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European Journal of Engineering Education

ISSN: 0304-3797 (Print) 1469-5898 (Online) Journal homepage: https://www.tandfonline.com/loi/ceee20

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EUROPEAN JOURNAL OF ENGINEERING EDUCATION
https://doi.org/10.1080/03043797.2019.1567691

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ABSTRACT
The article discusses the challenges and the potential approaches of competence-based programmes for higher education institutions, starting at their inception in the Bologna process. It focuses particularly on curriculum transformation and implementation of action-orientated learning concepts. Consequently, the article takes stock of recent learning factory approaches in Germany and identifies the gap between research and practice. It presents a new approach to apply a concept of competence and the corresponding didactical design, which has been implemented and evaluated in a learning factory run by the Center for Industrial Productivity at the Technical University of Darmstadt. The presented insights are based on multiple studies outlining curricular and methodological implementations of the competency model and its didactical framework. Furthermore, specific examples of application, qualitative results, and conclusions regarding two third-party funded projects will be laid out in detail. The article concludes by summarizing the findings related to future challenges for higher education.

ARTICLE HISTORY
Received 8 April 2017
Accepted 6 January 2019

KEYWORDS
Engineering education research; competency model; competence acquisition; didactical approach; learning factories

1. Starting point

Engineering represents a significant domain in Germany's higher education system. In the winter semester 2017–2018, 0.77 of 2.85 million students were enrolled in engineering courses at German universities. Accordingly, almost a third of all students in Germany study engineering, with 113,491 students majoring in mechanical engineering (Destatis 2018). The current university curricula in the field of engineering developed over the past 100 years and evolved from polytechnical colleges, which were the origin of the so called universities of applied sciences. The traditional focus and the popularity of engineering studies despite the demanding programme can mainly be explained by the outstanding labour market interest. Based on the economic demand and the quality of the studies, the engineering courses in German-speaking countries are also of great interest to international students. Despite the language barrier, 51,000 international students from Europe alone were enrolled in engineering faculties in 2017-2018 (Destatis 2018). Higher engineering education in Germany encompasses two main institutions: Approximately one-third of the engineering courses are currently offered by technical universities, while two thirds of the students are enrolled in courses offered by universities for applied sciences.

Moreover, engineers trained in Germany are in demand all over the world, both holders of former diplomas and those holding bachelor's or master's degrees. This suggests that the Bologna Process is based on a successful study reform in this economically important field. However, it must be assumed that the study courses underwent major formal changes whereas study content reflects only minor

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amendments. In retrospect, the Bologna Process was mainly a structural reform, and its only relevant aspect was the focus on competencies. While former diploma courses were mainly based on knowledge and abilities, the current bachelor's and master's degree programmes focus on competencies. In further consequence, the present study regulations lack of consistent competence concepts and thus still show evidence of the lasting endeavour for faculties to adapt to the change (Tenberg 2014).

In addition to the reforms of the Bologna Process, engineering studies required further development in terms of competencies since the professional profile has changed as a result of globalisation and digitisation. It became increasingly important to analyse and manage complex processes within the operational engineering areas and thereby to re-evaluate the original scope of the engineering domain. In addition, engineers in research and development areas were compelled to adapt to project work in adjacent areas of activity or to work with professionals from other fields. Due to the increasing communicative and co-operative requirements, interdisciplinary competencies were added to the theoretical, mostly professional-methodological engineering competence profile (Hippel and Daubanfeld 2013). Recent examples are ICT-based complex knowledge and database systems. Here, knowledge management still represents an essential tool to keep industrial production systems efficient and viable, while the increasing complexity of planning and controlling tasks depends on engineers being capable to act in the factories of the future (Westkämper et al. 2013).

In the past years, a considerable number of research studies addressed the question of which competencies may become important in the context of the digitisation of industry (Acatech 2016; Hirsch-Kreinsen 2014; Pfeiffer et al. 2016; Spöttl et al. 2016). Taking their findings into consideration, in 2016, mechanical engineering curricula of Federal Universities were analysed with the help of a qualitative content analysis. The obtained results however have shown only little accordance with the previously outlined requirements (Lensing 2016). So far, the question of the nature of engineering competencies remains unanswered by Bologna. Moreover, higher education faces new challenges in terms of competence theory, curricula, methodology and diagnostics with a need to be resolved.

2. Transfer of expertise in engineering education

The previous section implied that the Bologna reform, as well as the further settlements of the European educational scene, the European and the German Qualifications Framework (EQF, GQF), and the Qualifications Framework for Higher Education (HQR), has led to a substantial reorientation of the tertiary sector. In addition to the introduction of the bachelor's and master's degree programmes, the reorientation to competencies marks one of the significant innovations that have far-reaching implications and requirements for higher education. This not only refers to the curriculum design (examination regulations and course catalogues) but also implies considerable developments regarding teaching methods (didactical and methodical design of the curricula) and measurements of academic performance through competency-orientated examination formats (Pittich 2018; Tenberg 2015).

