) in variants that still comply with the same specifications or are interchangeable in subsequent operations. This form of integration can have both competitive (e.g., competing suppliers of the same manufacturer) or collaborative narratives (distribution of a product portfolio to several manufacturers, or harmonization of product variants among collaborating enterprises). Component variants can also serve as co-dependent complements (e.g., two sub-assemblies built by two suppliers that still have to fit), giving the opportunity of negotiating alternatives, tolerance requirements, or agreement on production quantities and coordinated product changes.

In *serial integration*, subsequent operations of a value chain are carried out at different sites. Here, a material stream is impacting processes via production quantity, quality and timing. Also, negotiation between sites is required during design changes, or incremental product improvement based on response from further up/down the value chain. The proper understanding and hands-on experience of such feedback loops are among the key benefits expected in collaboration of several learning factory sites.

Integration *across abstraction levels* consists in matching the processes in learning factories to different layers of the same complex design or production scenario. For example, a number of sites can perform value creation processes of equivalent abstraction level, while their function as members of a production network is then acted out at sites built for higher-level problems. This allows students in learning factories to experience each other's operation from perspectives below or above their own targeted range, understand their function within a greater picture, and gain comprehensive experience in typically collaborative actions as distribution of materials and resources, sharing of costs, risks and benefits, coordinated production, or matching of criteria in product portfolio harmonization.

3.3. Proposed roadmap for the sites in Wien, Győr, and Budapest

The complements and matches of characteristics of the facilities in Wien, Győr, and Budapest suggest a versatile narrative around a series of product life-cycle phases. This enables stand-alone courses or more comprehensive curricula. The product life cycle stages of interest would be design (with a higher-level production plan involving assembly alternatives and production cost estimates), procurement and testing of prototypes (with potential feedback and compatibility cross-check at premises working in parallel), and production (executed at various abstraction levels).

The product providing the production network context would be the slot car of courses in Wien, extended to a product family using the same propulsion group, combining different underframe and carbody types. Variants can be designed either (1) at several facilities initially working independently, with subsequent comparison and optional design harmonization, or (2) in a design community with feedback and adaptation being a part of the design process. The design of components can take into account local demands, sourcing opportunities, as well as characteristics of available production resources (e.g., manual vs. automated assembly) and estimated production costs.

Having completed the first pass of product (component) design, procurement capacities at Wien and Győr deliver feedback on the feasibility of the design decisions in their local production environment, and in context of prototype tests conducted with standard components on test-beds at each location. A full-fledged course could, thus, cover the nature of prototype design and procurement with feedback loops and iterative improvement.

Production of components and assembly of final products can be carried out both in Wien and Győr, with performance measures obtained—these can then be propagated to a higher abstraction level where the dynamics of a production network can be studied in the context of elaborating a portfolio of harmonized products, and distributing production assignments according to a production plan. The latter, higher-level, operations can be acted out in the Budapest facility. A possible assignment of product life-cycle steps to the facilities is shown in Figure 1.

The proposed narrative can be populated with courses in subsequent phases of course / curriculum integration, based on pre-composed examples of the same compound of consecutive product life cycle phases. (1) Stand-alone courses can start with preliminaries already given, and a subsequent evaluation can compare the outcome of the course with the rest of the (pre-planned) sequence. (2) In a next step, courses either remain isolated with regard to impact on follow-up actions but outcomes attained at different locations can be compared to each other, or a sequence of courses (typically as part of the same curriculum) can run in parallel with no direct interaction but a comparison at certain milestones. (3) In its full-fledged version, an entire sequence of design, procurement and production is acted out with several instances of courses in parallel and series (whichever is required in the given stage), and the outcome of a given stage will influence subsequent actions. The latter phase of integration requires the curricula of the participating institutions to be interoperable, which is realistically the achievement of several years of harmonization efforts. *Nonetheless, the general narrative specifies the product life cycle context only (without limiting the number of participating sites acting in parallel), leaving open the opportunity of participation for further collaborating premises.*

4. Conclusion and outlook

In learning factories built around a limited range of processes at a given abstraction level, it can be difficult to provide comprehensive hands-on experience of processes spanning value chains and production networks, since this includes cause–effect chains, feedback loops and interdependencies across multiple production units, and at different abstraction levels. Providing such insight within a coherent set of courses is a complex challenge but can be addressed by several collaborating learning factories that are either compatible with each other on the same process level, or complement each other on different hierarchical levels. The paper gave a first outline of requirements and possibilities of such collaboration, and presented a strictly *in-progress* view of one possible example involving four facilities. The collaboration scheme is organized around a production network narrative with iterative design of a harmonized product portfolio manufactured at several production sites with partially overlapping production resources. The modelling, control and communication infrastructure of the facilities enables the extension of physical processes by virtual components. The flexibility of gradual population of the scheme with courses / curricula of varying integration

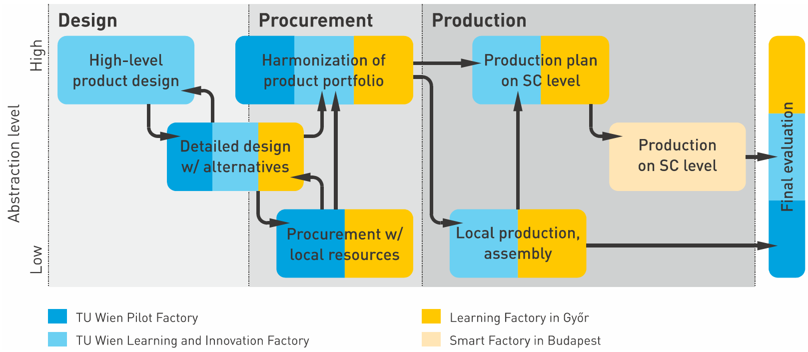

Fig. 1. Schematic diagram of the proposed design and production context.

level keeps the collaboration open to further facilities. As the collaboration is in its initial phase, further findings are expected upon gathering and evaluation of first operating experience in the following years.

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