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Sormunen, Kati

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9 Designing and Structuring the Invention Process

Kati Sormunen, Kaiju Kangas, Tiina Korhonen, and Pirita Seitamaa-Hakkarainen

Introduction

Implementing an invention project at school and intertwining it with transdisciplinary curriculum contents can be challenging and require much effort from the teachers. Further, many Nordic countries have revised their K–12 curricula for education to provide knowledge that reflects current and future society. It has raised a question of how to develop the professionalism of the teachers and the student teachers to address new needs of curriculum change and digital competencies (Kjällander et al., 2018). Especially when implementation of new fabrication technologies in formal school settings is in its initial stages, maker projects have not yet built up to the clearly defined best practices.

The teacher has a crucial role in developing students' creative and innovative qualities and habits by engaging them in participating in the sociocultural world through authentic making activities (Härkki et al., 2021). Invention projects are not based on a distinct subject but on skills that can be integrated into many disciplines. The meaning of the invention projects is built on transdisciplinary and engaging learning activities, but the implementation of these projects needs careful planning, designing, scaffolding, and support. The challenges are related to the transdisciplinary nature of nonlinear invention projects, new curriculum changes, projects' structures, and teachers' collaboration. The challenges include teachers' competencies in teaching new digital tools and how fabrication technologies are introduced into existing school environments. Also, teachers might not have personal experience with these novel ways of learning.

Previous studies have revealed that teachers need pedagogical support for practical examples, models, and structures to design and conduct meaningful maker projects (Andersen & Pitkänen, 2019; Smith et al., 2016). In our research projects, we have worked closely with teachers in the field and organized workshops aimed at developing teaching practices by modeling invention project phases, supporting teachers' digital competencies to implement invention projects in their schools, and getting familiar with pedagogical practices of team teaching (Härkki et al., 2021; see also Chapter 11 of this book). Similarly, the teacher education program addresses the same needs. The invention projects challenge student teachers' existing competencies, and there is a need for a framework that considers how invention projects need to be designed and what significant components and phases they

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should consist of to be appealing to various kinds of learners. In several workshops and courses in the teacher education program, we have introduced design principles and models for nonlinear learning projects complying with the National Core Curriculum for Basic Education (Finnish National Agency of Education [FNAE], 2016) policies and providing practical training for relevant digital technologies such as e-textile, programming, and robotics. A fundamental principle has been to engage and empower teachers and student teachers to innovate invention projects rather than to implement them directly (Andersen & Pitkänen, 2019; Kjällander et al., 2018). In this chapter, the invention pedagogy process model is based on research-based models of project-based engineering and learning by collaborative design (LCD). As a practical example of professional development of teaching new pedagogies, since 2016 we have been using the invention pedagogy course organized annually for master's-level teacher education students.

Pedagogical Processes for Invention

In an invention project, the work is guided by an open problem, which becomes more precise as the solution develops. Students work actively together toward a common object. The intermediate stages of the process (ideas) and the final output (the solution) are modeled with different artifacts. Perceiving the holistic view of the invention process helps both teachers plan activities and students in their work. It also enables teachers to facilitate, mentor, and supervise students' collaborative learning process (Jenkins et al., 2003; Stamovlasis et al., 2006). The invention projects are often longitudinal and can last from a few months to an academic year to provide enough opportunities to develop and experiment with common ideas through several iterative invention cycles. The first invention projects are often shorter experiments in which the skills needed to invent are practiced, and they can be implemented by organizing a one-week invention week. Such short experiments allow the teacher to experiment with structures that support students' active participation and for students to perceive how the project is progressing and learn what is expected of them. Learning can be supported by various participatory models and methods that highlight the steps of a nonlinear process typical of an invention process. Models are helpful, especially in project design, even if the invention process does not proceed linearly from start to finish in stages.

Several models and methods are suitable for the pedagogy of invention in which the student is an active actor (e.g., Krajcik & Shin, 2019; Schwarz et al., 2016; Seitamaa-Hakkarainen et al., 2010). At its simplest, an inventing process can be encapsulated into three steps: think, make, and improve (Martinez & Stager, 2019). Martinez and Stager (2019) based the process on the "learning by making" concept, in which making stands for working with tools and materials; tinkering for a playful mindset with problem-solving, experimentation, and discovery; and engineering for the "application of scientific principles to design, build, and invent" (Martinez & Stager, 2019). However, relying on learning sciences research, we argue that students also need to learn how to construct their understandings actively, make connections between disciplines, and apply them by working with and using ideas in real-world contexts (Sawyer, 2019). To this end, the teacher and the student need more detailed process phases, especially in early experiments, to identify related disciplinary practices and orient their work in the direction of an open-ended problem. Since the invention projects often emphasize science and craft and technology education, we have framed the pedagogical process of inventing on the project-based learning (PBL) that connects scientific and engineering practices as well as the LCD model in which knowledge creation is enrichened with design practices (Figure 9.1). Although created in different disciplinary contexts, the selected process models are close.

