INTEGRATION OF LEARNING AND RESEARCH IN A MULTI-PERSPECTIVE LEARNING FACTORY

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ABSTRACT

Many technical universities and polytechnics have manufacturing environments or learning factories to teach students about production and assembly processes. The University of Twente currently establishes a new workshop, including a specific learning factory. In this learning factory, design choices are made in such a way that the organisation, appearance and comportment of the learning factory can be harmonised with the learning intent, the learning path and the levels of experience and expertise of the learners or trainees involved. The learning factory serves different levels of learning simultaneously. To this end, a recursive master-apprentice model is ingrained in its design. This approach aids in implicitly blurring the distinction between 'learning' and 'research'. Although all participants have their own interests and goals, they strengthen each other's learning and research. The learning factory caters for addressing multiple perspectives simultaneously, ranging from e.g., a production process and quality monitoring, via logistics and real-time location systems to workplace ergonomics. This is only possible if a flexible and versatile architecture underpins the learning factory, based on serious gaming and digital twinning. In the learning factory, research initiatives thrive on the activities of learners; concurrently, learners benefit from the research initiatives and underlying systems – interfaced by e.g., serious games and digital twinning. The learning factory is under development, in which the paradigms of the learning factory are applied: it is infused by students and researchers working on prototype projects/solutions; this allows them to study the topics involved, while anticipating the structure and working of the learning factory in a way that vouches for the envisaged openness, flexibility, and manageable indeterminacy.

KEYWORDS

Learning factory, recursive master-apprentice approach, serious gaming, digital twinning, integration of education and research, Standards: 3, 5, 6, 8, 9

INTRODUCTION

There is no such thing as sudden experience. In production industry, vocational training and academic learning alike, conveying explicit theory may establish factual knowledge, but for obtaining insight, acumen and underpinned expertise, sheer theory does not suffice. Moreover, the intent of learning is often to establish the ability to make decisions in an informed, judicious and creative manner. This requires tacit knowledge, habitually transferred by 'learning-by-doing', from which learners build mature understanding. Traditionally, a master-apprentice approach allows for introducing learners to new processes, environments and knowledge. However, in highly optimised production environments, such approaches are well-nigh impossible. Especially in mass-production or large batch production, there is no room for interruptions – let alone errors. Over time, this has led to a variety of initiatives to replicate the primary processes in safe and permissive environments as the basis for teaching and learning. Such replicated environments have purposeful applications in education and academia as well. Students can get acquainted with production environments, they can be confronted with their own decisions, and as such, they can build elementary experience in dealing with production environments. Such 'learning factories' provide a reality-conform learning environment, in which trainees can discover and test approaches or conduct experiments on technological and organisational industry-related issues (Abele et al., 2017; Abele et al., 2015; Kreimeier et al., 2014). Learning factories provide the ability to support methodical modelling of effective competency development, enable feedback processes for the learner, and simultaneously open possibilities in production research. Establishing a realistic learning factory, however, comes with significant investments in terms of efforts and costs. In companies, the envisaged environment is often well-defined, and the learning objectives, the learning approach and the assessment ('readiness for the job') are inherently aligned (Biggs & Tang, 2011), often as a part of life-long learning initiatives. In academia, establishing effective and efficient learning factories is more intricate. After all, students are not being prepared for defined tasks, nor is the aim to convey replicable skills. Moreover, optimisation and evaluation can generally not be based on any 'real' production line or primary process. Hence, learning factories can mimic a specific (imaginary) industrial environment, or have a generic constitution (Abele et al., 2019). In both cases, limitations relate to the resources needed, scalability, mobility and effectiveness of learning factories (Tisch & Metternich, 2017). There is also a considerable risk of descending into a definite, rigorous (and perhaps even stifled) environment with predefined workflows, expected/predictable outcomes and ordained behaviour. This can be prevented by making the design of the learning factory an inherent constituent of its operation, challenging learners to deal with and influence changing circumstances. With this, the learning factory can become more versatile for multiple types of learners, but also become a breeding ground for research – related to the production environment, but also to the learning involved.