2.1. The underlying concept of competence development

Competence is described as a disposition to independent action (Chomsky 1962; Erpenbeck and von Rosenstiel 2007; Weinert 2001). Therefore, one may not be described as competent if one understood theory but cannot apply it, nor if one just imitates or repeats an action. In addition, the more comprehensive a field of activity is, and the more independent the individual reacts to occurring problems and changes, the higher the level of competence. Building up capacity for action requires action-based learning, while the ability to independent action requires comprehension-based learning. The effectiveness of action-based learning requires an authentic material and personal context in which the learners accomplish adequate tasks by going through cycles of planning, actual execution and differentiated reflection. The effectiveness of comprehension-based learning requires a thorough examination of technical objects, processes, systems as well as the production of scientific and mathematical references. The development of competencies only succeeds if action-based learning and comprehension-based learning are not conducted independently of one another but instead correspond with each other. Action-based learning contextualises knowledge and makes it applicable while comprehension-based learning decontextualises knowledge and thus makes it transferable. The progress of contextualisation and decontextualisation is slow. Therefore, the acquisition of competencies must take place in a combined scenario of knowledge acquisition and application of knowledge. In the case of action-based learning, it is necessary to model returning sequences from thinking and doing with varying realistic tasks to enhance the development of competencies. It becomes clear that the degree of competence development does not only depend on the quality of two different learning processes but also on an optimised dimension for learners being able to switch between action-based learning and comprehension-based learning (Pittich and Tenberg 2013).

2.2. Concepts of competence within German higher education institutions

The concept of competence is established within the German and international scientific community and is used both in the context of academic teaching as well as in the context of strategic university development. Bold statements such as Bachmann's emphasis that a (steady) ' … realignment of universities on the present and future developments (should be) expected in a globalised, knowledge-based economy' (Bachmann 2014, 14). Although the application, the foundation, and the design of concepts of competence show little consistency in this regard (Rhein 2011), Tenberg (2015) states that specific research on the comprehensive theory is only apparent in single marginal areas, however, it is not apparent in the core of the academic didactical overall approach. At present, there is no coherent university concept of competence which connects to the relevant state of research in psychology, pedagogy, and in highly indecisive contexts in the German-speaking world (Pittich 2018). Rhein is firmly committed to promote the ability to succeed in meeting complex requirements to a greater or lesser extent in (more or less) complex situations as a basic approach of higher education competency models (Rhein 2011). This is consistent across the accepted theoretical reference concepts of Weinert (2001), Klieme and Hartig (2007), which derive from Chomsky (1962) and White (1959). Competencies are described as human dispositions to successful management in different situations within the specific requirements of a domain (Tenberg 2015). While the widespread long-term implementation of international comparative studies on school education in the Organisation for Economic Co-operation and Development (OECD) area established this concept of competence in the context of school education, there is neither national nor international consistent research available on higher education. The established concept of competence, which is the HQR as a national concretisation of the EQF, cannot be equated with the OECD approach (Tenberg 2015) due to its theoretical and terminological vagueness (see Table 1).

The co-existence of knowledge and ability is highly problematic because applying both simultaneously instead of correlating them ignores the axiomatic relationship between competence and performance (Chomsky 1962). In the HQR, comprehension as a competence is equated with knowledge and ability. However, this classification has no theoretical basis. In the construct of competencies, so-called systemic competencies address latent affective-moral categories which are generally questionable or require a more precise clarification (Tenberg 2015).

2.3. Challenges in curricular transformation and the claim for action-orientation

The consequences of this current desirable objective of competence at German higher education institutions are first and foremost evident in the inconsistent ordinances of the universities, the study regulations, and course catalogues. In mechanical engineering courses, national comparisons show this inconsistency clearly (Tenberg 2014). Hence German study programmes may have differing objectives, the deficit of objectives presents itself a fortiori which was already evident before the

Table 1. Competence areas and levels of the qualification framework.

Area/Level	Bachelor-level	Master-level	Ph.D. level
Knowledge	Basic knowledge	Deepening of knowledge	Specialized knowledge
Comprehension, orientation in technical literacy	Textbook level	Specialist journal level	Writing for specialist journals
Systemic competencies, in the sense of reflexive qualifications	Closed-judgements	Open-decisive	New-shaping
Instrumental competencies, in the sense of operational skills	Direct knowledge application	Extended knowledge	Application knowledge generation
Communicative competencies (Information-related)	Information independent of the research context	Information from the consolidated research context	Information from the current research context
Communicative competencies (social-communicative)	Team-participation	Team-responsibilities	Team-leader

Bologna Process (Rhein 2011). Rhein formulated four prototypical concepts and perspectives of academic competencies (Rhein 2011, 220):

(1) 'Competence orientation as preparation for knowledge-orientated research' in the area of the activity of universities or non-university research institutions.
(2) 'Competence orientation as access to the instrumental character of science with its methods, concepts and knowledge stocks' in the sphere of activity of state or private research and development institutions.
(3) 'Competence orientation as preparation for the requirements of challenging tasks' in the field of activity of university graduates.
(4) 'Competence orientation as an emphasis on employability as well as citizenship' in the areas of activity of university graduates.

This brief presentation shows notable and distinct differences between perspectives (1) and (2), as well as between perspectives (3) and (4): 'While the third and fourth reading emphasise application contexts, the first two options move the concept of competencies into science itself' (Rhein 2011). Rhein's analysis reveals the challenges involved in the curriculum design and implementation of competence demanded in mechanical engineering. In Germany, the universities of applied sciences specialise in functional professional activity. Therefore, they hold a superior position compared to usual universities. The structure of bachelor's degree programmes can be defined as propaedeutically and does not provide professional qualification, neither did former diploma courses. This means that the subsequent master's degree programme must ensure integrating three different perspectives of competence which seems challenging, even with a wide range of differentiation and optional courses. Here, the special orientation can be found in: (2) 'Competence orientation as a means of access to the instrumental character of science with its methods, concepts and knowledge stocks' and (3) 'Competence orientation as preparation for the requirements of challenging tasks', since most university engineers work in company research and development or hold production-orientated strategic positions. In mechanical engineering, and most other disciplines at German universities, the qualification of young academics is not based on teaching but the early integration of outstanding students into research. However, the inclusion of aspects (2) and (3) within the qualification framework of technical universities poses another major challenge for a consistent implementation of the competence requirements. The strengths of the universities lie in the mediation of scientific knowledge. It does not lie in an effective transfer into a continuously changing professional reality. Recent didactic concepts for higher education prove that universities respond to the challenge of interlinked thinking and doing. Thus, several so-called learning factories were implemented in mechanical engineering to pursue this aim (Gronau, Ullrich, and Vladova 2015).

