

Article

Digital Learning Support for Makers: Integrating Technical Development and Educational Design

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Abstract: Makerspaces have gained momentum, not only due to novel manufacturing technologies but also the need for qualified workforce in production industries. Capacity building should not follow ad hoc procedures or arbitrary project designs to qualify for digital production, but rather should still leave room for creativity. As such, the quest has arisen for structured while empowering guidance of additive manufacturing. This can be of benefit for timely education, not only for qualifying existing workforce in production industries but also to attract students in production-related domains. In this paper, we aim to develop an integrated understanding of technical development and capacity-building support activities. We exemplify the proposed design science approach with a regional makerspace. This provides us with the user-centered evaluation of structuring additive manufacturing along an individualized education scheme. Thereby, additive manufacturing capacity building starts with individual goal setting and structuring requirements for an envisioned solution, which becomes part of a learning contract of a specific project. Learning steps are framed by design science and its stages and cycles, since artifacts can be of various kinds, stemming either from construction, modeling, material selection, or manufacturing. The evaluation study revealed essential benefits in terms of structured planning and individualization of capacity-building processes.

Keywords: makerspace; project-based learning; capacity building; additive manufacturing; design science



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1. Introduction

In 2005, when *Make*: magazine was founded by Dale Dougherty, his idea was to help people start a hobby and learn new skills [1]. Stemming from the idea of tinkering, where people could fix their cars or renovate their homes on their own, “makers” are enthusiasts of new technologies. Makers are people who “engage [. . .] in the creative production of artifacts” [2] (p. 496) and who try to build new types of products or variants of existing ones, utilizing novel materials and/or new technologies. The magazine provided a platform for the community where makers could learn from each other. In 2006, the first Maker Faire took the main idea of the magazine and created a space where makers could engage in conversation with each other. Thenceforth, more and more people, including children, became interested in sharing their ideas, constructing, and finally building their individual products in such collaborative settings [1]. This starting point enabled the establishment of the maker movement, engaging people in creative processes of producing something while learning and collaborating. Since then, the maker movement has become manifest in so-called makerspaces all over the world. These provide space for makers to participate in creative production processes, blending “digital and physical technologies to explore ideas, learn technical skills, and create new products” [3] (p. 505).

In addition to providing space for collaborative work, makerspaces aim to promote engagement and knowledge sharing actively, including the discussion of ideas, possible constructions, and socio-technical system designs [4,5]. Design spaces or even design

thinking labs promote collaboration with others. In an organizational context, makerspaces are often used for workers and companies to try and learn about new technologies. By exploring such novel technologies, collaboration between the workers is a key factor in designing new production (cf. [6,7]). In scholarly education, the idea of producing tangible objects by digital means (“making”) has become increasingly popular. Several learning theories indicate better learning results when students are engaged to “make” something, e.g., project-based learning [8] and problem-based learning [9]. Learning in makerspaces can also appear as computer-supported collaborative entrepreneurial processes [10], depending on individual empowerment. We understand empowerment as supporting someone with the authorized capability to perform and share certain activities. Hence, makerspaces, as spaces for empowerment, need to provide more than technologies, and support activities beyond skillful “doing”—“makerspaces should also implement the infrastructure to empower people in their self-realization” [11] (p. 519). Such spaces require didactic concepts that have not been at the center of research so far (cf. [12]).

In line with recent attempts to enhance creative problem solving in higher education settings through corresponding instructional design strategies in digital learning support systems (cf. [13]), we address the learners’ ability to generate and reflect on constructionist and sense-making ideas as part of key competency development for university students. It should empower them in taking effective actions in shaping and implementing technological innovations. The challenge lies in the effective stimulation of learners’ divergent and convergent thinking while promoting a systematic approach to identify project ideas, find creative approaches, and share results through meaningful utilization of support tools.

In this paper, we develop a digital learning support scheme for makers working on additive manufacturing projects. Bridging the gap between domain knowledge, self-regulated learning/making support, and institutional education structures, we feature a design science perspective on project-based learning. In the following, we first provide some background concerning learning concepts and learning support techniques relevant for makerspaces before reviewing such spaces as learning environments for additive manufacturing. We then suggest enriching the additive manufacturing process with a set of educational elements. These comprise activities for structuring capacity building in a self-managed way and provide a roadmap on how to achieve an educationally grounded approach to additive manufacturing in makerspaces. Afterward, we report on a field study evaluating project-based Business Informatics student experiences on additive manufacturing (AM) and reflect on the results in terms of a structured digital learning support framework. We conclude with a discussion of the results, and structuring topics for further research.

2. Conceptual Underpinning of Learning Support in Makerspaces

In their seminal work on educational makerspace development, Kurti et al. [14] refer to constructionism as the foundation for hands-on learning processes occurring in makerspaces:

“Constructionism, in turn, is the application of constructivist learning principles to a hands-on learning environment. Thus, maker education is a branch of constructivist philosophy that views learning as a highly personal endeavor requiring the student, rather than the teacher, to initiate the learning process. In this philosophy of learning, teachers act as guides for inquiry-based approaches to the development of knowledge and thinking processes. Upon reflection, it is natural to believe that the learner should initiate learning, as it is physically impossible for any teacher to mechanically rearrange and reinforce the physical neuronal pathways developed in the brain during the learning process.”

(ibid, p. 8)

This understanding is in line with digital learning support developments following constructivist principles for sustainable and appealing acquisition of knowledge [15,16]. While cognitive theories assume the mind to be a reflection of the real world, construc-

tivist perspectives argue that reality is individually constructed by the mind as it filters input from the world dependent on the respective situation. Therefore, knowledge is not acquired but rather created by each and every individual based on prior experiences and interactions [17].

Recent findings with respect to educational methodology and the construction of learning materials have revealed non-linearity in learning processes due to their cognitive and social nature [18]. Such findings suggest encouraging knowledge construction through a learner-centered and task-based learning design curriculum and supporting spontaneous interactions in an open and collaborative learning environment (e.g., communication and exchange of ideas, etc.). This openness results in accepting or provoking temporary disturbances, which should be resolved by providing resources that support reflective thinking. These findings can be considered as indicators for meta-cognitive processes requiring a corresponding design and architecture of learning support systems [19]. They should enable the way stakeholders conceive learning and how knowledge is stored and handled to become immanent to learning designs. Addressing learning management in terms of knowledge management activities becomes important when more and more people are deeply engaged with technology and are permanently connected to others. Thereby, the border between formal and informal learning settings becomes blurred (cf. [20]), which represents a design issue itself. The latter requires aligning organizational and individual learning strategies and management.

Once cognitive and social aspects of learning are intertwined, learners prefer authentic contexts as they help them to gain a better understanding of learning tasks and represent a familiar testbed for acquired knowledge. In this case, such context cannot be provided, and “digital natives turn to their own learning communities, which oftentimes remain relatively disconnected from their formal educational communities” [17] (p. 67). Hence, for community-driven knowledge management and organizational development, a learner-centered context and integrative perspective seem to be substantial.