The Project-Based Engineering Process

The PBL is widely used globally and is also applied in Finnish science education (Sormunen et al., 2020) and various STEM or STEAM projects. PBL has its roots in Dewey's (1959) idea of real-world problems capturing students' interest and provoking serious thinking as the students acquire and apply new knowledge in a problem-solving context. Learning scholars (e.g., Krajcik & Shin, 2019) have refined Dewey's original idea that active inquiry produces deep learning. PBL is based on an active construction of knowledge by participating in real-world activities, experiencing phenomena in various scientific practices, constructing shared understanding in collaboration with teachers, students, and community members, and using cognitive tools to support students' problem-solving skills.

Figure 9.1 depicts the project-based engineering process, which emphasizes the engineering practices that are essential in solving real-world problems and creating artifacts. It is cultivated from the PBL process moving through overlapping phases (Krajcik & Shin, 2019). The process is initiated by asking and refining questions, but when the emphasis is on designing and engineering, the process begins with identifying a problem, which can direct learning in numerous directions (Krajcik & Delen, 2017; Krajcik & Shin, 2019). However, emerging real-world questions and teacher-set learning goals guided the project throughout the process: Students search for solutions in collaboration with their peers by designing and conducting investigations and gathering, analyzing, and interpreting information and data. Students are scaffolded with learning technologies to solve emerging problems during the inquiry process and to help them move beyond the information gathered toward a tangible artifact. Students' learning is visible by creating shared artifacts and reporting on the process. During the project-based engineering process, they learn about and apply scientific concepts, principles, and practices, much like in the complex social situations of expert problem-solving (Krajcik & Shin, 2019). Many methods and models focus on engaging students in design to learn science, but we claim that design as its own discipline has its own design practices that need to be emphasized, such as the role of external constraints and various mediums for external representations.

The Learning by Collaborative Design Model

Previously, we have developed the LCD model to facilitate design processes and students' design thinking (Seitamaa-Hakkarainen et al., 2010). Theoretically, the