2.4. Added value of learning factories for engineering education

For some years now, German universities implement learning factories as an element of combining theory and practice for integrative mediation of thought and action. In engineering science, learning factories are not only the most consistent but also the most widespread approach towards education and training. In the following (Section 3), a structured overview introduces present learning factories of Higher Education Institutions in Germany. Subsequently, the common basic concept is presented as part of competence theory and set into context of didactics in technical education. Nowadays conceptualisation of learning factories is based on various definitions which are partially convergent (e.g. Barton and Delbridge 2001; Pullin 2009; Roth et al. 1994; Siqueira, Barbarán, and Becerra 2008; Tian 2011). Therefore, Plorin (2016) developed an integrative definition of learning factories, which is the basis for further reading. Based on an extensive term frequency analysis of 42 common definitions, the following integrative definition framework emerged:

> Learning factories offer the possibility of realistic representation of a factory (sub) system with the necessary products, processes, and resources in an experience-orientated, participative, digital as well as realistic learning environment. The individual must apply acquired knowledge, existing experiences and motivation at an interactive level to increase competence in his or her work environment. The work environment sets out the prerequisites for industry, research and teaching to simulate interdisciplinary and multidimensional transitive learning situations into trend-guided fields of activity in a case-orientated manner. (Plorin 2016, 63)

These cases cover a wide range of production-related content of mechanical engineering.

3. Assessment of learning factories

The first approaches of competency-orientated learning environments for engineers emerged in the context of the so-called hands-on engineering in Anglo-American engineering education (Lamancusa, Jorgensen, and Zayas-Castro 1997). Penn State University sought for possibilities to complement highly theoretical teaching formats with phases of practical implementation and application. In realistic contexts and concrete action situations, learners should reflect on the previously discussed topics (Lamancusa et al. 2008). Since the late 2000s, European universities used learning factories as a tool to provide learning scenarios in teaching. In this context, the pioneers of these treatments joined together, for example, through the 'Network of Innovative Learning Factories', the 'Initiative on European Learning Factories', the collaborative working group 'Learning Factories for future-orientated research and education in manufacturing' within the International Academy for Production Engineering (CIRP) or the 'International Association of Learning Factories' (Abele, Metternich, and Tisch 2019).

Taking the findings of previous studies into account, an increase from roughly 25 learning factories (Wagner et al. 2012) to more than 120 learning factories worldwide is evident (Abele, Metternich, and Tisch 2019; Groß et al. 2016; Mavrikios et al. 2017; Micheu and Kleindienst 2014; Plorin 2016). In the course of the study at hand, more than 50 learning factories have been identified within the German educational system, which emphasises the leading role of German universities regarding learning factories. It must be said that only around half of the identified learning factories in Germany are visible and documented externally while the other half remains inaccessible for assessment purposes (Lensing 2016).

Steffen, Frye, and Deuse (2013) and Abele et al. (2015a), for instance, made recommendations for describing and clustering the different applications and orientations of learning factories. However, in the context of the present assessment, it is only the morphology of Abele et al. (2015a) which may be considered as a good practice example. In a first step, it comprises learning factories in the narrow sense (i.e. on-site training with real value-added physical products) and learning factories in a broad sense (remote, purely virtual, e.g. services) (Abele et al. 2015a) as well as integrated teaching methods (Abele et al. 2015b). About one-third of the learning factories can be described as learning factories in the narrow sense, as defined by Abele et al. (2015a), and two thirds as learning factories in the broad sense. The objectives of the project range from the use in higher education teaching to the processing of scientific questions in (third-party funded) studies, to the use as service-orientated demonstration and training platforms for the industry. At present, a clear focus is on the use in higher education and the qualification of external company specialists or managers, in each case focusing on the development of professional and meta-disciplinary competencies. Academic learning factories only adopt research approaches and publish literature on this subject in (multidisciplinary) scientific journals. All higher education learning factories identified in the analysis can be assigned to mechanical engineering. Only the learning factories in Darmstadt and Aachen include interfaces to the automotive or textile sector. Learning factories in Reutlingen and two sites in Bochum address and focus on logistics, among other things. Other learning factories, such as those in Braunschweig and Darmstadt (ETA or η-Factory), for instance, aim at energy efficiency. Other learning factories (for industrial purposes) concentrate on the topic of assembly activities. Despite this content segmentation, two third of the learning factories focus on production technology (e.g. resource efficiency, lean production and quality management). Just under one-third of the learning factories take aspects of digitisation into account. It is expected that this proportion grows in the future in response to the mega-trend of Industry 4.0.

Reference examples in the following: (1) the LPS (Chair for Production Systems) Learning Factory of the Ruhr-University Bochum, (2) the Learning Factory 4.X and the Learning Factory on Global Production of the University of Karlsruhe and the Karlsruhe Institute of Technology (KIT) as well as (3) the Center for Industrial Productivity (CiP) of the Technical University of Darmstadt (TU Darmstadt). Firstly, the selection is based on characteristics of the respective (scientific) documentation and its format. Secondly, the thematic content of the learning factories and their integration into academic teaching determines this selection.