This publication depicts the design of a learning factory to demonstrate how multiple perspectives (ranging from production processes and quality monitoring, via logistics and real-time location systems to workplace ergonomics) can be involved in a factory for learning and research. Based on the background of the new learning factory and its educational approach, it elaborates on the contemporary master-apprentice approach that is introduced, in relation to the integration of learning and research that is anticipated. To orchestrate the learning factory and its (didactic) organisation, a background in serious gaming is used, in which a variety of digital tools are prerequisites, but simultaneously are tools for further development.

CONTEXT AND SCOPE

The Faculty of Engineering Technology at the University of Twente hosts educational programmes in (among others) Mechanical Engineering (ME) and Industrial Design Engineering (IDE) at BSc./MSc. level and has a variety of PDEng. and PhD. trajectories. With around 450 first-year students per annum, the programmes aim to educate professionals with in-depth technical expertise and know-how, with a particular focus on interdisciplinarity and on specific competences in addition to only technical knowledge. The programmes integrate education, research and (industrial) practice, to allow for concurrent knowledge generation, reflection and contextualisation. One of the main agents in education is project-led education.

Project-led education

Both for ME and IDE, the programmes build on project-led education, mainly to immerse students quicker and more profoundly in the fields of expertise involved (Dankers et al., 2013). Students work in 10-week projects, covering 30-50% of the nominal study load, in groups ranging from 4 to over 15 students. Projects are not fully pre-structured, challenging the students to take control and ownership of their own learning. Given the impact of educational projects of considerable scope, complexity and scale on the overall program, adequate balancing of the learning aims, and implementation of projects and courses is essential (Fresemann et al., 2018; Luttikhuis et al., 2014). Project-led education instigates a demand for understanding/learning or creating knowledge, while carrying responsibility for the results, while focusing on the contents of the field of expertise as well as on social and communication skills. After all, the 'best' idea or concept is only viable if supported by the entire team – requiring adequate presentation with appropriate persuasiveness.

In engineering, project-led education confronts (groups of) students with the consequences of their decisions in design and development trajectories, by challenging them to implement or materialise their ideas/concepts. In this, focus and reflection on all different fields of expertise involved, but foremost on the subjacent design/development processes are essential (Tomiyama et al., 2009), to challenge the engineer's ability to approach problems from different perspectives (Damgrave et al., 2021; Damgrave & Lutters, 2016). This strengthens the ability of students to not only acquire knowledge but to become a versatilist: an engineer who can be a specialist for a particular discipline, while at the same time being able to change to another role with the same ease. Consequently, students 'experience' projects and education, but from the start, they are immediately dared to control, govern and take ownership of their projects. With that, students initially take pride in more or less succeeding to produce prototypes; later, with more advanced topics and more perspectives involved, they become eager to get more grip on and control over the processes involved. Ultimately, students should inherently anticipate foreseeable consequences of decisions in design and development trajectories. To achieve that for topics ranging from fabrication processes, assembly processes, quality control, process planning, production planning to facility/asset management and factory lay-out, the access to a well-equipped, adaptive and flexible learning factory is an essential prerequisite.

Development of a new learning factory for education and research

Over time, deliberately enforced by project-led education, the workshops at the faculty transformed from 'exclusive domain of trained technicians' into a coherent set of shared facilities where students, staff and technicians co-operate to produce prototypes, test designs and build research setups. At its core are workshops that offer access to elementary production machines. As satellites, workshops related to e.g., metrology, additive manufacturing, Virtual/ Augmented reality, Smart Industry and plastics processing are connected. With an ongoing increase in student numbers, the facilities needed increased capacity. At the same time, the educational projects call for the incorporation of innovative production processes and for integrating digitalisation initiatives. Likewise, operational management of production machines, assets and factory environments receive increasing attention in education and research. Moreover, the evolvement of educational and didactical approaches calls, and allows, for advanced interactions between theoretical discourses and industrial applicability. Here, possibilities prompted by digitalisation/Industry 4.0 infuse thinking on learning factories in terms of flexibility, modularity and reconfigurability that was previously impossible or infeasible. All in all, the shared facility required reinvigoration beyond 'continuous improvement', in which explicit attention for the principles of learning factories can play a significant role.