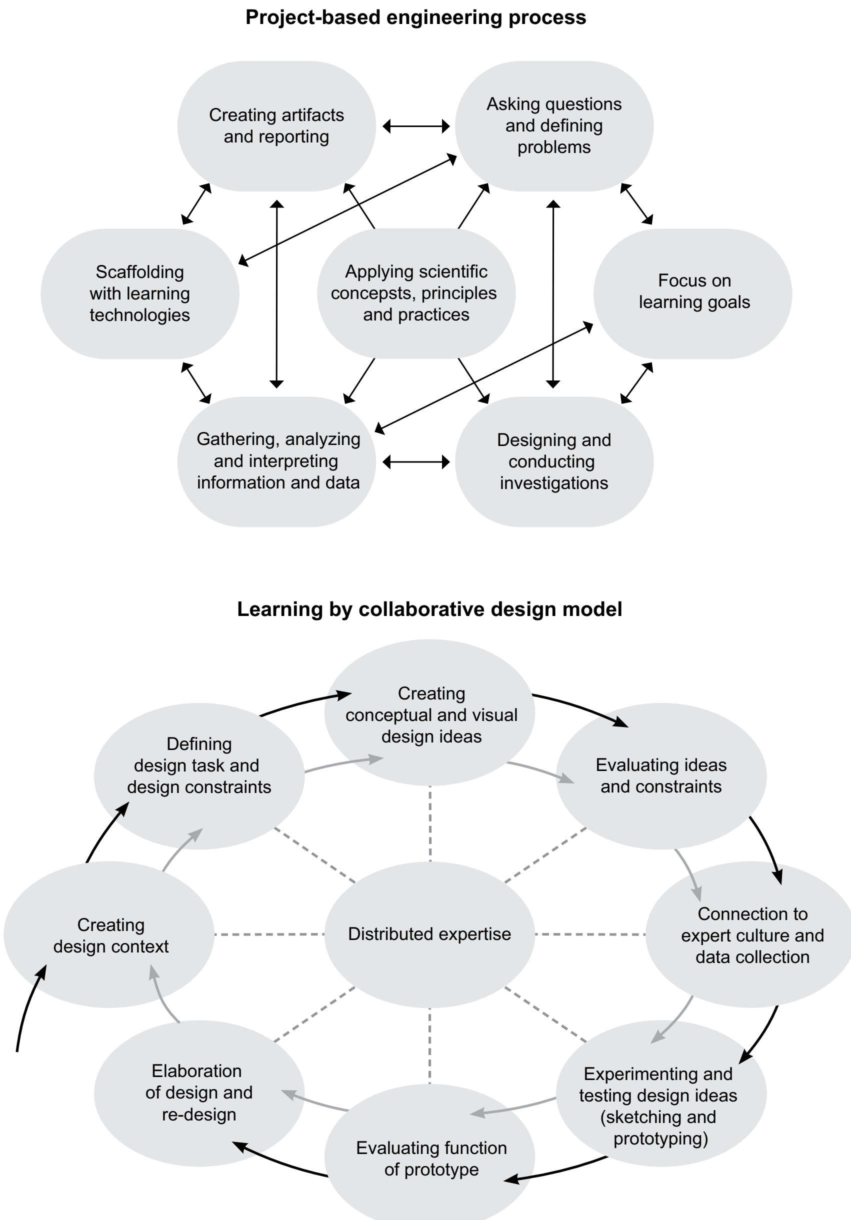


Figure 9.1 The project-based engineering process modified from Krajcik and Delen (2017) and Krajcik and Shin (2019), and the LCD model modified from Seitamaa-Hakkarainen et al. (2010).

LCD model is based on academic concepts of progressive inquiry and design thinking (Cross, 2011). According to Cross (2011), design thinking can be seen as a designer-like way of knowing: designers need to have the capability to define, redefine, and change a given problem situation through design activities. In the design process, problems and solutions co-evolve, and designers problem-solve in solution-focused tackling of ill-defined design challenges (Cross, 2011). Within the LCD model, the design integrates thoughts and actions, and designers navigate complex and messy design situations through iterative reflection-in-action and the creation of various external representations and material prototypes. The aim of the LCD model is to engage the students in collaboration toward an explorative and iterative design process to generate knowledge through making (Seitamaa-Hakkarainen et al., 2010). Thus, the LCD model emphasizes the socio-material aspects of designing: how conceptual design ideas are cyclically developed through various visual sketches, mock-ups, and prototypes toward final artifacts. The model describes the design process as a spiral in nature by approaching the optimal design iteratively through successive design cycles. In the LCD model, a starting point is an idea in which all participants are working to develop the shared design object by sharing their expertise socially. The model emphasizes that collaboration should occur at all stages of the design process by creating shared design contexts, analyzing design constraints, collecting, and sharing new knowledge, prototyping, and providing feedback for the artifacts being designed. The question is not simply to divide labor between various parts of the overall design project, but the whole design team has a central role in this activity.

The LCD process starts with all participants performing a joint analysis of the design task and design context. They must analyze the design constraints (i.e., external requirements). Various, sometimes conflicting, factors that affect the design process and define its requirements must be considered when framing the design context. The design constraints form the design context by defining the intended users and their unique needs for the artifact, the function of the artifact, and the resources available. The efforts of the participants are organized toward developing shared design ideas (conceptual artifacts), embodying and explaining those ideas in visual sketches (graphic artifacts or inscriptions), and giving the ideas a material form as prototypes or results (e.g., produced products). The design process appears mediated by the shared artifacts being designed from the beginning to the end. Thus, constant cycles of idea generation and testing of design ideas by visual modeling or prototyping characterize the design process.