Regarding (1): The LPS Learning Factory of the Ruhr-University Bochum was founded in 2009 and addresses the topics of complex process optimisation, resource efficiency, and management/organisation. In the past few years, the focus has been on Industry 4.0 (Meier et al. 2015). This learning factory is used in university teaching as well as in services offered by industry employees. In addition to the focus on lean workshops, a further focus is set on Management and organisation of work-modules. The LPS learning factory aims at making all (future) processes within the production value stream representable (project *WorldFactory*) and, in addition to the physical production of products, at mapping virtually the process order with its entire range of material and information flows via the Manufacturing Execution System (MES). The thematic orientation of the learning factory, as well as the topics of the learning scenarios, is documented in various publications (Meier et al. 2015; Wagner et al. 2015). To a low degree, these reflect the didactical-methodical investment and design.

Regarding (2): The 4.X Learning Factory was developed as part of a cooperation between Karlsruhe University of Applied Sciences, Karlsruhe Institute of Technology (KIT) and Karlsruhe University of Education. The learning factory portrays the complex interrelations of product development and development processes and implements communication and visualisation technologies. The interdisciplinary orientation aims to build an awareness of the complexity in product development and manufacturing processes. It concerns areas such as engineering, economics, information science, and education and social sciences. 4.X is available for teaching students of the colleges mentioned above but also for further industrial education purposes. Additionally, KIT's Learning Factory on Global Production addresses the issues of production design, scalable automation, on-site and global quality assurance, network and site planning in the context of globally networked production processes. The aim is to raise awareness and give an overview and understanding of most varying production requirements in global value-added networks (Lanza et al. 2015). The learning scenarios address students as well as employees on different hierarchical levels within globally operating companies. Publications and empirical studies on 'Learning Factory 4.X' and 'Learning Factory on Global Production' (LGP) concerning the didactical design in specific are currently still pending.

Regarding (3): The CiP learning factory of the TU Darmstadt was founded in 2007 as the first learning factory with a complete value chain in Europe. Subsequently, its purpose is to address issues concerning production such as lean production and lean management which is used not only in research and teaching but also in industrial training services. In the context of the CiP and its research and development projects, numerous publications have emerged over the past decade (including Abel et al. 2013; Abele et al. 2015a, 2015b; Abele, Grosch, and Schaupp 2016; Abele, Metternich, and Tisch 2019; Metternich 2016; Tisch et al. 2013). The early publications focused primarily on topics of production engineering and have been increasingly supplemented by didactical-methodological representations (Hambach et al. 2015; Hambach et al. 2017) in the past few years. The extracted and outlined basic ideas were taken on board by other universities in Germany (including Plorin 2016 and Lensing 2016).

Considering the overall picture including the three referenced learning factories, it should be noted that learning factories provide a functional framework for situated learning (Ehrenmann 2015). The focus is on action-orientated learning (Gerstenmaier and Mandl 2001), as well as problem-based learning (Boud and Feletti 1997; Cachay and Abele 2012). At present, many company-owned and university learning factories conduct an analysis and discuss implementing, implicitly or explicitly, the design of learning and examination scenarios (Abele, Metternich, and Tisch 2019). In the core area of industrial engineering, key topics are, for instance, process optimisation regarding resource efficiency, lean management and quality management. Further topics associated with advanced digitisation are in the early stages (Meier et al. 2015). Special training courses are being offered to managers, trainers, engineers, shop floor employees or students in the form of workshops. The technical approach is predominant while the relevant learning scenario aspects beyond subject boundaries are often ignored (Bauernhansl, Dinkelmann, and Siegert 2012; Plorin 2016; Steffen, Frye, and Deuse 2013). The main intentions of learning factories in universities are the intensified accentuation of experience and action, the creation of initial experiences in the field, as well as overcoming inhibitions of action in complex productions. This has led to learning scenarios which are mainly of habitual nature and in contrast to a real production process, interventions and adaptations can be made without risk or cost pressure and thus used for learning (Cachay and Abele 2012). However, this emphasis also makes clear that imparting of specialist knowledge and background knowledge may play a subordinate role.

4. Didactical approach for development of competencies in LFs

In two third-party funded studies by the CiP at TU Darmstadt, an empirical development and implementation design became the first comprehensive approach to systematic competence orientation. This refers to the '*Idefix*' project (the German acronym stands for: 'Innovative learning modules and -factories: validation and further progress of a new knowledge platform for tomorrows excellence of production'), which was founded by the German Federal Ministry of Education and Research (BMBF), and a follow-up project founded by the German Research Foundation (DFG): '*Learning Factories for a versatile production*'.

Here, the following steps were outlined: (1) development and implementation (Section 4.1), (2) Implementation of the competency model into a curricular framework concept (Section 4.2), (3) Implementation of the curricular framework concept (Section 4.3), (4) Explication of a compulsory learning methodology compliant to the competency model (Section 4.4), (5) Conceptual implementation of the curricular concrete learning settings using the explicit learning factory methodology, as well as (6) implementation and (7) diagnostics of the workshop. In the present paper, the focus is on steps (1) to (5) in the following Sections 4.1–4.4.

4.1. Process model of teaching and learning in technical domains

The stages are based on a technology-based process model (Tenberg 2011) as a cohesive approach to competence development (planning), conceptual design (preparation), implementation and review (evaluation). Figure 1 shows the process model and illustrates how, in (technical) teaching-learning scenarios, the teaching process, which is characterised by the stages of planning, preparation, execution, and evaluation, is conceptualised with the learning process.