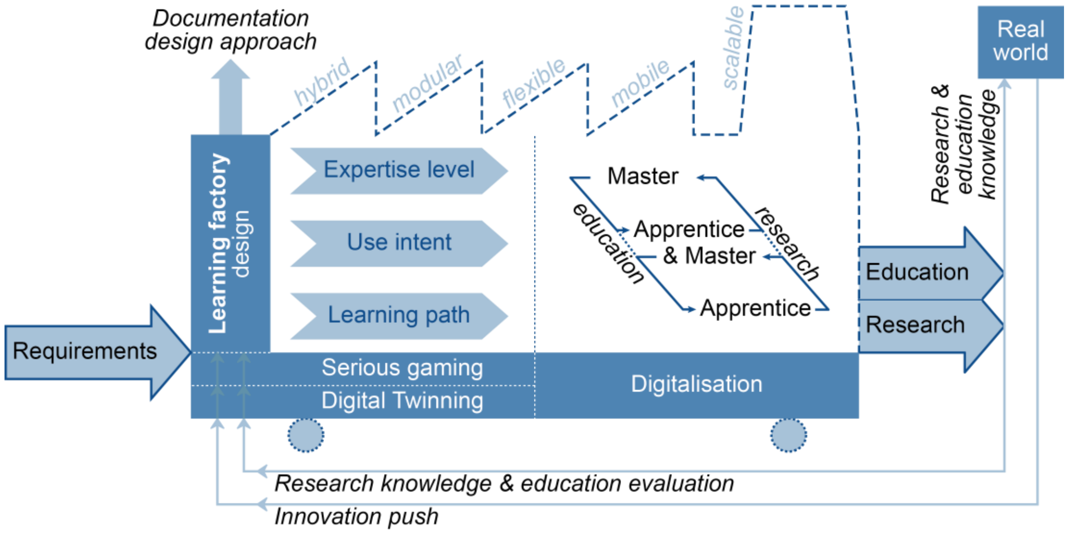

Figure 1. Schematic overview of the design and embedding of the learning factory

Currently, the concept and design of the new workshop is finished, and construction is about to start. The workshop will cover around 3000 m^2 with different ‘environments’, hosting specific sets of processes/materials, at multiple levels of aggregation. Thus, activities range from exposing learners to individual production processes, via process planning to establishing planning/monitoring approaches for multiple environments. Whereas the entire facility essentially acts as a learning factory, there is one ‘environment’ that is referred to as a specific learning factory. This learning factory (of around 150 m^2) allows for repositioning/ reconfiguring assets and resources to set-up modular production or assembly lines; it is explicitly based on the learning factory philosophy, but with a few twists. Figure 1 depicts a schematic overview of the thinking behind the learning factory. To counteract challenges as mentioned above, the design of the learning factory is inherently modular, reconfigurable and flexible. This avoids rigidity over time, but it also allows for different types of involvement for students with different perspectives or at different levels. Beginning undergraduates will experience the different production/assembly stations as a means to understand the processes and the workflow involved; at the same time advanced learners may be responsible for configuring/optimising the production/assembly line the inexperienced students encounter.

Inherent to the focus on project-led education and challenge-based learning, the new workshop has been designed in such a way that it indeed (within reasonable limits) facilitates student-driven operation and learning, and can engage in all nonconforming ideas, plans and ventures that are the outcome thereof. After all, whereas exposing inexperienced students to production/assembly lines sounds excellent in theory, there are obvious risks – especially if the line is setup/ran by other students. The main pitfalls relate to safety and to the investments in assets, resources and tools. After all, if inexperienced users are given the responsibility to operate machines at their own discretion, clear and explicit precautions should be taken. In ‘traditional’ learning factories, the inherent response often is to introduce workflows to assure safety and to protect machinery. It is not uncommon that students are required to hand in plans and can then observe how a trained operator executes these plans. As such, this may avoid risks, but it certainly impedes purposeful, effective and efficient immersion of learners in a production environment. Yet, by design, risks related to safety or damage can be mitigated. Not only is safety made an inherent topic in all projects, in the workshop, access to dangerous or vulnerable equipment is arranged on a per-machine basis, registered on student ID cards. Access is granted after passing e.g., a safety training, introductory practicals or basic operator training. Dependent on the machine type, a minimum number of students/staff can be required to check-in at a machine before it may be operated. Next, the production/assembly line in the learning factory employs a specific type of equipment: lower-force/scaled machines, but with control systems identical to the controllers on industrial-scale counterparts (see figure 2). With that, the students experience the same interfaces and programming as used in industry, yet at relatively low-cost machines, rendering any errors, mistakes or experiments significantly less impactful. For example, in the assembly line, different types of robots are used that 'speak the same language' (in this case Robotic Operating System (ROS)) as any full-scale version. The same yields true for e.g., the automated guided vehicles (AGV), or controllers of the desktop CNC-machines. With that, it is certainly not the intent to make the learning factory as robust as possible – rather, by design, resilience is an inherent part of the thinking behind its design.