The Invention Pedagogy Process Model

Both previously presented models have been the backbone when we developed our invention pedagogy process model. Both project-based engineering and LCD models are well known in Finland, and we have introduced them in our workshops for teachers in the field and teacher education courses. Both models view the complete science or design process as involving several phases. The invention pedagogy process model has been developed in research-practice collaboration since 2015. Through over 50 invention projects organized in early childhood and school settings, we have found that the classes benefit from a well-structured and designed project plan and a visual process model that structure students' open-ended, nonlinear creative processes. Nonlinear learning does not mean aimless and unrestricted activities, but the process requires clear planning and structuring. Based on participants' experiences and research findings, we have designed, tested, refined, and developed the invention pedagogy process model (Figure 9.2), which follows a seven-phase path: (1) orientation to the topic and work; (2) defining the invention challenge; (3) brainstorming, information gathering, and evaluation of ideas; (4) testing and developing the chosen idea; (5) evaluation and approval of the plan; (6) modification, implementation, and fabrication of the artifact; and (7) presentation and evaluation of the work. Understanding the holistic invention process helps teachers and students to work.

Careful planning is essential in the implementation of invention projects. A project's planning considers the various phases of the process. It ensures that some of the tools, materials, and content used during the process and the skills required are already familiar to the students. These cannot be entirely determined in advance, but the teacher can ensure that students are not overburdened with new content and skills to be learned in the assignment. When planning invention projects, it is worth considering the boundary conditions of the project, which are based on the skills of the participating students and the available resources. The larger the project is, the more it requires teachers' well-designed orchestration. It is worth outlining the project schedule and phases when planning a project. The plan is unlikely to materialize as expected, but it will help teachers and students to understand the use of time and the extent of the output to be implemented. In addition, it is necessary to consider how to involve students in the planning of the project. Preplanning also

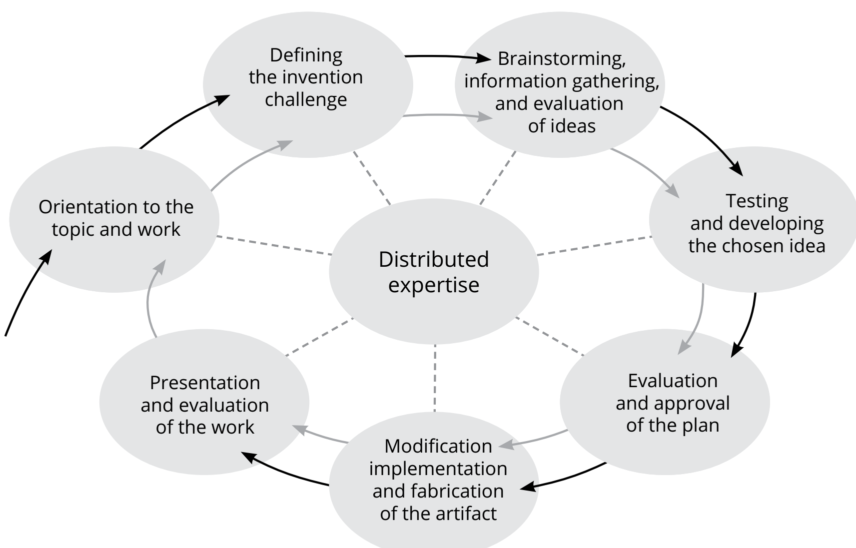


Figure 9.2 The invention pedagogy process model

helps to assess whether students have the skills to use the tools needed to work. These issues are discussed further in the next chapter (see Chapter 10 of this book).

Case: Invention Pedagogy in Teacher Education Course

This case example illustrates how the implementation of the invention pedagogy process model was taught to teacher education students. Teacher education has a crucial role in supporting teachers' learning of new knowledge and competencies that they may not have learned in their initial days (Lavonen, 2021). Therefore, it is essential to connect novel development and research findings like designing and structuring the invention process to the teacher education program. In Finland, the high quality of education is based on university-level teacher education, equipping teachers with deep and broad research-based professional knowledge and skills (Lavonen, 2021). When entering the field, they have the competencies to phase practical challenges, apply research-based knowledge about teaching and learning, and develop their expertise further (Lavonen, 2021).

Invention Pedagogy Course Design

The invention pedagogy course (five credit points, optional studies) was organized at the University of Helsinki for master's level teacher education students following the principles of research-based teacher education. The objectives of the course were to become acquainted with the pedagogical aspects and components of invention pedagogy, become familiar with research and practices in the field, and plan and implement transdisciplinary and phenomenon-based teaching that utilizes pedagogical approaches to maker and design education. The main goal was that after completing the course, the student teachers could design, apply, and develop learning entities that support creative invention.

