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# Co-Creation of Production Resources and Processes in Pilot and Learning Factories—a Case Study ⋆

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**Abstract:** Even though co-creation is mostly considered in the context of product and service development in business-to-consumer relations, the approach can very well be applied when production resources are targeted by collaborative problem solving, and a manufacturer takes the role of the customer. However, exploring partly unknown solutions to partly undefined problems does bear risks, requiring a shielding of live production from potential damages. The paper examines a possible solution to such challenges in the form of pilot factories and learning factories by presenting and discussing the structure and selected use cases of an example facility from the perspective of co-creation and its infrastructural support.



*Keywords:* Production planning and control; Flexible and reconfigurable manufacturing systems; Internet-of-Things and Sensing Enterprise; Digital enterprise; Work in real and virtual environments; Human operator support; Pilot factory; Learning factory.

## 1. INTRODUCTION

Past decades have witnessed a shift towards product and service life-cycles with prolonged collaboration of groups that were largely separated by one-way exchange transaction interfaces in earlier practice. In this context, *co-creation* is considered a viable approach to win and maintain interest and benefits—of all parties involved—in cases where value perspectives are undisclosed, unknown or evolve out of initial uncertainty (Tian et al., 2021; De Silva et al., 2022). The impact of co-creation is further leveraged by contextual changes regarding creating and conveying value: i. e., growing emphasis on services associated with products (Vargo et al., 2017), a shift towards *service logic* (focus on *value-in-use* created by actors as opposed to *value-in-exchange* at individual transactions) or *service-dominant logic* (mutual benefits on a *service-for-service* basis) underlying the processes of creating value (Saha et al., 2022; Ramaswamy and Ozcan, 2018).

Changes in value perception and value creation mechanisms related to co-creation have captured the attention of research for several decades (Ueda et al., 1998; Márkus and Váncza, 1998; Ueda et al., 2009; Grönroos, 2012; Zhang et al., 2020), and co-creation has established notable role in business and industry since the early 21st century (Ranjan and Read, 2021). Still, the domain keeps evolving considerably, as evidenced by the diversity in interpretations of its fundamental terms and concepts, and recurring initiatives of reorganization and re-consolidation of views regarding the field. Saha et al. (2022) review recent sources within a time-span of 15 years, suggest clear interpretations for roles and actions (most importantly, co-production, co-design and co-innovation as processes targeting subsets of value co-creation), and formulate trends detected in recent literature. As opposed to examining co-creation as a process or phenomenon per se, Ranjan and Read (2021) conducted a broad review to identify drivers of co-creation in an ecosystem perspective. The ongoing development of the field is also evidenced by the introduction of new structuring viewpoints—Ramaswamy and Ozcan (2018), for example, propose a novel dimension of interactions to be relevant to mapping the domain. Ramaswamy and Ozcan (2018) and Saha et al. (2022) both summarize a cross-section of application domains with notable recent penetration of co-creation practices. As suggested by intensity of interest and frequency of cases reported, *business-to-consumer* (B2C) relations still count as the main application domain. Nevertheless, growing adoption by the *business-to-business* (B2B) sector (Jaakkola and Hakanen, 2013), public services, and higher education (Dollinger et al., 2018) indicates a radiation of co-creation patterns into a much wider application spectrum.

The recent reviews outline that further opportunities remain to be identified and harnessed. As exemplified in this paper, such challenges exist in industrial automation, too, where the gradual transition to *cyber-physical production systems* (CPPS) is anticipated to pose unforeseen challenges, best explored and addressed as they appear, both in industrial innovation targeting specific problems, and in higher education preparing future engineers for a more autonomous, open mindset. Both industry and education share common issues when it comes to collaborative ex-

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ploration of the unknown: (1) direct connection to live manufacturing resources bearing the risk of impacting an entire production system, and (2) the disadvantage of obscured explorability of a system optimized for production only. The manufacturing community has been aware of these drawbacks, and they have been addressed in several ways. Often, experiments and pre-assessment are carried out in virtual systems which can expand the horizons of discovery (Nassehi et al., 2022). Digital platforms also serve as common ground for mutual understanding and exchange in a co-creation process (Takahashi et al., 2017).