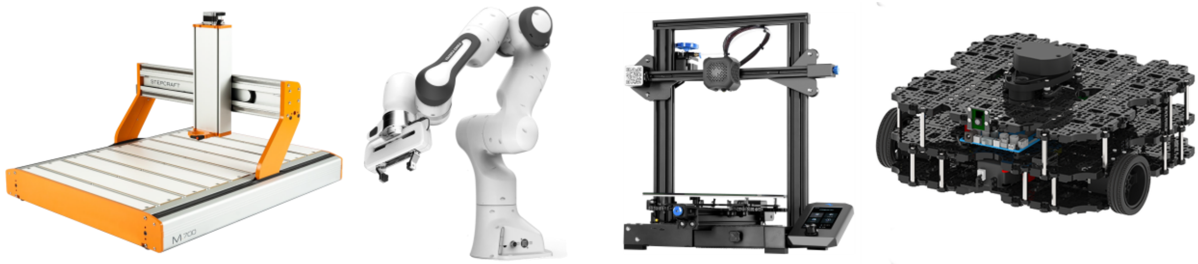

Figure 2. desktop production assets (low-force/scaled) with industry-standard interfaces.

RECURSIVE MASTER-APPRENTICE APPROACH

The learning factory foremost facilitates education and learning. Yet, the activities of students and staff determine the effectiveness, efficiency and impact of the learning that takes place. In this, the 'traditional' master-apprentice approach has significant advantages, especially as the conveyance of tacit knowledge is involved. It facilitates addressing multiple perspectives in an integrated manner and it offers an adequate manner to focus on both theory and its practical implications (Loyer & Maureira, 2014). Foremost, it allows for implicit and explicit reflection on activities, their underlying decisions and the decision-making processes. At the same time, 'traditional' master-apprentice approaches habitually rely on all parties being present at the same time at the same location while co-operating on the same task. Given the attainable student-to-staff ratios, and the different fields of expertise involved in academic education, such an artisanal approach becomes infeasible. Therefore, a contemporary interpretation of the master-apprentice approach is required, which allows for differentiation in time and location of staff, but also for inherent quality control of the knowledge that is transferred. This involves solutions that virtualise processes, observations and training to transgress simultaneousness of activities and locations. For this, a sound information backbone is required, which monitors, guides and controls what information is available to whom in what format. To this end, digital twinning is integrated in the learning factory, as an approach to transcend rigidity by process orientation (Lutters & Damgrave, 2019); to allow for, and control, flexibility and the change of perspectives, serious gaming is used. This digital twinning and serious gaming (described in later sections) give context to both the master and the apprentice in their endeavours. Foremost, however, the contemporary interpretation can introduce a way of thinking that is related to the different levels of aggregation in the learning factory. As mentioned, beginning undergraduates may be executing tasks that are defined/planned/optimised by graduate students, and these graduate students may be studying optimisation methods in the context of a PhD. research trajectory. Alternatively, undergraduates may be studying takt time variations, contributing to a sensitivity analysis performed by graduate students. Thus, what may be a challenging learning intent for some students, may be input for advanced learners. With this, different students work simultaneously on similar topics at their own level, but also provide a wealth of information, input, reflections and creativity for learners at a different level. This implies that teaching staff is no longer the only instigator in teaching, but that they inspire, guide, and motivate students to engage in a master-apprentice relation themselves, co-operating in peer learning at different levels. Coached, steered and assessed by staff, this is beneficial for all learners involved, as beginning learners have access to experience of and contextualisation by advanced learners, and the advanced learners benefit from the output of the beginning learners. Moreover, advanced learners also (implicitly) benefit from being forced to explain/teach their own work and considerations. Such aspects add value over the already existing way of working: the topics that will be addressed in the learning factory are already part of the current educational programme, yet in a less connected and integrated manner. By bringing these topics together in the learning factory, courses and projects (even over different educational programmes) become more entangled, leading to a more realistic environment for exploration, but also for peer learning and for students that learn new topics while simultaneously guiding beginning learners. This implies that a master-apprentice relation can become a relative notion. A recursive master-apprentice approach embeds students in the knowledge and insights of advanced learners and staff, thus allowing and challenging them to progress to levels and topics that enable them to council subsequent 'beginning learners'. A student will thus be master and apprentice at the same time. This forces them to internalise knowledge to the level that they can convey it to their 'apprentices' – where experienced staff provide safe, constructive and contextualised environments. This makes learning more active, and challenges learners to replicate, use, reformulate, reflect on, and creatively use the expertise they are building and conveying. With that, explicit and tacit knowledge are less disparate, allowing learners and educators to focus more on the rationale in and of decision making than on the sheer 'correctness' of solutions. This also impacts the assessment in education: in concordance with project-led education, emphasis can be more on formulating, developing and evaluating knowledge and decisions than on replicating factual knowledge. Still, factual knowledge is a clear proviso for reaching adequate decisions; and thus (access to) such factual knowledge is an agent that no longer needs not be examined as a learning objective in itself.