The process model is based on learning orientation, contextualisation and processor (operator) orientation. In this context, learning orientation means that self-organised and reflected learning are the starting point for the concept of teaching. Instructions are not excluded, however, they are underrepresented and subordinated to a pupil-active overall approach. 'Contextualisation' means that the learning scenarios follow generally real-world and professional identity contexts, i.e. approaching specific problems which are set up with authentic materials and media, et cetera. Processor orientation means that the learning and development procedures are based on professional activities and business processes, which are designed as 'complete actions' in the sense of Hacker (1973), including the steps of planning, execution and checking. However, the competency model of didactics in technical education is at the core of these development projects.

4.2. Competency model of teaching and learning in technical domains

The Competency model (Figures 2 and 3) was developed during an empirical validation study on professional and methodological competencies in wood technologies. The theoretical background, the empirical research methodology and the corresponding results (Pittich 2013, 2014a, 2014b) have been included in the third-party funded studies. The basic starting point of the dispositional approach is a knowledge-based competence theory. The theory of Erpenbeck and von Rosenstiel (2007) appears to be appropriate and compatible since it has a knowledge-based and fundamentally theoretical background and it is implementable on the empirical level. The resulting working model distinguishes four competence classes: (P) Personal, (A) Activity and action-orientated, (F) Professional-methodological and (S) Socio-communicative competencies as well as two types of competence: evolution and gradient strategies (Figure 2).

The four competence classes identified result from the subject–object or subject–subject relationship and form mental or physical (self-organised) actions (Erpenbeck and von Rosenstiel 2007). In addition to the competence classes, the model contains so-called competence types. Erpenbeck and von Rosenstiel refer to these as gradient strategies or evolution strategies. The former are so-called self-control strategies (Erpenbeck and von Rosenstiel 2007), which are mainly algorithmic and used predominantly by the individuals within the framework of manageable processes or actions. In contrast, evolutionary strategies (self-organisation strategies) are of

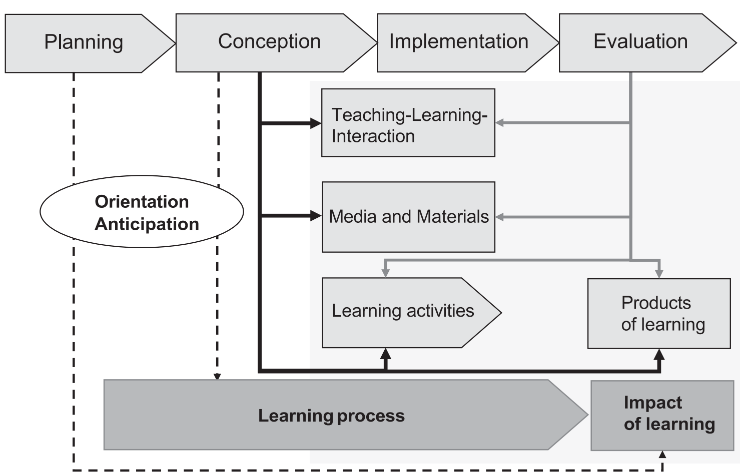

Figure 1. Process model of teaching and learning in technical domains (Tenberg 2011).

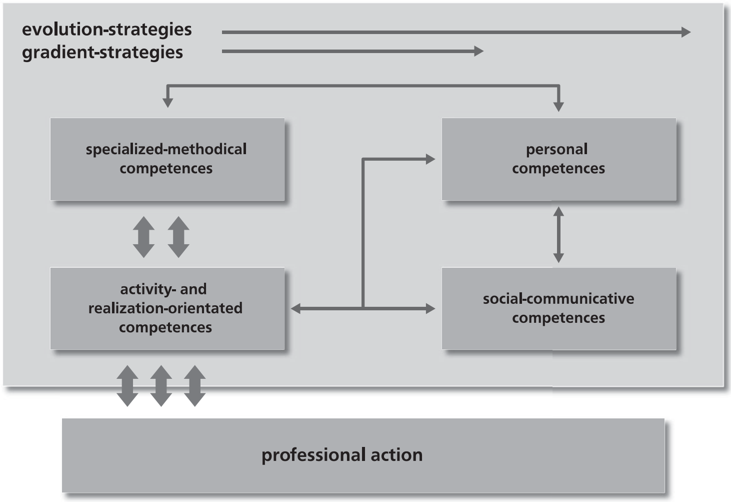

Figure 2. Competency model with reference to Erpenbeck and von Rosenstiel (2007) combined with the extension of professional activities (Pittich 2013, 45).

heuristic nature and preferably used in extended problem-solving situations. The distinction between competencies in accordance with the demands for the respective situations is congruent with the empirical basis of findings of the industrial/commercial competence research in the German-speaking area (Knöll 2007; Nickolaus 2011a, 2011b; Nickolaus, Gschwendtner, and Geissel 2008; and Abele 2014).

For further clarification, Pittich (2013, 2014a) presented and validated an approach to the modelling of professional and methodological competencies. Based on an analysis of cognitive-theoretical models, a critical factor for high-quality (technical) knowledge is the aspect of (technical) understanding. In the subsequent discussion, the following forms of knowledge evolved from a cognitive-theoretical work model: factual knowledge, process knowledge and conceptual knowledge. Conceptual knowledge represents a form of comprehension knowledge and plays a prominent role within the knowledge model which focuses on comprehension and offers context in terms of reference and explanation of knowledge types (factual and process knowledge). An individual requires elaborate conceptual knowledge only to be aware of respective reasons which can be used in (professional) situations to solve (professional) problems. Figure 3 illustrates the interplay of the different types of knowledge concerning professional activities and the degrees of freedom and variability.

The results of this study are summarised in the following table (Table 2): (a) the working model of Erpenbeck and von Rosenstiel (2007) and Renkl (1994).