Many cases, nevertheless, still require hands-on experience with tangible, visible and operating equipment in a shielded environment, for which *pilot factories* (Dassisti and Semeraro, 2018) and *learning factories* (Abele et al., 2017) are a solution. Both represent real processes and real manufacturing environments (1) separated from large-scale live production, (2) mostly reduced in dimension and complexity, yet, (3) retaining at least as much functionality as required to support either didactic goals pursued via hands-on experience (in learning factories), or the testing and development of solutions to new challenges and new technologies (in pilot factories). Overlapping and mutually enabling goals and activities often make a dual usage of the same facility—as a learning factory and as a pilot factory—worthwhile (Hennig et al., 2019). Moreover, examining actions in such facilities has shed light on their usefulness in supporting co-creation both in prototype development and in education (Møller et al., 2023; Mogos et al., 2021; Lanz et al., 2019). In fact, major steps of co-creation—as summarized by, e. g., Hidayati and Novani (2015)—can very well be identified in roadmaps of such facilities, even if no formal co-creation approach is originally intended.

With literature on co-creation in pilot and learning factories still being sparse, the main goal of the paper is to highlight the relevance of co-creation to pilot and learning factories, and to promote a mutually beneficial connection of the two areas. To this end, the paper examines the example of a facility designed and operated without an original intention of co-creation. For each track (pilot factory and learning factory), a selected scenario is examined, and qualitatively matched with a four-stage model (Hidayati and Novani, 2015; Galbrun and Kijima, 2009): (1) during *co-experience*, parties discover each other's expectations and capacities; (2) *co-definition* establishes mutually consistent understanding of the problem; (3) *co-elevation* is the evolution of expectations and value propositions of what can be achieved; and (4) *co-development* yields products and services (stages (1)–(4) can form a cyclic pattern).

The early stage of investigation and the small sample size of available cases preclude a quantitative analysis at this point, therefore, the paper does not aim for more than raising interest and proposing further research, proceeding as follows: Section 2 gives a brief summary of the facility infrastructure and its deployment roadmaps. Section 3 highlights selected cases of industrial development and education, while Section 4 identifies co-creation steps, discusses the role of existing roadmaps and infrastructural properties in supporting the adoption of co-creation approaches, and outlines how further adoption of a co-creation approach can be of benefit to the operation of pilot and learning factories.