Integration of learning and research

As the recursive master-apprentice approach entangles learning activities at different levels, the distinction between learning and research blurs. After all, where undergraduates may still work within explicit, closed and pre-defined boundaries, their work may simultaneously be part of a more explorative research project. As a practical example: undergraduates use virtual or augmented reality solutions to be taught/instructed on an assembly process, whereas the development and testing of such solutions is part of a research project. With that, students get acquainted with research, research methods and new developments in a 'living environment', whereas the researchers have direct access to a purposeful and realistic testbed. If staff incorporate such dependencies in their educational efforts, students see and use research outcomes, and they are directly challenged to reflect on the applicability and (dis)advantages thereof, as this forms valuable input for the research projects. This again contributes to making the student learning experience more realistic and immersive.

In the learning factory, many integrative approaches are employed to spark engagement, motivation and creativity – of learners and researchers alike. Firstly, such integrations relate to the different levels of aggregation; as students that learn/experience production line concepts like Kanban, quality monitoring, or collaborative robots, can simultaneously participate in research related to planning strategies, quality management, or workplace ergonomics. Secondly, integrations can address different perspectives/aspects that play a role in the learning factory; students use technology like IoT sensoring, assets under development, automated guided vehicles, real-time location systems (Thiede et al., 2021) as facilitators in their work, whereas their activities are simultaneously a significant testbed for research on Industry 4.0 or Smart Industry. With that, the learning factory acts as a pilot production plant (Lutters, 2018; Lutters & Damgrave, 2019), being a facility that allows a company to develop, test, improve and upscale (parts of) a production environment while not hampering primary processes and avoiding investments where possible. Next to the engineering-oriented integration of education and research, also integration with other aspects or research domains are envisaged. One of the most obvious is to render the learning factory an environment that allows for educational research. However, also user-oriented research related to, for example, user interfaces, manuals, repair, maintenance, behaviour design, organisational issues, and even workplace wellness are integrated in the foundations of the learning factory.

SERIOUS GAMING

The learning factory under development is an open, indeterministic, volatile and only partially defined environment, characterised by uncertainty as well as ambiguity. Such variability and ambivalence are intentional and inherent to the design, implementation and its use. Hence, also its organisation, management and control mechanisms must be imbued with the ability to act on open situations, behaviour and internal as well as external stressors. As the learning factory cannot thrive on closed or rigid methods or processes, as mentioned, a different approach is found in applying serious gaming as a driver and instigator of activities as well as of the environments in which the activities are contextualised. Serious gaming allows staff and students alike to create, capture, simulate, assess and replicate situations or conditions in the learning factory. These situations can for example replicate industrial situations, exemplary use cases, specific setups or tasks, conditions for decisions, or even uncertain, unspecified or arbitrary situations. With that, serious gaming can be a way to expose learners to a situation and simultaneously a way to guide, influence and contextualise their attempts for finding, evaluating, probing and evaluating solutions. Additionally, serious gaming is inherent to education in the learning factory itself, as it allows for easy simulations and what-if scenarios, especially if the digital underpinning of the factory (see next section) provides adequate foundation and support. Whilst the focus of serious games often is on improved learning outcomes of learners, serious gaming can also consider the impact of gameplay on other stakeholders like the education provider and facilitator, the training instance, and the real-world system or environment portrayed (Von Leipzig et al., 2022). Moreover, personalisation of learning trajectories by integrating different perspectives and variable scenarios is possible. Serious games offer a platform to aggregate learner behaviours and results, and use these to dynamically configure, adjust and tailor the game or environment to individuals and contexts, ultimately providing a learning environment of improved quality, effectiveness and efficiency. In research on modular, re-usable and configurable serious games, an architecture has been developed (Von Leipzig et al., 2022) that is largely also applicable for learning factories. The main justification for this is that, like the learning factory, the serious game architecture considers an environment as being open, dynamic and prone to stressors. Moreover, different levels in the serious game architecture (e.g., modularity, re-usability, parametrisation and contextualisation) are in line with what is required in the learning factory. An especially useful aspect of the serious game architecture is the 'bidirectional' learning approach, enabling the contextualized adaptation of learning material, experiences and learning trajectories based on the aggregated behaviour and results. This is relevant for the design and organisation of the learning factory, but foremost for the recursive master-apprentice approach.