In addition to the behaviorist, cognitivist, and constructivist perspective, already taking into account social and cognitive factors in learning, the situated cognition theory (cf. [21]) has been proposed to frame self-regulated learning processes with social, cultural, and physical contexts. Schuitema et al. [22] report on a positive relationship between autonomy support and relevance and self-regulated learning. Recently, the process nature of self-regulated learning has been underlined by stating that most of the respective models “[. . .] include the basic assumption that learning is primarily a process (and not merely a result) composed of varying combinations of static individual characteristics and skills that contribute to performance” [23] (p. 206). Various models on self-regulated learning have been proposed since then, mainly conceptualizing it as a recurring cycle of three to four stages, including self-evaluation and monitoring, goal setting and strategic planning, strategic implementation and monitoring, and strategic outcome monitoring [24–26]. For instance, Winne and Hadwin [27] have proposed a four-stage model distinguishing between task definition, goal setting, and planning, enacting study tactics and strategies, and meta-cognitive adaption for future learnings. In the first stage, information on conditions related to the task is processed by the learner. In this regard, not only task-specific conditions (e.g., time constraints), but also cognitive as well as motivational conditions are of relevance.

Cognitive conditions are concerned with information stored in the long-term memory, such as how one has performed on prior tasks, whereas motivational conditions relate to the perceived competence or particular interest associated with a specific task. In the course of the second stage, the learner aims to develop a plan for coordinating and enacting study tactics. Aside from other factors, this stage includes selecting specific learning strategies and plans as well as setting standards for their enactment. The third stage is concerned with the actual application of selected study tactics and aims for the construction or re-organization of subject matter knowledge. If necessary, learning strategies and plans

eventually are adapted, which might trigger changes in beliefs, conditional knowledge, or standards for judging qualities of study tactics.

Considering the underlying process of self-regulated learning, a general pattern is revealed including three main phases [26]. All models require some kind of preparation phase at the beginning, which is then followed by the performance or execution phase. Finally, an appraisal phase allows for adaptations with respect to applied learning strategies and plans for the purpose of increasing one's effectiveness. For instance, the model proposed by Winne and Hadwin first requires the processing of conditions related to a specific task, followed by some kind of goal setting and planning procedure (cf. [27,28]). These stages are subject to the preparatory phase as they are essential to the actual execution of learning strategies and plans. In the model suggested by Zimmerman, processes associated with the forethought stage (i.e., task analysis and self-motivation) are considered to be the equivalents [29–32]. The application of specific learning strategies and plans as well as processes related to self-control and self-observation are viewed as related to the performance phase. Finally, processes related to the adaptation of one's meta-cognition and self-reflection are considered to be part of the appraisal phase.

Meta-cognition has been addressed prominently in the context of self-managed learning processes (cf. [23–26,33–37]). Thereby, meta-cognition cannot be considered as subordinated to self-regulated learning or vice versa, as they are “parallel and intertwining constructs that are clearly distinct yet mutually entailed both developmentally and in their functions in human thought and behavior” [38] (p. 386). According to Veenman et al. [37], Nelson [39] proposed a first model representing meta-cognition, assuming that learning takes place at two different levels, i.e., the object level and the meta-level (cf. Figure 1). The meta-level holds a model of the object level, which is used for constant monitoring of the learning process. The model, however, is constantly updated as the learner exerts executive control over his or her learning process. This conception of meta-cognition has become widely acknowledged and often is associated with distinguishing between knowledge about one's cognitive processes and monitoring and regulating these processes (cf. [40]).

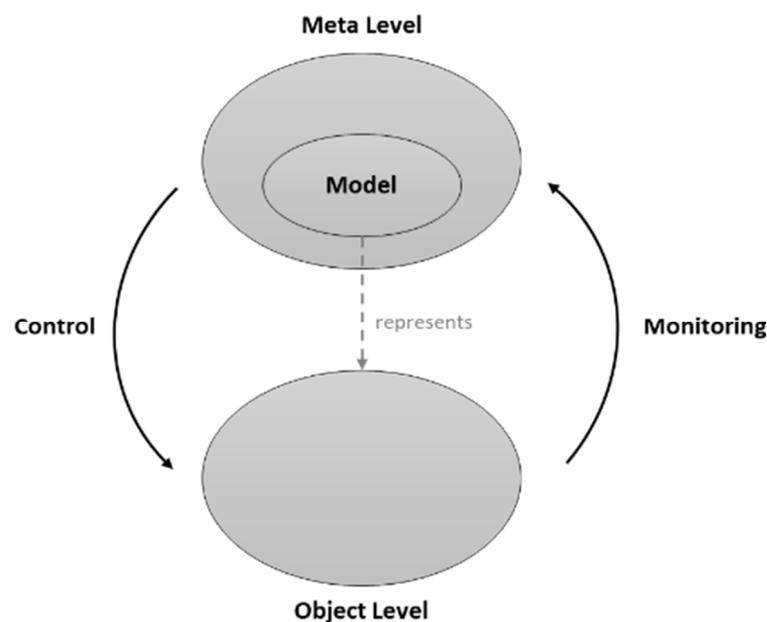


Figure 1. Model of meta-cognition according to Nelson [39].

Overall, self-regulated learning and meta-cognition seem to couple multi-faceted processes tightly. They address fundamental activities required for learning management of concrete skill development as well as capacity building of learning-how-to-learn. Thereby,

not only cognitive but also emotional and motivational factors play a crucial role in learner engagement, and thus learning outcomes.

3. Designing Makerspaces as Collaborate Learning Environments

Even though technology skill training dominates education in makerspaces (cf. <https://project-manus.mit.edu/wp-content/uploads/2017/09/MIT-Project-Manus-Annual-Report-fin.pdf>) (accessed on 18 January 2021), they aim for learner inspiration and immersion [6]. Both are considered prerequisites for inquiry-based learning [14]. The basic driver for participating in collaborative learning of construction processes is curiosity, which triggers playful engagement of learners when they explore their unique interests and pursuits, including the possibility to fail in implementing particular ideas. Although it is out of the question that training is important for expensive production machinery, an issue well addressed by providers of additive manufacturing equipment, concepts for a proactive statement or constructive feedback, empowering a budding engineer or scientist to solve a problem in its original context, e.g., a device required for achieving a specific result, still lack empirical evidence (ibid).

Originally designed in library settings, contextual material about how to use technology and to access relevant information and literature has been provided. In this way, makerspaces could be designed as knowledge spaces [11] for collaborative learning. However, qualitative studies reveal structural assets facilitating capacity building, such as the study performed by Kayler et al. [6] involving undergraduate students in a course at a small public liberal arts university. Students were immersed in maker culture using a learner-centered project-based approach to learn about and use 3D printing, and other resources and tools. Not only did peers and collaboration matter when applying learner blogs and end-of-course evaluations, but so too did time, trial and error, and the role of persistence and failure as an inherent part of learning processes. A survey of several Do-it-Yourself (DIY) communities by Kuznetsov and Paulos [41] reveals learners want to engage in information exchange. Collaboration emerges through receiving feedback about their object and mutual education. The motivation behind engaging in such communities is to meet and interact with people with similar interests. Another factor for participating in DIY projects is that makers want to express themselves in front of peers while they learn new skills, solve problems, and challenge themselves.

A report by Smay and Walker [42] on a preparatory school for Pre K (age 3) to Grade 12 with classes of a dynamic arts program shows the necessity of preparing and thus structuring makerspace learning experiences. In that case, two media specialists and the technology teachers collaborated to transform an available space into an inviting makerspace. Aiming to develop twenty-first-century skills, they provided a motivating setting for learners to start with questions and explore a corresponding design space. The learners were motivated to try out various ideas, and to combine ideas and learning experiences in which they could also fail and retry ideas and learning steps. They succeeded in making the makerspace an integral part of the learning experiences through project-based learning. The learners experienced that knowledge of the tools available is vital to extending their use later on when projects and challenges are presented to them.