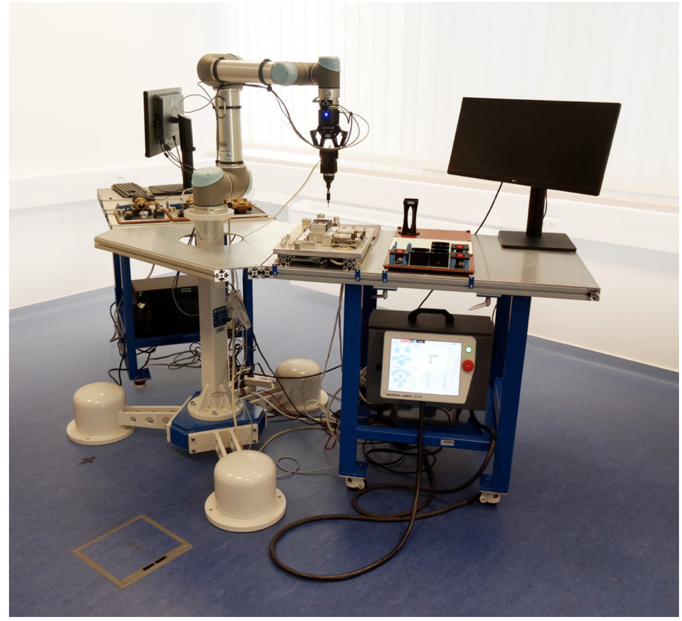

Fig. 1. Reconfigurable open workstation at the learning factory in Győr

## 2. EXAMPLE FACILITY—STRUCTURE AND DEPLOYMENT MODELS

In 2018, the Institute for Computer Science and Control (SZTAKI) started operating a demonstration, research and education facility at the premises of Széchenyi University in Győr, Hungary (Kemény et al., 2018b), named *Industry 4.0 Learning Factory*. Available to both academia and industry, it represents a factory shop floor in transition to a cyber-physical production system (CPPS), targeting collaborative assembly/disassembly and geometry survey operations on workpieces of up to 200–300 mm in any dimension, as well as intra-logistics operations.

### 2.1 Infrastructure and operation principles

Most of the 150 $m^2$ area of the facility is occupied by open collaborative workstations surrounded by free shop-floor surfaces. Each of the workstations is equipped with a collaborative robot (UR5 or UR10) mounted on a central frame. Table surfaces can be docked with the central frame in various configurations, allowing even the fundamental physical structure of the workstations to be subject to layout (re)planning (see Fig. 1). The dimensions, human and robot accessibility of workspace and optional sensors are optimized for human–robot collaborative assembly. Reconfigurability is also supported by a pool of appliances, available either as pre-fabricated modules and end-effectors, or as components prototyped on demand. The facility currently offers the in-house *DIWAS* framework for worker assistance, while future development will also target multi-modal human–machine interfaces. Processes at multiple workstations can be coupled in a more complex manufacturing scenario, with intra-logistics options ranging from manual material transfer to structured delivery with mobile manipulators. The communication and control infrastructure follows the physical and process organization principles of the facility, and grants a given degree of autonomy on multiple levels. Each workstation has its own field control layer, a local supervisory control and data acquisition (SCADA) node, and a PC host for more abstract and computationally demanding operations, as well as to connect to a facility-level manufacturing execution system (MES), built on the *MESS* integration platform developed in-house (Beregi et al., 2021). Digital models of selected components are available mainly for design and preassessment, with bi-directional interaction being an option for actuated components, primarily robots. Extension by entirely virtual components is also possible to simulate integration into a larger-scale production environment, as well as connections to remote sites via their corresponding virtual representation (Kemény et al., 2018a).

Co-located with the CPPS shop floor is also conventional automation equipment: a scaled-down production line and sorter for standard workpieces of fixed geometry (FESTO Didactic), and a conventional workcell with conveyor belts, material transfer hatches and two conventional industrial robots (FANUC). This enables users to explore how CPPS can work together with conventional automation.

### 2.2 Facility deployment models

Serving multiple purposes—research, demonstration, industrial pilots, technology transfer, training and education—the facility enables interaction of several user groups in academia and industry. While the facility regularly hosts research and one-off student projects with many of the activities overlapping, the regular operation of the facility can be characterized by two distinct roadmaps.

The *industrial track* responds to industrial demands in live demonstration of new technologies, elaboration of solutions requiring R&D insight, knowledge transfer, and industry-targeted training. Projects in this track usually involve problem solving in close collaboration with the industrial client, and construction/testing of production equipment prototypes. Clients can add their own equipment to the facility, and can reciprocate for the R&D services by leaving components installed by contract. Aside from targeted training sessions, knowledge transfer is also facilitated by close collaboration with industrial staff during common elaboration of a solution. The development and training spin-off *EPIC InnoLabs* manages the industrial track as an integrator.

The *educational track* offers the facility for individual student projects (e. g., experiments for a thesis, with a supervisor assigned), and also uses the infrastructure in the strict sense of a learning factory for courses with definite didactic content undergoing incremental improvement. While integration into higher education curricula does have an enormous latency, a summer school course in layout and process planning for collaborative assembly has already been developed in collaboration with Fraunhofer Austria who also operate a comparable facility.