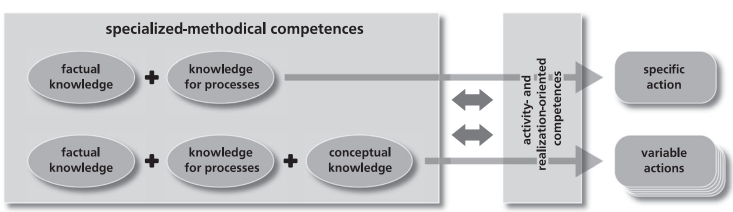

Figure 3. Work model concerning professional-methodological competences by using the theories of Erpenbeck and von Rosenstiel (2007).

This modelling assumes that individuals can perform a specific action based on factual and process knowledge. A specific action usually occurs in action routines. The range or the flexible applicability, i.e. the variability of action, is restricted because an adequate background is missing or is only rudimentary. Conceptual knowledge is required to achieve a variable, i.e. flexible, independently expandable and changeable action (ability). These assumptions show that factual and process knowledge, as well as the corresponding conceptual knowledge, determines professional and methodological competencies. Their quality manifests itself in the situational flexibility of individual actions. The empirical findings of Pittich (2013, 2014a, 2014b) imply that (1) correspondence of knowledge qualities and quality of action is to be established and that (2) the conceptual knowledge, which includes immediate aspects of action but also basic background knowledge, is a crucial component of expert action. The curriculum in a didactic-methodical design must implement the theoretical basis (Section 4.2). These related units from specific actions, and thus respective knowledge, are transferred into a particular teaching-learning concept and formulated in a methodical way (Section 4.4). To examine the intended learning objectives, it is necessary to implement an adequate competency diagnosis eventually.

4.3. Implementing the competency model into a curricular framework concept – didactical transformation I

In the context of the curricular implementation of the outlined competency model, the focus will be on professional and methodological competencies, as these are at the core of the competence development and a fundamental condition for the development of interdisciplinary competencies. In the following, a corresponding learning situation is presented which is already intended to anticipate the methodological implementation (described in Section 4.4).

This curricular framework was developed in the 'Idefix' project in various modules of production technology. The following example shows the curricular image of partial competencies in the module 'Production Engineering – Traceability of Components or Assemblies'.

The implementation of the outlined curricular framework concept or the formulation of professional and methodological competencies are an example for generating curriculum-compliant competencies using the module 'Production Technology – Traceability of Components and Assemblies'. The core contents of the module are measures and methods for documenting and recording the physical and digital (production) processes. The aspects of knowledge and corresponding actions (right column), identified in ex-post analyses, were combined using the instrument of the action-knowledge-competence matrix and formulated as a partial competence (left column) (Table 3).

In the present example, the action: 'Learners optimise the product creation process in the context of a Manufacturing Execution System (MES)' was placed in the right column. Subsequently, the dimensioning of factual, process, and conceptual knowledge complete the corresponding knowledge. The example shown does not only refer to the traceability system but also to the hardware and software competencies used where actual knowledge of product and information flows is an inherent value. Process knowledge refers to handling, application, and use (timing) of artefacts

Table 2. Module n.n. - structure of the action-knowledge-competence matrix.

Comprehensive competence: …				
Areas of competence	Knowledge (in depth and breadth)			Actions Partial treatment of overall competence as learning action = performance
	Action-orientated level		Reflection level	
	Professional knowledge			
	Factual knowledge (what)	knowledge for processes (how, when)	Conceptual knowledge (why)	
…	…	…	…	…

Table 3. Module: Production engineering – traceability of components or assemblies.

Comprehensive competence: Learners are able to fundamentally understand (digitized) production processes in their complexity and to grasp, evaluate and optimize them				
Areas of competence	Knowledge (in depth and breadth)			
	Action-orientated level		Reflection level	Actions
	Professional knowledge			
	Factual knowledge (what)	Knowledge for processes (how, when)	Conceptual knowledge (why)	Partial treatment of overall competence as learning action = performance
…	…	…	…	…
K 3.4: Learners optimize the product production process with the aid of digital images of the physical production process – for example by the combination of data-driven analyzes from a Manufacturing Execution System (MES) and their knowledge of the production process used plus knowledge about the physical product flow.	Traceability systems: • Use and application fields • Guidelines, standards and data models Hardware/Software: • Input and output masks • Evaluation functions • for large amounts of data • Database systems • Identification technologies or identification techniques Product/information flow: • Scheduling characteristics • Manufacturing features • Production technologies	Dealing with data bank systems Identify deviations from the usual booking practice (Manual posting) Management of production Data management Influence of environmental variables and or the production technologies used Suitability of the respective identification technology Consistency of the digital/physical product and information flow (VSM/value stream analysis) Integration of new components in production processes Customer complaints, supplier management	Legal necessity, where necessary, for the documentation of component origins and processing Transparent display of all information and product manufacturing processes in terms of: • sustainable use of resources • continuous improvement Identification of disturbances and changed environmental variables Justification for necessary adjustments/changes in the production practice used to date	Learners optimize the product production process in context of a Manufacturing Execution System (MES)

and technologies in the respective production process. Aspects of the necessity and function of traceability systems, as well as the expected disturbance and environmental variables in complex production processes, identify conceptual knowledge. In this example, conceptual knowledge represents the background of comprehension. Following the detailed description of the table cells, the individual categories of knowledge can be linked with the corresponding actions for competence formulations. As the formulation of competence ('Learners optimise the product production process by using the digital image of physical production processes – for example, by combining data-based analyses from the MES and the knowledge of the manufacturing processes used and the physical product flow') implies in Table 3, knowledge serves as a disposition of observable action (performance). Thus, the result is a competency grid for each module, which may be implemented in further methodical steps including appropriate tasks and learning scenarios. This approach leads to professional and methodological competencies which are considered as the product of a first didactical transformation. At the same time, they serve as a starting point for further methodological considerations of the didactical framework. In the following section, a further step of the overall approach will be outlined particularising the curricular action-knowledge-competence matrices in the corresponding learning activities.