However, running the Minimakerspace project in Denmark has led to the following insight:

“[. . .] even though there is a broad consensus about how digital skills are essential to do well in our future society, there is less certainty about the best way to introduce the youngest children to the digital world. A key idea of the Minimakerspace project is that we should be making IT and learning technology a part of children’s daily life, instead of considering it as something separate from the other offers of kindergartens. That means incorporating themes from the pedagogical teaching plans, so that the selected technology helps to support the personal, social, linguistic, motorial, and aesthetical development of the children.”

(<http://minimakerspace.dk/didactic-design/?lang=en>) (accessed on 18 January 2021)

This approach is seconded by academic experiences reported by Wilczynski and Cooke [43], who besides generating a sense of community and culture concluded that there is no single model of what constitutes a makerspace. It needs reflection on resources, material, and structures that best meet maker needs for design-centered functions. For example, some projects can be managed by learners whereas others require professional staff to direct operations. Hence, learning in makerspaces can occur in many ways, ranging from structured classes to self-organizing learner projects.

Carulli et al. [44] observed the particularities of design activities before actual production as part of preparing additive manufacturing for successful capacity building. Such activities comprise exploring material, designs, and revisiting or reproducing production planning. The reported educational experiences focusing on the pre-manufacturing stages revealed the benefits of shifting 'stereotyped' educational processes to the simulation and testing of real design, production, distribution, and entrepreneurial processes (from idea to market and from idea to business). Learners should work individually to design their own production lines creating machines, tools, or products, while the laboratory should promote direct interaction with peers and the public that can suggest to designers some alternative solutions to industrialization, production, and consumption.

Summing up, learning support needs to:

- (i) Include structured facilitation promoting design in an open and peer-to-peer educational setting.
- (ii) Provide practical and experimental making facilities.
- (iii) Stimulate idea articulation and probing of design and production in a "collaborative self-learning" setting by interacting with local or virtual communities.
- (iv) Have easily configurable formats for different educational target groups and purposes.

With respect to (i), the open and peer-to-peer setting is characterized by the opportunity for students to collect feedback whenever required, as well as contact peers and hosts whenever the students need to do so. The mentor and peers provide content through the learning support platform. With respect to (ii), the makerspace needs to be more than a location for tools to produce digital artifacts, as they need to provide a social setting for active exchange and mutual support. With respect to (iii), sharing of ideas, as enabled by the makerspace (ii), stimulates articulating new ideas and experimenting beyond individual interests. With respect to (iv), individual projects must be supported by involving students from different backgrounds. These requirements have influenced the selection of the makerspace in this study and guided the design of self-regulated and collaborative making.

4. Didactically Grounded Process Design for Additive Manufacturing

In this section, we sketch a didactically motivated learning process chain for additive manufacturing according to the existing concepts and findings detailed in the previous section. We provide the (i) basic concept, i.e., empowerment, (ii) a staged procedure as educational value chain, and (iii) exemplify its utilization designing a makerspace learning experience for 3D printing.

According to their original concept, makerspaces should not only provide machines and technologies to manufacture new and (innovative) products and promote respective skill deployment, but they should also facilitate learning on a more abstract level. Hence, learners in makerspaces should become aware of completing additive manufacturing tasks to create a product or object, as well as its usage, the materials to be processed, the technologies required for production, and, most importantly, how to organize the learning process to achieve the desired result. Hence, empowerment needs to be encouraged from the human learning perspective, and from the product side.

The empowerment of makers from the human learning perspective can happen in two different ways, namely on the individual (cognitive) or organizational (social) level. The individual empowerment focuses on the individual maker. Hereby, a maker should be encouraged to learn about additive manufacturing and the area of application. An individual maker should obtain relevant skills to realize the idea of an object towards the finished

item on his/her own. Furthermore, individual empowerment can be utilized for workers of a company who receive advanced training. Additive manufacturing can be a success factor for companies. Organizational empowerment emphasizes organizational thinking, and encourages new ways of using modern technology in, e.g., production settings.

In addition to empowerment on a human level, it can also be encouraged on a product level. We consider empowerment to be relevant to three different areas, namely, the production itself, the product innovation, and the process innovation. The first empowerment should happen for the production of the object itself. Individuals or groups should be able to explore and acquire necessary skills to produce the product themselves. Apart from producing the product, empowerment in the area of product innovation should be encouraged. An exploration of all possibilities related to an idea should be established, whether concerned with materials, technology, or even modularization of a specific component. Sustainable materials should be considered a key element in a product innovation process. Accomplishing awareness about the whole life cycle, from the production of the base material through to the recycling of it, should be made explicit. Furthermore, product innovation not only means the creation of something completely new but can also be seen as the redesign of the component itself.

Empowerment can also be established for process innovation. Individuals or groups who use a makerspace for an organizational purpose should acquire necessary skills to create new or modified processes in their company. Empowerment can help to redesign or create new ways of implementing the product into their process. Moreover, process innovation is possible for individuals or groups within a company. By designing innovative new processes and products, the life cycle of a product can be reduced and the process can be executed more efficiently. Collaborations with other areas in a makerspace can lead to even more new processes. Moreover, design thinking labs can help to reorganize rigid processes and show new ways of thinking about a process.

In additive manufacturing, a process can be implemented to structure the path from idea to actual product. Furthermore, the organizational view of integrating such technology in their production can also be attached. The process can be broken down into eight distinct phases. The upper part of Figure 2 refers to the pre-printing process of a maker whereas the lower part captures the production, post-production, and the process for organizational implementation.

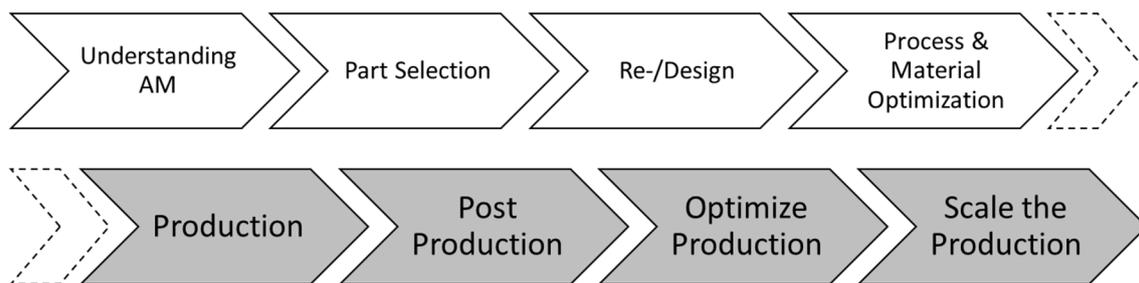


Figure 2. Stages in additive manufacturing capacity building.

Phase 1: Understanding Additive Manufacturing. Before going into production, makers need to understand the basic principles of AM. The basic concepts include printing technologies, different materials, and the dimensional perspective. While the printing technology decides which materials are suitable, the dimensional perspective stays the same. The technology varies from fused deposition modeling, stereolithography, to selective laser sintering. Depending on the desired object, each technology offers unique specifications that should be considered. Moreover, the material choice differs depending on the technology. Essential for every 3D print and model is the awareness of the three dimensions, i.e., width, height, and depth.