## 3. CASES RELEVANT TO CO-CREATION

Since the facility started operation in September 2018, it has hosted several industrial pilot projects, individual student and research projects, and a summer school course. Although originally not set in a co-creation perspective, stages of a co-creation approach can very well be identified in many of the completed projects. Here, we will highlight four selected cases characteristic of the relation of learning/pilot factories to co-creation, and assess the two most relevant cases in more detail in Section 4.

### 3.1 Cases in the industrial track

*Case 1—Workcell design and physical prototype.* In this development project, the customer asked for an optimized workcell layout using a UR10 robot. The complexity of layout constraints, dimensional tolerances and the targeted task class exceeded the capabilities of "manual" cell design, calling for computer-aided optimization and benchmarking methods in which SZTAKI has already gained robust competencies in previous R&D activities. A virtual model was built up and populated with known constraints and performance criteria in close collaboration with the client, followed by a mixed-initiative solution procedure, in which numerical software tools performed optimization and automatic benchmarking, while acceptance checks and certain engineering decisions were made by human experts on both sides. Simulation and real-life tests were successfully completed in a physical environment built up at the learning factory facility, using the hardware readily available on site. A live solution was then installed by the client's own engineering staff at the client's premises.

*Case 2—Generative robot programming with calibrated virtual models.* This R&D project responded to a specific industrial demand, but involved much applied research, conducted under frequent feedback from the industrial client. The application case envisaged the use of the client's existing industrial robots for grinding. Time-varying geometrical deviations of the belt grinder unit required frequent corrections to the robot motion. Characteristics of the robot path called for generative offline programming, relying on a virtual model that can be recalibrated by measurements that do not largely interrupt production. Here, too, a virtual environment was built up to serve as part of the system and as common ground for customer and solution provider, based on which a feasible solution was elaborated in close collaboration with the client. The roll-out of a real-world workcell required repeated refinement of the solution, resulting in a longer follow-up.

### 3.2 Cases in the educational track

*Case 3—Summer school course in layout and process planning.* In collaboration with Fraunhofer Austria, SZTAKI elaborated a summer school program for the learning factory, and an initial run took place in 2021 (Kemény et al., 2021). The topic of the course are layout and process planning for collaborative assembly of a pre-defined compound workpiece. Adapting the debut of the course to travel and attendance restrictions during the pandemic period, lectures and consulting sessions were held online, allowing multiple forms of student–student and student–instructor interaction. Participating students were sent packages with sample workpieces and 3D-printed fixture and gripper models by mail, while online access was granted to a virtual model and a design/planning suite. Student teams built their solutions in the virtual environment, and shared the results for review and consultation with local staff at the learning factory. The latter was also responsible for building up the students' designs and guiding participants to remedies of problems surfaced during real-life tests. Concluding the course was a common evaluation of solution alternatives. Several students engaged in follow-up consultation, mostly concerning re-use of insight gained in the course for their own future work.

*Case 4—Individual student projects.* Over the past years, several one-shot student projects have been conducted, mostly in preparation for master's theses or as integral part of a mechatronics curriculum. The projects roughly follow a common pattern. Initially, the learning factory operator publishes a project topic—often in conjunction with ongoing R&D or reflecting needs for new mechatronical components—at the associated university, to which students can apply. Upon selecting the applicants, the project supervisor and the student (or team) negotiate requirements and a first draft agenda. Next, students research literature and material sources, and establish common views with the supervisor. A preliminary plan and material budget are then negotiated, followed by one or more iterations of solution development, testing and validation involving the supervisor. While students are required to work independently, the supervisor usually gives advice and shares core knowledge on a regular basis. Findings obtained may be new to both the supervisor and the students. In addition to new knowledge, the projects yield working mechatronical solutions which remain installed in the facility if they prove sufficient utility.