4.4. Corresponding conceptual implementation and methodological concretisation of the curricular framework concept – didactical transformation II

Based on the competency-orientated learning objectives of the action-knowledge competence matrices, further conceptual steps were taken within the 'Idefix' study. In contrast to the first curricular transformation (Figure 1: step *Planning*), the following considerations determine the second transformation with a didactical-methodological orientation (Figure 1: step *Conception*). In the overall approach of the CiP learning factory, this step is described as determination of the activity order (Figure 4).

The determination of the activity order (*order of activities*, Figure 4) shows two didactic points of reference related to:

(1) the learning systematics (logic) and
(2) the learning activity.

Regarding (1), learning systematics are relevant at the level of the conception of technical teaching scenarios and can be understood as anticipatory planning systems or systematisation logics of the intended learning processes (Tenberg 2011). In the context of technical teaching and learning, Riedl and Schelten have distinguished these as a basic orientation in 'Fachsystematik und Handlungssystematik' (2000); engl.: 'subject and action classification'. A subject classification approach is 'oriented to the arrangement, method, and view of the corresponding sciences' (Riedl and Schelten 2000, 155). Subject classification distinguishes itself as highly differentiated with a concerted structure. It also shows an objective knowledge or content logic validated by the respective specialist sciences. In contrast to subject classifications, a system of actions does not follow the objective logic of a technical discipline but is based on actual professional activities. Actions can be understood as conscious, motivated and targeted (Hacker 1986) and, for example, on so-called action-regulation schemata (Hacker 1973). Tenberg (2011) proposed a similar distinction between (a) development and testing activities; and (b) systematisation activities. Development and testing activities are learning activities that are more closely related to the real action. These include, for instance, creating professional information material or even addressing a professional problem. Indicators of development and testing activities are the logical action orientation in the context of direct action. During the course, the learners set their own goals, review their achievements, and adjust their further (learning) action. Thereby, learners find new methods of dealing with and solving specific situations, et cetera. In this context, testing means applying, implementing and realising.

Systematisation activities refer to learning activities which are more closely related to technical or scientific systems and specialised terms. These include, for example, comprehension, comparison or abstraction of technical information materials, performance and evaluation of experiments, or embedding of technical sub-information into the disciplinary system. Systematic orientation is characteristic for systematisation activities, which requires relativising but also moving away of the direct-action context. In this process, the learner is to activate, check, supplement, expand or even correct the existing knowledge systems based on objective knowledge (e.g. technical literature and scripts). These representations indicate that there are recognisable connections between a learning system (logic) and learning activity. Action-orientated learning scenarios rather show activities of

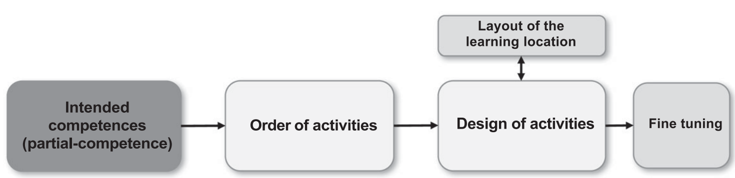

Figure 4. Concept for the methodical design of competency-orientated learning scenarios.

exploring and experimenting, whilst systematisation activities are increasingly identified in learning content-related scenarios. Acquisition of competence, as assumed and modelled in sections 1.1 and 1.2.1, requires both development and testing activities and systematisation activities. In addition to these different learning systems and activities, reflection and control play an essential role as effective forms of feedback on learning. Without feedback a teaching-learning process from a theoretical and interactionist perspective is deficient (Tenberg 2011). Reflections and controls provide both teacher and learner with information about the effectiveness of the learning scenarios. Thereby that a match between what has been learned and what should be learned becomes possible.

In the context of the CiP learning factory, two different activity sequences (Figure 5) evolved from these basic theoretical and didactical-methodological considerations through the action-knowledge-competence matrix.

After entering a learning sequence, two learning activity variants are accordingly conceivable:

(1) Learning activity variant 1 (top) shows the first theoretical approach. Traceability systems are described as well as their fields of application. Furthermore, hardware and software competencies, which are used in a production process, are specified. The project also outlines the handling, dealing and application (timing) of these artefacts and technologies in the respective production process. After the theoretical base is set, it is put into practise such as the actual testing of an MES in the context of a production process.
(2) The reversed path is used in learning activity variant 2: the direct discussion with a concrete MES adopts a more casuistic approach. Following this practical development, the generalisation mentioned above takes place through systematisation (e.g. overview, strengths and weaknesses, areas of application).

Irrespective of the order of the two types of activities, these form the methodological substance of the learning environment, together with the reflection and control elements. Focusing on learning objectives and their requirements for knowledge, understanding, and action, the learners need to prepare a path or several paths with guidelines, instructions, and media, which can be interesting, motivating, individually applicable and collectively implemented. However, as in the previous didactical sub-segments emphasised, the focus is also on the basic model. For instance, it is the manner how competencies are described here, how they are differentiated in aspects of ability and understanding, transformed into curricula and finally taught using systematic learning processes.