Phase 2: Part Selection. In addition to understanding the basic concepts of AM, the desired object needs to be broken down into individual printable parts. Apart from the high variety of functionalities of 3D printers, not every object can feasibly be printed.

Phase 3: Re-/Design. The design and/or redesign phase is necessary to build a 3D model and convert it to a printable file. There are several methods available to generate a 3D model, including modeling with a 3D software or 3D scanning of an object. Different printing parameters and sometimes scaffolds (to steady the objects) need to be considered. Furthermore, this phase can be revisited to optimize one’s object.

Phase 4: Process and Material Optimization. The preceding phases allow one to understand and design the desired object. By enabling the maker to have a clearer idea of an object, this phase decides what technology and materials to use. The context and usage of the objects determine the appropriate printer and material, which can vary, e.g., making it more robust, water-resistant, or even flexible.

Phase 5: Production. In the actual printing process, the 3D printer will be loaded with the chosen material, and the model is transferred to it. After setup, the 3D printer is started in order to print the selected file.

Phase 6: Post Production. The post production phase triggers the remaining finishing touches of the objects. Some technologies require curing and therefore hardening the object or removing scaffolds. Moreover, objects can be sealed with specific paint or powder to make them more resistant to environmental influences.

Phase 7: Optimize Production. For an individual maker, the process ends with performing post-production activities. However, makerspaces are often used as testbeds for organizations to gain insights into new technologies. Organizations can optimize their production by re-designing their object, rethinking certain parameters, or refining post-production phases.

Phase 8: Scale the Production. The last phase shifts the focus to future development. Since the production industry currently explores Industry 4.0 settings, companies need to design their products according to new technological capabilities. This stage offers the space to explore networked and self-adaptive production.

5. Aligned Structuring of Learning Support by Design Science

Design Science has attracted intense attention over the last decade (cf. [45,46]). Its dual while iterative nature with respect to design artifacts and design theory equally supports practical development and conceptual advancement. The Relevance Cycle (Figure 3) connects the environment of the maker (project) with the core development activities. The Rigor Cycle relates these activities to a knowledge base that informs the project. The Design Cycle iterates between the core development activities: building and evaluating artifacts.

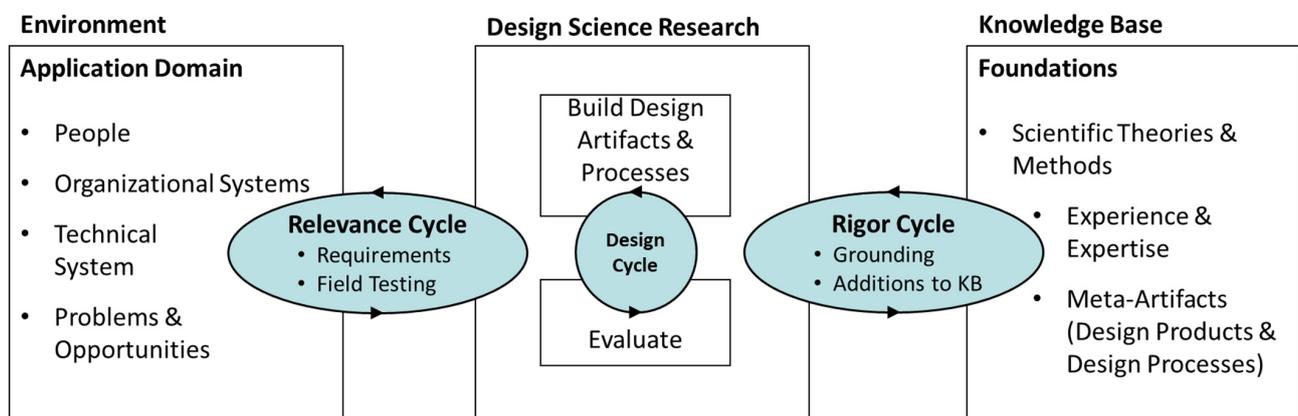


Figure 3. Design cycles embodied in pragmatic and methodological contexts (according to [46]).

The original framework has been operationalized by Peffers et al. [47], allowing us to frame the AM learning stages as shown in Figures 4 and 5. As contracted, learners or-

ganize the capacity-building process facilitated by a mentor. Learning is triggered by a maker’s interests in AM. Each project starts with systematically developing a specific goal and defining learning milestones and interventions for reflecting on achievements and clarification. In this stage, competencies are also addressed: *knowing* refers to having knowledge and fundamental understanding, *applying* empowers a maker to plan and produce an artifact by utilizing AM in an informed way, and *innovating* features novel developments by means of AM technologies. In order to structure the activities in the project and convey the capabilities of AM, a learning contract is negotiated between all project members and the persons responsible for each project. It is documented and signed by all parties. The documented learning outcomes also provide the basis for evaluating the project results.

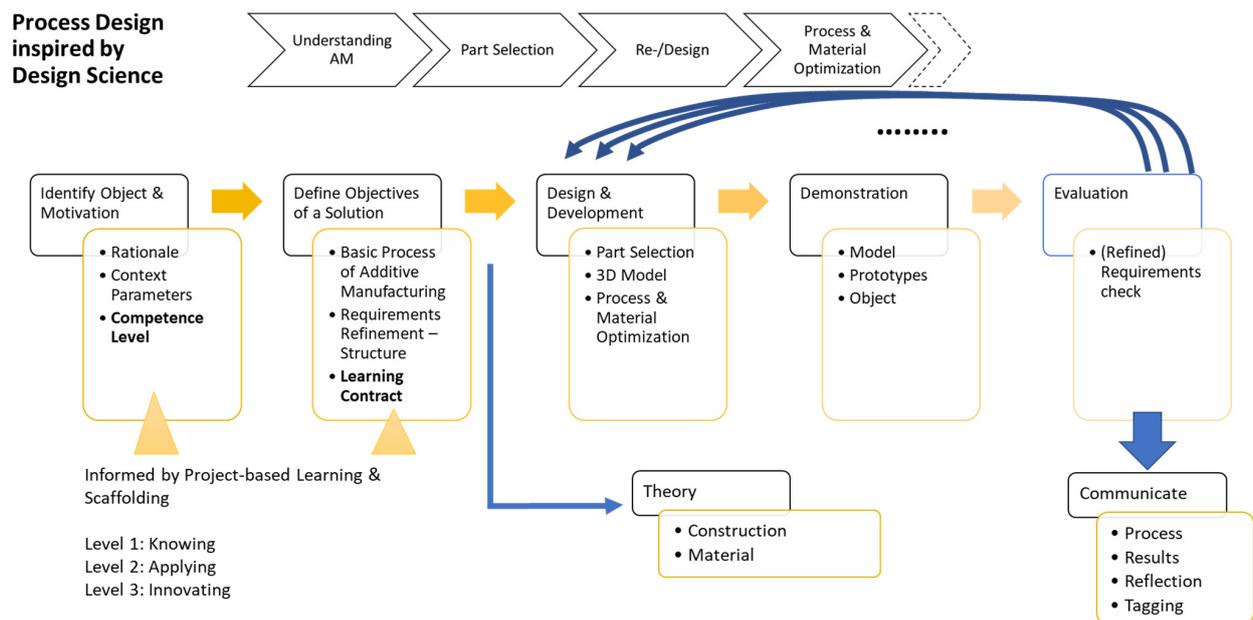


Figure 4. Process design inspired by Design Science.