## 4. FINDINGS AND IMPLICATIONS REGARDING CO-CREATION

### *4.1 Co-creation characteristics in the selected cases*

While the four co-creation phases, as named by Hidayati and Novani (2015) or Galbrun and Kijima (2009), can be identified in all cases summarized in Section 3, their degree of matching co-creation characteristics, volume of actions, involvement and role of actors show significant differences owing to the specific setting of the cases. Length limitations of the paper do not allow a detailed discussion of all cases—instead, one representative case has been selected for each track based on its potential and relevance to co-creation, and their discussion has been extended by implications of the given track as a general context. A summary of characteristics is also given in Tab. 1.

*Findings for the industrial track.* Case 2 exemplifies a research-intensive industrial project where both the nature of the problem and possible solutions can only be fully clarified once research has given more insight into what can be realistically achieved with the concrete industrial application constraints. As in all projects completed so far in this track, the industrial partner took the role of a client/user, while R&D experts at SZTAKI were involved mainly as providers. The problem-related context was largely application-specific and determined by the user—this is common in other industrial projects, too. Co-experience and co-definition phases resulted in intense interaction and yielded considerable additional (domain) knowledge for both actors involved, contributing to the cumulative *value-in-use* created and acquired by both parties in the project. The outcome of research and negotiations conducted through the co-definition phase allowed the goals to be more precisely formulated in co-elevation. Iterations in elaborating, validating and adjusting the specific solution had more of a co-development character, yielding the major part of value-in-use as additional know-how and theoretical findings for the research participant, and an automation solution for the industrial partner.

Some general remarks—also based on industrial projects conducted independently of the pilot factory—can be added to the specific findings from Case 2. Although no quantitative analysis has been made to date, completed industrial projects leave the impression that open research problems are a key driver regarding the intensity and mutuality of interaction, and contribute much to a balanced yield of value-in-use for all participants. Projects with dominant development or knowledge transfer character, on the other hand, result in more unidirectional connections with pronounced value-in-exchange involvement. Moreover, experience shows that lasting and frequent iterations or follow-up projects are rare in the small-business sector where incentives for most pilot factory projects originate. This is, according to testimonies from the companies themselves, due to the current business climate compelling small enterprises to prioritize daily survival over long-term innovation strategies. This circumstance also makes it difficult to initiate multilateral projects where the pilot factory and its operator SZTAKI would act as a facilitator between multiple contributors.

*Findings for the educational track.* Individual student projects of Case 4 involve the most intense and most balanced interaction of participants in the educational track, creating multiple facets of value-in-use on both sides. In Case 4, it is typically instructors/supervisors who set the problem context, but regarding the values yielded, both supervisors and students can be viewed as providers and customers alike. Moreover, project stages and milestones match well with co-creation stages: an initial negotiation of each other's expectations and resources equals well to co-experience. Subsequent literature search and simultaneous consultation on a regular basis map well onto co-definition, followed by agreement on a solution plan for co-elevation. Elaboration of a solution, normally involving regular consultation, multiple checkpoints of validation and iteration as needed, comprise co-development. The process yields predominantly value-in-use for both actors involved: students gain domain knowledge and practical skills they can put to use in their professional career, as well as academic credits and thesis material needed for progress with their curriculum. Owing to feedback and common experience, supervisors gain didactic insight, and in many cases, even new domain knowledge—one shall keep in mind that the targeted application domain is rapidly evolving, and research conducted by students is likely to capture findings beyond the supervisor's existing scope of knowledge. Projects in Case 4 also deliver tangible and usable mechatronics solutions tailored to the requirements of the learning factory facility, representing another form of value-in-use enriching the supervisor's side.

In contrast to the industrial track, continued student participation underlies different dynamics, since students successfully proceeding with their curriculum are not likely to stay in the same participating position for prolonged time. Instead, it becomes crucial to ensure continuity across subsequent projects performed by different student teams (see also remarks on consistency in the subsection below).

While typical learning factory projects are anticipated to be less balanced regarding direction of knowledge transfer and yield of value-in-use, their favorable orientation towards partnership in learning and continued development of didactic content matches well with comparable reports of co-creation in other fields of higher education (Dollinger et al., 2018; Magni et al., 2020). This congruence highlights the relevance and anticipated impact of connecting co-creation approaches with learning factory practice.