5. Results

Regarding the outlined didactical-methodical scheme comprising the model of competence (Section 4.1), the explained competencies (transformation I) and the mediation of competence approach (transformation II), it is important to emphasise that this proceeding has already been extensively

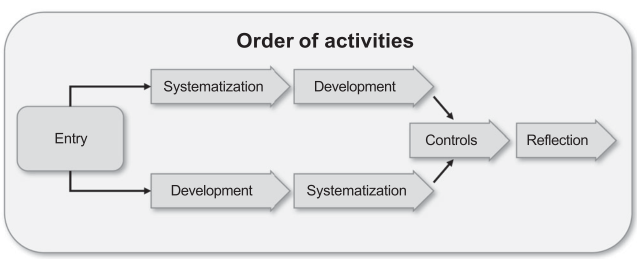

Figure 5. Model of the basic order in context with different learning activities.

researched in two third-party funded projects. Based on the findings of these preliminary studies (Pittich 2013, 2014a, 2014b; Tenberg 2011), the focus was set on the implementation of didactical transformation whereas the BMBF-funded project 'Idefix' concentrated on a breakdown of the overall didactical design (Tisch et al. 2015). The DFG-funded project ('*LFs for versatile production*') primarily outlined the mediation of competence approach (Hambach et al. 2017). Based on the principles of design-based research, these studies were both designed and realised at the CiP learning factory at TU Darmstadt. The main arguments for using a design-based research approach in both projects were the following: (1) the theory-driven development concerning the overall didactical concepts and (2) a particular focus on furthering enhancements regarding the theoretical and empirical state of research (Section 3) in the context of competency-orientated learning in learning factories for higher education.

During the project, 'Idefix' organising (curricula) and conceptual material for trainers and instructors, who teach in learning factories, has been developed. The most notable results were the following: (1) the development of competency-orientated curricula, based on the theory of competence (Pittich 2013; Tenberg 2011; Section 4.2) and the action-knowledge-competence matrix as well as (2) its didactical-methodical realisation in learning situations and activities. Preparatory analyses and constant multi-level evaluations proved that a thorough scientific understanding of methodological competencies in technical education is necessary for instructors becoming capable of implementing these formats of training independently and at a didactical and methodical level in learning situations and activities appropriate to target groups and topic areas (Section 4.2; Tisch et al. 2015).

Within the project 'learning factories for versatile production', a greater focus was on realising the topic and recipient specific learning situations and activities. Therefore, training sessions conducted in the learning factory were recorded from several perspectives for documentary purposes. Those were analysed eventually (Hambach et al. 2017) regarding behavioural aspects using a competency grid which was aligned with the competency model (Section 4.4) and the curricular means. Consequently, the supervised trainers faced the results to correlate their self-perception with the findings. A series of problems was identified regarding the mediation of professional and methodological competencies in learning factories, comprehension and perception (Hambach et al. 2017). Finally, the conclusion drawn conveyed a considerable need to improve training and coaching for learning factory teachers. However, appropriate approaches refer to (1) professional–technological issues and target topics of specific learning factories and (2) underlying principles of the overall didactical–methodological concept. Referring to (1) professional–technological training measures appears to be less problematic in the context of, e.g. university learning factories, since these include the current scientific discourse and state of research in engineering. This also applies to learning factories in schools or companies as they concentrate primarily on direct execution in professional practice. Regarding (2) The development of consistent didactical-methodological approaches presents a significant challenge. Both concepts pursue consistency regarding the underlying principles of the overall didactical-methodological approach. As previously mentioned, only a few consistent approaches are present. Within the framework of the concept described in this paper (see Figure 1, Section 4.1 and the following chapters), improvements particularly regarding the steps of planning and conceptual design, also referenced as didactical transformation I and II, as well as the step of evaluation (referring to diagnostics), seem to be adequate starting points for further design-orientated development of the approach.

6. Conclusion

Higher education is more challenging than ever as the established aim of imparting high-quality knowledge has added a new competence claim. At this stage, the premise is rather rhetorical than adressed didactically thus higher education teaching shows currently no consistent educational goal. The current attitude stating 'anything goes' in terms of generating curricula stems from a gap between research and practice in this context. Therefore, unless academic competencies are precisely defined, every possible approach may be considered as appropriate. In engineering studies, Bologna´s competence claim aims has not been implemented. Even before the Bologna process, study programmes were designed to strengthen the transfer of knowledge into an adequate capacity for action. For instance, construction has been and still is compulsory for a mechanical engineer during studies. It is hardly surprising that the aim of Bologna has been reversed when applied to these study programmes: The curricular concept formerly being called 'ability' is now basically labelled as 'competence'. Irrespective of these processes, higher education learning environments have been implemented in order to impart competencies during the past two decades. In mechanical engineering, alternating integration of understanding and action can be staged directly in learning factories which are exemplary for learning environments. The impetus for realising these complex and expensive treatments did not come from focusing on the premise of academic competence development; it rather came from creating a learning environment that makes respective subjects comprehensible and manageable in its overall complexity. The four exemplifying sections (4.1–4.4) show that such a learning environment can consequently be enriched ex-post in a technical-didactic manner. The focus is on a viable basic model which concretises the relationships between competence, knowledge, understanding and action. On this basis, a curricular framework concept can be generated eventually as well as fundamental ideas for its methodical transformation. So far, this has been implemented successfully in only a few learning factories which nevertheless have proved their worth. As usual, didactics or education do not necessarily require science. Nonetheless, the theoretical approaches, curriculum models and basic methodological concepts presented here offer a path that can lead learning factories from a didactic-intuitive stage into a didactic-explicit stage. This provides the essential prerequisite for analysing learning environments on a scientific basis which means not only investigating them more closely in their mode of action but also making dynamic and further progress.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Bundesministerium für Bildung und Forschung [grant number 03V0137] and Deutsche Forschungsgemeinschaft [grant number 220204719].

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