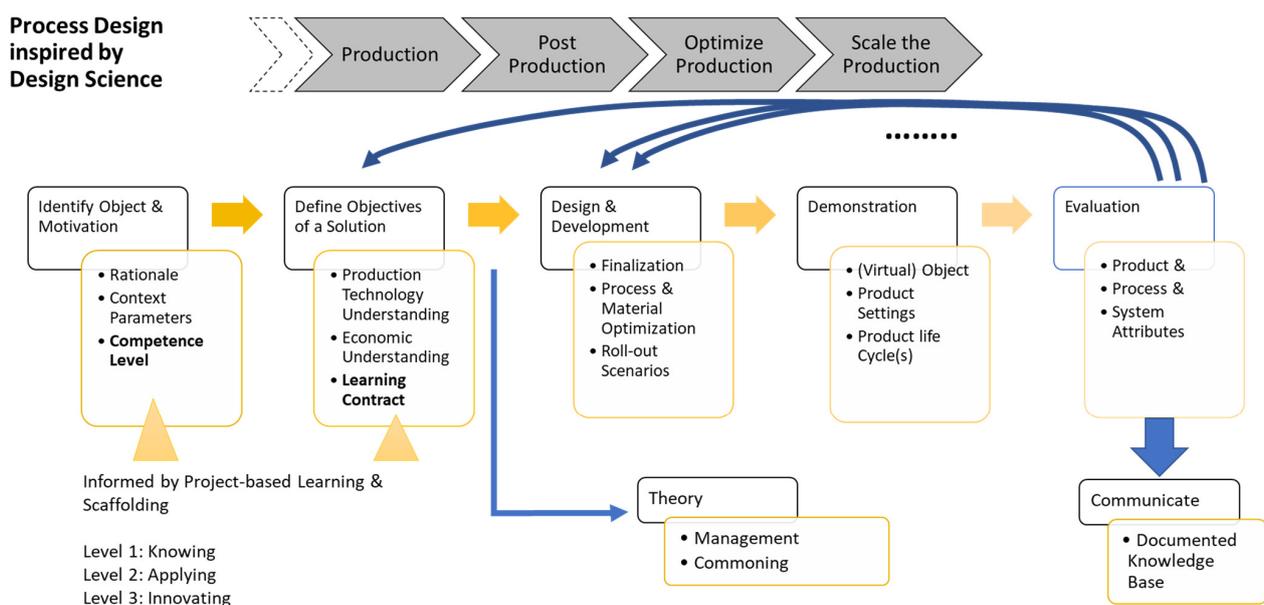


Figure 5. Framing post-production.

A learning contract is composed of:

- *Project organization*: Name of project, duration, face-to-face requirements, credits, contact, role(s) in the project, and relation to other project groups or projects.
- *Current level of competence*: 1—Knowing, 2—Applying, 3—Innovating.
- *Project objectives* including justification and desired competence level.
- Content-related activities referring to technical work (construction, material, production) and (re)search.

The design cycle activities within the project work:

- **Working with provided content**: Elaborating on the content that belongs to the project. This content is available to makers at any time in the course of their project, and thereafter for self-studies in the form of videos, multimedia documents, additional resources, and examples. Usually, content is studied in individual learning phases prior to interaction or attendance phases. It is prepared according to project-specific questions (to facilitators or peers) for effective knowledge creation.
- **Project Management**: In the course of their project work, all makers acquire competences in planning, calculation, execution, evaluation, and evaluation of projects.
- **Applying acquired content** in the context of project work. If support is needed, the facilitator or mentor and, where required, experts can be contacted in addition to peers. The learning contract provides a structure for evaluation and reflection, including the learning process, and thus, meta-cognitive aspects.

The project work can be accomplished in various forms:

- **Self-study**: Each learner acquaints him/herself with the relevant knowledge content for his or her concern. Content is prepared for capacity building as well as created by learners in the course of their project work. Due to the direct relation to the practical questions and the respective concrete research process, content is mainly recognized in its respective project context and can therefore be perceived sustainably.
- **Peer-to-peer setting**: The learners are part of communities they may organize themselves in order to plan and design the implementation of the projects collaboratively. The group affiliation, the bottom-up sense of community, and the responsibility of each individual for the success of the project work of the group is intended to increase the intrinsic motivation of individual learners and thus the efficiency and self-efficacy of the capacity-building process.
- **Face-to-face meeting**: Personal meetings of learners with mentors or facilitators are part of the capacity-building process. In particular, workshops help to digest self-paced content that is linked to practical project tasks.
- **Knowledge transfer phases**: Each project is documented in a shared memory, both from a process and results perspective. Both can contribute to future designs.

6. Field Study

In this section, we describe our first field study with the presented approach. The field study was conducted under the supervision of a Business Informatics lecturer as part of a class in practicing distributed systems engineering. We detail the setting, environment, and stages and report on the design cycles as experienced by the learners.

6.1. Setting

The study was conducted in a semester-long class for Business Informatics students in their third year. Six groups with two or three students were asked to extend their competences in AM and sensor technologies by visiting a regional makerspace. Fourteen students participated in the study, three of them female in one group, and the rest male in groups of two (with the exception of one group of three male students). The average age was around 23 years. The objectives of this class were to design and build an AM artifact including sensor technologies by applying previously learned knowledge and obtaining first hands-on experience.

The projects were designed for students to acquire their knowledge and produce their desired AM ideas in a self-organized way. After the initial first class, the students were invited to the makerspace to explore their options. Within two weeks, the student groups had to define their AM project idea and their learning contract. The teams were invited to present their ideas and learning contracts detailing the ideas in terms of project specifications in front of the class. To structure student work throughout the semester, the teacher organized three feedback discussions every three to four weeks, set at the end of every cycle. However, the exact work packages for every milestone/cycle were defined by the teams themselves. The teacher, acting as a mentor during the semester, reviewed each milestone at the specified feedback session to monitor learning progress. After concluding the three cycles, the student groups presented their completed projects and consolidated their documentation in the provided e-portfolio system.

6.2. Study Design

6.2.1. Environment

The regional makerspace provided several different AM technologies, which ranged from Fused Deposition Modeling to Selective Laser Sintering. The following 3D Printers were available to the students to explore: Ultimaker S5 and 3, Formlabs Form 2, Prusa MK3S, and Markforged Mark Two. Moreover, the makerspace provided a Lasercutter and CNC milling machine. Next to the machines, the makerspace offered a computer room to model objects and a community room for exchange.

6.2.2. Developing a Portfolio

Within the semester-long class, the students were asked to complete a portfolio realized by the open ePortfolio system Mahara (mahara.org, accessed on 18 January 2021), to document their learning process. Each team was provided with a portfolio space and journal to report on the progression of their competence development. The portfolio was structured into three parts: learning contract, portfolio, and learning diary.

Learning Contract

The learning contract, which is the basis for evaluation, was to be recorded in the first section of the portfolio. A predefined template helped the students to structure their contracts in the aforementioned areas (Figure 6). Before going into details about their projects, students had to describe their level of competence in the respective area. Furthermore, they had to define a goal of competence to reach within this semester. In the project description, students had to describe their idea and the theoretical and practical work they wanted to achieve during this semester. Moreover, the resources of the project had to be described, and milestones to structure their work through the semester had to be given. Afterwards, students had to describe what documentations they wanted to hand in with the respective purpose.