DIGITAL(ISATION) PREREQUISITES & OPPORTUNITIES

Where openness and indeterminacy are essential characteristics of the learning factory, it is obvious that its government and control cannot be based on settled process descriptions and workflows. With advancing digitalisation and Industry 4.0 approaches, also industry explores changing attitudes towards process-driven conventions. To allow for the required flexibility and to exploit and research digital(isation) prospects, the learning factory (and the overall new workshop) embraces an information-driven approach. As this approach can be ingrained from the design phase, digital representations of the learning factory can be the basis for its operation, but also for its management and control. This is done by means of digital twinning (Lutters & Damgrave, 2019), which allows for capturing the as-is current situation, but also for exploring potential futures in providing simulated could-be representations of the learning factory, or parts or aspects thereof. The information that enables such representations is integrated in the design of the learning factory; the production/assembly line will apply not only IoT based sensoring for process conditions and for line behaviour, but also real-time location systems and e.g. vision systems or motion capturing. This transpires in the context of industrial software systems for production/logistic control and management (like ERP, MES, CAQ), again allowing learners to use lifelike systems in a low-risk environment. Conjointly, the elements in the environment not only provide control mechanisms based on condition monitoring of the learning factory, but it also allows for exceeding individual levels of aggregation as the information can be used by different perspectives involved for different purposes. This immediately facilitates and strengthens the recursive master-apprentice approach. Moreover, the digital twinning approach allows the learning factory to have a hybrid constitution: with all the information that is available, the learning factory can be accessed physically, but also in virtual reality. Next to ‘acknowledged’ use of virtual/augmented reality for instruction and training, the learning factory also uses virtualisation to, for example show/experience alternative solutions in decision making, to switch/integrate different perspectives, to role-playing in serious gaming, to contextualise process/production planning, or to immerse in potential future configurations in the learning factory. Such techniques take learners along a learning curve that can be comprehensive, contextualised and effective – whereas all technology also allows for singling out and spotlighting hurdles or omissions in a student’s ability to fathom a topic. By generalising and aggregating such meta-information, the learning factory as a whole can ‘learn’ from how it’s being used (Von Leipzig et al., 2022), enabling bidirectional learning, but foremost inherent optimisation of the learning factory (Thiede et al., 2016) and its educational/didactical approaches.

Conjointly, this approach means that the system architecture and the IT-backbone of the learning factory require significantly more effort than is necessitated by the simple production/assembly activities taken places. However, like the machines (in figure 2) use industrial interfaces, also allowing the students to experience and interact with industrial-scale infrastructure and systems adds to the learning experience and the realism of the environment. Moreover, the digital backbone of the learning factory is instrumental in integrating the different perspectives involved. It facilitates beginning learners to do and contextualise their work (as ‘employees on the production line’), it allows advanced learners to aggregate information for planning or factory lay-out purposes (as ‘managers of the production line’), and it constitutes a vast testbed for researchers. The digital(ised) version of the learning factory is instrumental in assessing learning and learner’s progress, in identifying threshold concepts, in indicating/ interpreting behaviour, but foremost as an inherent resource in learning and research involved.