### *4.2 Role of the infrastructure in co-creation*

The learning factory facility has been designed and receives repeated upgrades to maintain a consistent infrastructural core that is flexible enough to host both physical and virtual customization and extension as tracks of knowledge transfer and solution finding proceed. This is supported by a number of key characteristics: (1) modularity and easy reconfigurability of physical shop-floor components, (2) support for extending the existing physical infrastructure with new components, (3) flexibility and connectivity of the planning and execution infrastructure in accordance with shop-floor configuration, (4) availability of virtual representation components pursuing a modular approach similar to their physical counterparts, (5) capabilities for coupling virtual representations and control flow of existing physical equipment with purely virtual components or remote systems.

The cases in Section 3 illustrate the vital role of the learning factory infrastructure as a backbone across co-creation stages. In most projects and courses completed so far, the infrastructure exhibited much utility in establishing compatible views of the parties involved, by conveying insight during co-experience and co-definition, and by connecting participants' subjective views (i. e., presentations) through a common background (i. e., representation). The facilitating effect of a consistent model has already been witnessed in earlier R&D (Erdős et al., 2014)—this has been confirmed again by projects in the facility. Moreover, matching the findings with the co-creation perspective is expected to give further insight into the nature of collaboration facilitated by a common reference model.

### *4.3 Implications for future cases*

Future projects in the facility are expected to remain demand-driven, both in the industrial and in the educational track. Therefore, the weight of interaction and collaboration will mainly be determined by the character of the given project or course. Nonetheless, relating the actual evolution of the project to the fundamental approaches and methodological knowledge of co-creation is expected to improve guidance and prevent some of the potential pitfalls arising, e. g., from hidden inconsistency in views or weak incentive for continuity across subsequent projects. The impact of infrastructure limitations—by biasing insight and engineering decisions—has not yet been systematically examined, but the quality of project outcomes is likely to benefit from further investigation.

Table 1. Key characteristics of projects in the industrial (top) and educational (bottom) tracks

| | Actors | Value-in-use created | Factors influencing continued action |
|---|---|---|---|
| Industrial track | Industry (mainly user) | • Factory solution<br>• Re-usable solution elements<br>• Domain knowledge | + Recurring new challenges<br>+ Funded opportunities<br>– Restrictive business climate |
| | R&D staff (mainly provider) | • Re-usable algorithms, approaches<br>• Domain knowledge<br>• Solution experience | + Matching R&D interest<br>+ Funded opportunities<br>– Limted budget/capacities |
| Educational track | Students | • Domain knowledge<br>• Practical skills<br>• Academic credits<br>• Thesis material | + Continued interest in topic<br>± Curriculum progress<br>– Constrained own resources |
| | R&D staff as supervisors | • Domain knowledge<br>• Didactic experience<br>• Re-usable physical solution | + Matching R&D interest<br>+ Funded opportunities<br>– Limted budget/capacities |

## 5. CONCLUSION

The paper examined the presence and relevance of co-creation in a pilot/learning factory environment which allows production-related research, pilot development and education without direct exposure to risks and limitations of live industrial production, but retaining relevant production functionalities for hands-on experience. The connection of learning factories with co-creation is sparsely represented in current literature, therefore, the priority of the paper was to raise interest and inspire further research in the combination of the two fields. The paper relied on the example of a dual-use pilot and learning factory facility for highlighting a limited number of characteristic cases, wherein co-creation patterns and their implications were identified. The small sample size available for the given facility, as well as the lack of attention to co-creation characteristics during past projects precluded a quantitative analysis at this time, allowing qualitative matching and formulation of assumptions only. Nevertheless, the potential impact of seeking co-creation in a pilot/learning factory environment already outlines steps of future research: aside from adequately targeted and structured recording of future cases in the given facility, substantial progress is expected by extending research to further sites of comparable operation practices, and broader channeling of responses and findings from all parties involved.


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