Portfolio

The second part of the portfolio (see also Figure 7) was the description of the project itself. Students were able to document their process, give necessary inputs about the technologies, and give insights in to their projects and competences. First, the students documented their theoretical findings about the technologies, materials, and examples, which helped to complete the second milestone with the first 3D models and prototypes. The 3D models and their findings helped to redesign their objects and produce their final objects as well as their documentations.

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Learning Contract

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Competency presentation

The competence presentation in this section is intended to describe the competence level of team members. The potential for a possible further development in the sense of limitations is to be derived from the competence presentation.

Example

All team members have experience in configuring various software systems to support collaborative work. However, experience in the configuration and application of such a system in the context of distributed software development has not yet been gained.

Guiding Questions

- **Which skills and competences do the individual members already contribute to the project?** (Separate presentation of the competencies of the members)
- **Where are the limits of the competences available in the team?** (Where do the individual members or the team want to develop into?)

Student 1:

School education

'deleted to preserve anonymity'

Especially my previous education is very important for this project. There I acquired the following competencies:

- Computer and network technology: developing computer systems for different application areas.
- Automation technology: developing and programming computer controls for industrial robots, assembly systems and dealing with PLCs.
- Telecommunications: selecting, programming and maintaining computer systems for call switching and billing.
- Audio and video technology: recording, storing, transmitting and reproducing sound and images at various system levels.
- Electronics: Handling and programming of microcontrollers (for example Raspberry, Arduino and C8051). Construction and calculation of electronic circuits, as well as troubleshooting and maintenance of these. Building test circuits on breadboard. Soldering of circuits in the high voltage as well as in the low voltage range.

Student 2:

School education

'deleted to preserve anonymity'

Knowledge that can be useful for this project I have acquired mostly in internships:

- Building and maintaining large IT systems
- Implementation of projects with the help of a Raspberry Pi for monitoring IT systems such as network load/storage capacity
- Implementing projects using a Raspberry Pi to provide multimedia support for trade show booths.
- Programming small applications to support business operations in personnel management and customer service

Limitations of the team:

No one brings the following necessary skills:

- Handling 3D printers
- Product design with plastic elements
- Basic knowledge in biology with regard to water consumption by plants.

How the team complements each other:

- Student 1 brings the experience in sensor technology and in building electronic circuits (soldering) to the project.

Published

✕ Unpublish
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Figure 6. Learning Contract example of Mahara (translated to English).

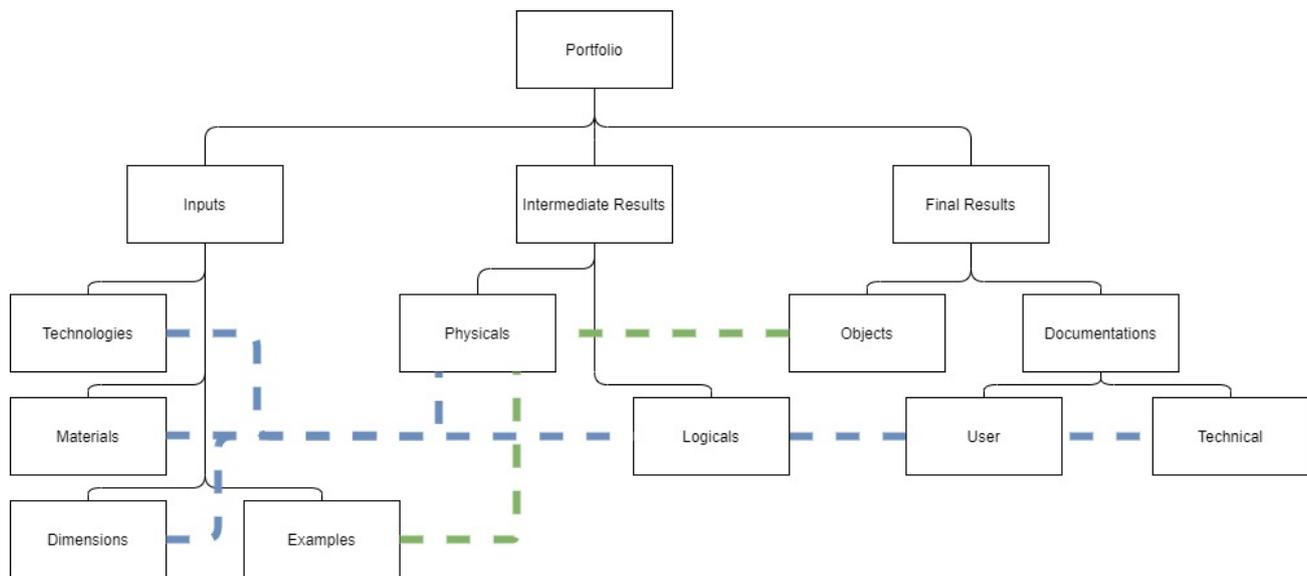


Figure 7. Portfolio structure.

Learning Diaries

The last part of the portfolio contained the learning diary. Based on the given guiding questions, the students were asked to complete an entry in their learning diary every time they worked on their project. The items were specifically designed for a project to be implemented in a makerspace and contained general questions about the specific work process and milestones, and specific items concerning the maker competence and the utilization of the makerspace facility (Figure 8).

Assessment

At the beginning of the semester, the assessment criteria for the class were given. The criteria were specified as follows:

- Learning contract: 10%.
- Initial presentation: 10%.
- Knowledge acquisition/theoretical underpinning (cycle 1): 10%.
- First and final prototypes/practical implementation (cycles 2 and 3): 60%.
- Active student participation: 10%.

The first assessment of the student groups' work was given after their finalized learning contracts and initial presentations. The aspects for grading of the learning contract contained the comprehensiveness of the idea, milestones, competence presentation, and the level of completeness. The assignment was judged according to their presentation skills and illustration of the learning contract. The cycles helped the teacher to assess the students during the semester. After cycle 1, the students were graded by their consolidated findings of their knowledge acquisition. After completing cycles 2 and 3, the practical implementation of the project was graded according to its applicability, implementation, and the learning path and competence enhancement of the students. After the final presentation of the students, their active participation during the semester was considered and graded.

6.3. Study Implementation

Stage 1: Identify Object and Motivation: Students were first introduced to the class objective to design and build a distributed system by combining AM and sensor technologies. The students were invited to join the regional makerspace to explore their options and identify their project ideas. The makerspace hosts gave a first overview of possible projects and introduced the available technologies and the respective parameters. The teams could

explore the makerspace and discuss their desired learning goals and the competencies they wanted to achieve. The project ideas had to contain a rationale, to further describe the need for and goal of the project. Furthermore, context parameters to design and build the object successfully were discussed with the hosts and teacher. In this stage, the students gained deeper knowledge about their competence level and developed first ideas about their project design.

The screenshot shows the Mahara Learning Diary interface. At the top is the Mahara logo and a search bar. Below is a navigation menu with a hamburger icon and the title "'s Journal". To the right of the title are buttons for '+ New entry' and 'Settings'. The main content area displays a journal entry titled 'Journal Entry: Milestone 2' with a 'Published' status and 'Unpublish' button. The entry contains several questions and answers related to a 3D printing project milestone.

Journal Entry: Milestone 2 Published

Posted on:
Last updated:

What was the goal of this meeting or individual work?
We wanted to start our first 3D Print with the first parameter.

What overarching goal/milestone does this meeting/individual work relate to?
Milestone 2

Which work steps were carried out in the period under review for the purposeful processing of the project?
We first installed all necessary programs on our laptops, to print all objects. Afterwards we received some training on the Prusa 3D Printer, to print independently without a host.