In delineated prototype environments, students are already studying the system architecture for the learning factory, by establishing variants, implementing and examining system components, and also by testing prototypes in other student projects. In this, co-operation with industrial suppliers of e.g. ERP and MES software has been established, to the benefit of learners, researchers and the companies alike. Especially the multifarious use of digital twinning and virtual/augmented reality receives ample attention in prototyping, which confirms that learners as well as researchers do benefit from virtual access to simulated foreseeable consequences of their intended decisions. Learners and researchers manifest the importance of the ability to correlate and contemplate risks and opportunities.

IMPLEMENTATION

Whereas the new building for the expanded workshop and learning factory will be completed in early 2023, this does not mean that the establishing of the learning factory is dependent on that. Over the years, already many small projects have been executed to experiment with the philosophy that will underlie the learning factory. In several selected educational projects, students have already been working in ways that partially represent the situation and possibilities in the learning factory. As these projects have only been possible in segregated groups, locations and periods and could not yet have the foreseen common core, the envisaged overall integration has not yet been achieved. Nevertheless, multiple projects already clearly demonstrated added value for the learners, but also for the learning factory under development. For example, using the desktop machines with industrial controllers (see figure 2), groups of students have already been establishing initial versions of modular and reconfigurable production and assembly lines. Such initiatives are assessed on technological and educational merits and are used as the basis for simulations of the learning factory under development.

Mindful of the recursive master-apprentice approach, these lines were tested in an undergraduate project, whereas the development took place in the context of a PhD project focusing on the digital twinning of production lines. Likewise, students have been working on establishing serious games to introduce new students to machines and processes in the workshop, to adequate preparations to enter the workshop and to safety and working conditions. Not only did the students that were involved acquire more profound knowledge in a more (inter)active manner, but their work did also actually influence and change the design of the new building and the envisaged process architecture for the educational environment. The same yields true for multiple groups of students that have been working on topics like digitalisation, IoT, virtual/augmented reality, synthetic environments and location systems. Quite some infrastructural decisions in the design process of the new workshop have been influenced by such projects – even changing some guiding principles in thinking about educational workshops. Moreover, well-nigh all student groups involved did inherently phrase a ‘the bigger picture’ of their work, providing themselves with better understanding of their project and with a framework for decision making and reflection, while supporting the faculty in establishing and maintaining the paradigm for the new workshop and learning factory. If this ‘bigger picture’ can be shared based on the envisaged learning factory, student groups will benefit even more in terms of sharing, re-using, improving and reflecting on their own project in its context. Here, again, it is essential that the learning factory remains partially unpredictable, indeterministic and even incomplete – to avoid rigidity as well as straightforward and ascertainable project outcomes. After all, foreseeability would entice students to state the correct answer rather than to establish and internalise ways to obtain an underpinned solution. However, if students in their project can set the stage for the context in which other students do their projects, variation and volatility are safeguarded. Until the workshop building is finished, groups of students continue to work on developing and establishing parts, aspects and approaches for the learning factory, in consultation with researchers and teaching staff. With that, the implementation trajectory itself adheres to the reasoning behind the learning factory, employing the recursive master-apprentice approach. This has the advantage that efficacy and pellucidity of the efforts involved are inherent to the approach, but that, to elucidate and convey learnings on e.g., financing and staffing currently require complemental efforts.

CONCLUDING REMARKS AND OUTLOOK

In an environment characterised by increasing pressure on the existing workshop facilities, the design and realisation of a new, larger and more elaborate workshop environment and an associated learning factory are characterised by a learning-by-doing approach. Given the envisaged openness, adaptability and volatility of the new environments, there is no primary or overarching process that ordains the development activities. Here, that is seen as an advantage: an opportunity to make flexibility inherent to the structure and scheme, but also to integrate new (and even currently unknown) technology/ies in the learning factory. With that, there is ample room for the recursive master-apprentice approach that has already been implicitly identified and staged in a variety of educational projects but is now pointedly identified as a viable means to convey, contextualise, and internalise knowledge in an effective and efficient manner. Although not instigated and driven by a predefined research question and methodical, quantitative scrutiny, there is broad consensus that the emerging recursive master-apprentice approach is effective and purposeful. Because of its paradigm, and the opportunity to incorporate digitalisation and new technology, it is considered an evolvement of the already implemented project-led education. Moreover, it will enable further integration of education and research in an environment that confers industrial reality, albeit in an open and flexible manner.

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