Did the individual team members process the work steps separately from each other? If so, which member made which contribution?
No.

What competencies did each team member want to improve through each step?
With this first print, we wanted to get to know the printer and the software better. The host helped to understand the different parameters of the printer and showed us how to insert the material.

How could an individual increase in competence be determined?
After initial struggle with the parameters, we were able to easily set up the printer and start the print on our own.

How could an individual increase in competency be determined?
We were able to achieve a better know-how about 3D printers.

Were any resources needed for this section of the project? Were materials such as videos, books, blogs, etc. used? For what purpose were these tools used?
Only the hosts were used, to better understand the 3D printer.

Which machines or rooms were used there?
Prusa 3D Printer

Figure 8. Learning Diary example of Mahara (translated to English).

The project ideas ranged in the area of application. Two student groups were interested in developing an intelligent watering system for a plant, where sensors help to identify the dryness of the soil. Another group wanted to explore sensors that collect data about the environment, such as temperature and density. Their aim was to integrate a 3D print by developing a weather resistant case for the sensors and a platform to show the collected data. A group of three students looked into a temperature stabilizing box for 3D printing materials, which can be attached to the 3D printer. Furthermore, they collected the data

on the temperature with a sensor. The last two groups looked into different 3D printing materials and scanned their durability with special sensors and collected the data on the performance.

Stage 2: Define Objectives of a Solution: After visiting the makerspace, students were asked to complete their learning contracts. These included questions about the project idea, competence level and desired goal, resources, milestones, and documentation. The teacher reviewed the contracts and improved them if inconsistencies were found. A crucial part of the learning contracts are the milestones. The first milestone required the students to obtain an understanding of used technologies, materials, and overall resources for AM. The second and third milestones determined the progress of developing the desired objects and served as a basis for assessment. When achieving a milestone, the teacher invited the students for a feedback discussion to review their work. Feedback was provided to them in a context sensitive way, i.e., referring to the project as structured in the learning contract. The structure of the project was defined by the students. Furthermore, the outcome of this stage was identifying a first concept and constructing ideas for the projects. After the learning contracts were approved and documented in mahara, the students were asked to work on their projects in a self-regulated way.

Before going into the first cycle, the students had to present their project ideas, including the learning contracts' crucial points: idea, competence level and desired goal, and milestones. Afterward, the presentations were graded by the demonstrated presentation skills as well as the level of completeness.

Cycle 1: Achieving Milestone 1: Knowledge acquisition

Stage 3: Design and Development: As mentioned before, the objective of this class was to design and build an object using AM and sensor technologies. Before modeling and printing, the teams had to familiarize themselves with the available technologies. The objective of milestone 1 was to acquire the required knowledge to manufacture their envisioned object in the project successfully. Therefore, students started to gain knowledge by using online sources, such as videos, tutorials, and various other information. Furthermore, students visited the makerspace and talked to the hosts about their design ideas. The outcome of this phase was the result of their search and various design choices and technology decisions.

Stage 4: Demonstration: Throughout the collection of information, some student groups decided to print certain types of object found online. They wanted to see the printing process and feel the material in order to decide whether the proposed AM approach was feasible for their own ideas. Furthermore, the students assembled their research in the respective part of their portfolios and documented their findings as well as their design choices and decision.

Stage 5: Evaluation: As mentioned before, the students discussed their conceptual part of the milestone and their technology decisions in the feedback discussion with the teacher. In the feedback sessions, the student groups could explain their accomplished work and show their acquired knowledge. The students were able to gain deeper knowledge in their area of interest and could more clearly explain their intended future work. The teacher, acting as a mentor in this stage, provided deeper insight into the subject, additional inputs, and feedback on project ideas when guidance was required. Afterward, students were asked to design and print their first prototypes entering the second cycle of the Design Science process. Furthermore, the preparation of the theoretical underpinning was graded by the teacher. Focus for grading has been the completeness of the findings with regard to the project idea, student understanding of relevant concepts, as well as their documentation in mahara.

Cycle 2: Achieving Milestone 2: First Prototypes

Stage 3: Design and Development: In the next cycle of their project, the students designed their first prototypes using a 3D modeling software. A few students acquired knowledge about the used program via Internet sources, while some decided to visit a workshop hosted by the regional makerspace. The workshop provided first modeling

guidelines and helped students to design their objects according to intended use. The makerspace also provided a room with computers and useful gadgets to facilitate modeling objects. Some groups used this facility and asked for help with their designs from the makerspace hosts.

Stage 4: Demonstration: After completing their first designs, students started to print their models. One group decided to print a miniature version to find out whether the applied parameters fulfilled the required structure and robustness criteria. The makerspace hosts helped the teams to prepare and correctly start the 3D printer and gave insights into the printing process and explained the various parameters for a successful print job. Moreover, some students completed a post-production process by clearing the objects of scaffolds and other residues. Furthermore, the students documented their process in the portfolio.

Stage 5: Evaluation: After the teams concluded their first print process, the objects were evaluated to ascertain whether they were operating as specified in the requirements. It appeared that some groups designed the holes for the sensors too small, or the printed box did not close at all. Another team decided to redesign their ideas so that the object could withstand different weather conditions. Consequently, all groups decided to redesign and reprint their objects according to their newly gained insights. The first prototypes were discussed in the feedback session with the teacher. Failures and success stories from the first trial were shared for redesigning. Teacher inputs helped the learners to proceed.

Cycle 3: Achieving Milestone 3: Final prototypes

Stage 3: Design and Development: In the preceding step, the students discovered that a redesign of their object was necessary. The gained knowledge was used to identify the flawed design parameters. The aforementioned holes for the sensors were enlarged, while some students completely redesigned their box to close it correctly. Some groups changed the infill of the objects to develop a more robust product. Furthermore, the students invested more time to think about the post-production process. One group rethought their material choice so that the product could withstand environmental influences. Other groups placed the object in the printer differently, to minimize the use of scaffolds and printing time.

Stage 4: Demonstration: After completing their redesigns, the students printed another prototype. Most of the students consulted the hosts again, to confirm the validity of their selected parameters. The printed objects were cleared again of residues and scaffolds.

Stage 5: Evaluation: After completing their latest print job, the students evaluated their prototypes with respect to the documented statements in the learning contracts. Some groups had changed their plan when completing the project, and thus had to document their learning path and the parameters they needed to change. In the feedback discussion, the students explained their modified processes, pitfalls, and success stories throughout the semester. By explaining the process during the semester, the teacher and the students gained a better understanding about their learning process. Feedback discussions and reviews about their accomplished work seemed to be an effective way to handle unpredicted scenarios, as the students learned to explain and communicate development processes that deviate from contracted plans. After completing the last cycle, the teacher graded the practical implementation, focusing on the applicability, implementation, and the learning path and competence enhancement of the students.

Final presentation and consolidation of results

After completing all cycles, the students were invited to present their completed projects. The presentations included their learning path, their perceived competence enhancement, and a demonstration of their final results. Furthermore, they had to consolidate their findings and results in mahara. Afterward, the teacher graded the overall active participation throughout the class and the semester.

Grades

By completing the last presentation, all assessments for grading the class were available. Out of 14 students, 12 obtained an A while only two students received a B in this

class. This deviation occurred because their overall active participation and presentation skills lacked commitment.

7. Results

The findings showed that all students, regardless of the kind of project they were working on, completed at least three cycles of the Design Science process. The cycles were derived from the milestones the students had to achieve. The initial two phases were preparation stages, whereas the other phases were part of completed design cycles. In reference to the AM stages as shown in Figure 2, students only went as far as the post-production phase. The goal was not to implement an optimized and scaled production, as these refer to industry projects.

It turned out that even though students had gained knowledge before working on their projects, they still needed help, e.g., from a host, an Internet source, or their mentor. The most common way to find information was searching the web and selecting videos or tutorials, whereas personal assistance was mostly provided by the makerspace hosts, who ensured proper print preparation and production for each team.

The students reported on a suboptimal use of the portfolio portion of the class. Whereas the learning contracts and diaries provided a structure, the portfolio section did not. The students were able to complete the learning contracts rather easily, whereas they lacked structure in the portfolio portion. Students were unclear what exactly to document and what to omit. Furthermore, the learning diaries, even though guiding questions were provided, were seen as additional work rather than a reflection on their learning process.

By reflecting on the gained knowledge and the competence levels, students confirmed that their level of competence in the field of AM has increased significantly. Some of the students decided to buy a 3D printer for personal use.

The Design Science approach seems to help students efficiently structure their AM tasks. The cycles helped the students to understand the different milestones and the required sub-goals before actually printing 3D objects. The approach to complete three cycles seems to be efficient with respect to the capacity-building process in the AM domain. The first cycle improves conceptual understanding and provides fundamental experience, while the subsequent cycles focus on the prototype itself. Hereby, the second cycle serves the purpose of a first trial producing the object, and the third enables production of a refined version of the object based on previous experiences.

8. Discussion

The study shows an increase of learner knowledge in Additive Manufacturing and a successful demonstration of the different Design Science cycles in terms of students structuring a project of their own and planning its development according to digital production needs and capabilities. Overall, the cooperation with the regional makerspace was sufficient for the student groups to complete their projects. With respect to the curriculum, students reported they had never experienced a class like this before. Moreover, the open concept was appreciated. The students were able to overcome difficulties that occurred when working on the project in a self-organized way. The approach also showed that students had fun and liked working on projects they had proposed individually. The groups were reflective about their competences, failures, and successes, and were able to transform experienced failures into knowledge gains in a self-regulated way.

The students were asked to hand-in a portfolio that included a learning contract, documentation about their project, and a learning diary about their work at the makerspace. None of the students were familiar with the concept of learning diaries when commencing work on the project. Therefore, input and work instructions had to be given. Moreover, students had to get acquainted with the software solution, which was not considered at first by the lecturer. Overall, the students were able to complete their portfolios and hand-in all required documentations. However, for future learning experiences, the goals of portfolio

work and learning diary entries need to be revisited to communicate better the intention of the respective tasks.

When coordinating with the makerspace team, details about the class setting and the requirements for learners had been laid out, discussed, and agreed upon. However, some makerspace hosts and employees were not sufficiently briefed. Consequently, some student groups experienced organizational difficulties when starting to work at the makerspace location. However, the hosts from the respective stations were helpful to the students and facilitated learning how to work with certain materials and how to handle 3D printing.

Overall, all objects could be printed and presented successfully. The feedback discussions with the lecturer seemed necessary in order to ensure that students were well informed of each project and to guide them toward further work, although the design cycles supported the planning and organization of the AM project work quite well.

The successful completion of the project and support of the makers allow us to generalize the findings in terms of proposing an integrated learning support framework. It targets empowering makers by aligning domain-specific value chains of making with educational facilitation. As shown in Figure 9, the design science approach serves as a link between the various support ingredients.

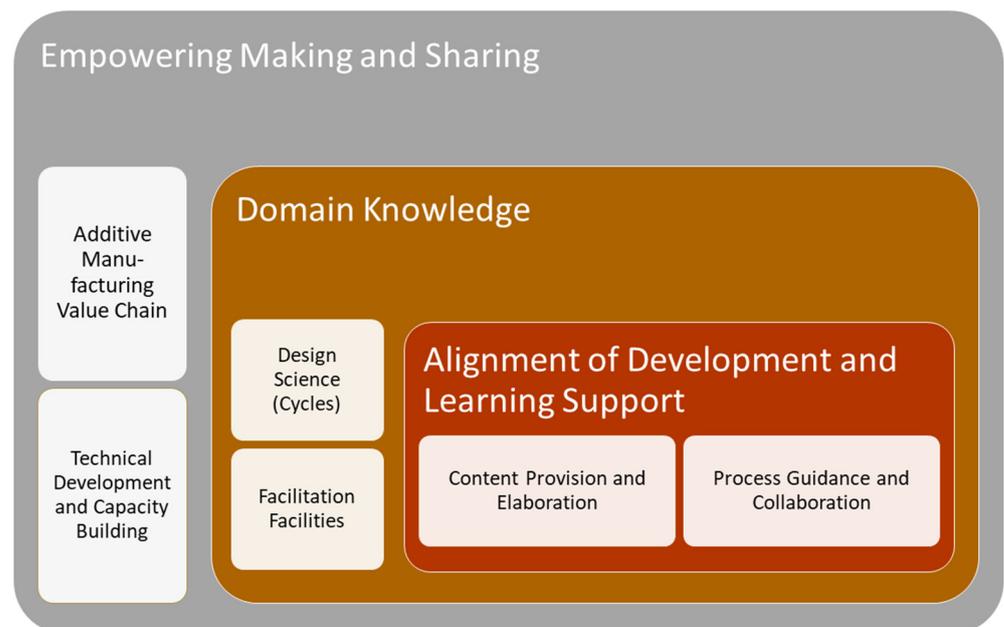


Figure 9. Empowerment of Makers: Aligning Technical Developments and Pedagogical Facilitation.

The framework consists of three interconnected layers, with the common ground driven by the educational objective of empowering making and sharing, in accordance with the maker movement's principles. Components are on the one hand domain-specific knowledge, such as the AM value chain, and the operational learning tasks. They are denoted technical development and capacity building, referring to development projects and learning activities. Both provide the frame for domain-specific design science processes including design cycles and learning support facilities.

The operational core of the framework resides on top of the two underlying layers and is characterized by the alignment of development and learning support. It coordinates content provision and elaboration with process guidance and collaboration. The latter includes sharing elaborated content and project results, according to the maker principles.

9. Conclusions

Since makerspaces penetrate learner settings of various kinds, collaborative learning scenarios increasingly focus on tangible construction activities. In this work, we started to reflect on structuring maker processes according to project designs for digital production in a self-organized while meta-cognitive way. We have reviewed respective learning support concepts and existing designs of makerspaces with respect to facilitating learner empowerment. Our didactic approach to project designs comprises fundamental activities required for learning management of concrete skill development as well as capacity building of learning-how-to-learn. We feature peer-to-peer idea articulation and probing of design and production in a “collaborative self-learning” setting. Based on a constructionist learning concept, we have framed project-based making by Design Science cycles. This considers capacity building as a bootstrapping process for economically viable production in a self-organized and meta-cognitively reflected way.

The reported field study confirmed the feasibility and effectiveness of Design Science-based learning cycles since learners could experience accurate feedback along their path to finishing their individual projects successfully. Based on the generalization of findings leading to a three-layered framework for aligned development and capacity-building support, further empirical studies will be set up and designed to identify further learning support needs and evaluate corresponding adaptation features.

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