The course design began with an orientation lecture (1.5 hours) on the theoretical basis of invention and maker pedagogy and two three-hour sessions during which student teachers learned technology orientations of inventing. After these orientation sessions, the students participated in the invention pedagogy workshop, including four three-hour sessions that followed the invention pedagogy process model. Student teachers kept a learning diary during the course and an invention process portfolio during the invention process sessions. In both, they mirrored their experiences with national and international articles.

The rationale was that teachers or student teachers have rarely been involved in nonlinear and open-ended design projects addressing real-life contexts and lack the experience to manage such processes (Andersen & Pitkänen, 2019; Smith et al., 2016). Further, within short technology sessions, we guaranteed that they have some understanding of digital tools and materials to work while inventing. Further, by the invention pedagogy process model structure, we can demonstrate and provide student teachers with their own experiences from a learner's perspective. We have used a similar approach with similar content in all our workshops for teachers in the field. In the following, we present the invention pedagogy process model through these course sessions, enriching them with examples from course implementation and teacher-student portfolio entries.

The Phases of the Invention Pedagogy Process

The actual invention process was introduced to the student teachers in the fourth session, in which they participated in the teacher-led process. To design the structure of the invention process, the teacher educator used research-based good practices gained from several co-invention research projects conducted at schools.

Orientation to the Topic and Work

The invention process begins with an orientation phase in which group work is set up. The creative process requires a creative atmosphere (Fisher, 2014) in which group members encourage and support each other, so it is worth doing exercises that help grouping for the first few times.

> *Orientation to Work and Building Team Spirit.* The invention pedagogy workshop began with a group exercise aimed at building team spirit and tracing and making visible the knowledge and skills of the group. The teacher had prepared a list of words that described the strengths and skills needed during the project. First, the student teachers chose three to five words that represented them. Then we grouped them into teams of four, and each student presented their strengths and skills to the other group members. The team's final task was to visualize their group's strengths using the word cloud or graphic design tools.
>
> *Orientation to the Topic.* Before the workshop, the student teachers had to do an orientation task to envision the future (Perttula & Sääskilahti, 2004). The assignment was as follows: "You travel in time, first, five years, then 50 and 100 years onwards. You are standing in a place where the kitchen of a Finnish home was in 2021. Fill in the worksheet: What do you see around you when you look at (1) the kitchen as a space, (2) the person in the kitchen, and (3) the technology?" The student teachers discussed their envisioning in their teams and gathered a common vision using Google Jamboard.

Defining the Invention Challenge

After orientation, an invention challenge is determined, and the teams set out to find a solution. The form of the challenge and design constraints (Cross, 2011) has a vital role for students: It should be challenging enough to engage in problem-solving but not too hard for them to follow the challenge independently. When implementing an invention project for the first time, starting with a limited topic is recommended. It is also necessary to plan the goal of content and skills pursued in learning.

> *The invention challenge* was introduced to student teachers using a recent newspaper article about how stress negatively influences people's eating habits. Student teachers defined the concept of eating habits so that everyone had an understanding of the subject and listed lousy eating habits on sticky notes.

> The goal was to bring together as many perspectives as possible for the next phase. Finally, the teacher educator introduced the actual invention challenge: "How will unhealthy eating habits affect humankind if we ignore our habits?" The teacher educator used a picture of morbidly obese humans from the Wall-E movie to evoke thoughts.

Brainstorming, Information Gathering, and Evaluation of Ideas

At the beginning of the brainstorming phase, students throw in ideas, i.e., they try to produce as many crazy and playful ideas as possible. In this phase, it is worth utilizing various ideation methods and encouraging students to familiarize themselves with previous applications of the research subject (see Chapter 5 of this book). Information gathering provides new perspectives on ideation. At this stage, students try to delineate the problem by evaluating the ideas produced and considering the boundaries set by the teacher for the invention challenge. These can include the tools or materials available or the conditions set by the teacher in relation to the teaching objectives.

> *The brainstorming session* began with the automation and robotics ideation connected to the visions of the future kitchen from the previous phase. The teacher educator reviewed the most common sensors (e.g., temperature sensor, motion sensor, light sensor, and touch sensor), and the student teachers became familiar with the operating principles of the sensors. Then a distant model ideation method was used, and the teams tried to find inspiration for the design problem using distance domains. In this case, the teams looked at the analogies using the Wall-E robot and its features and properties.
>
> 1. *A distance model*: In the first stage, the teams produced at least five qualities from the image of a distant model (e.g., expressive, compassionate, able to stretch the "hand").
> 2. *An "insanely fun" idea*: In the second stage, the team produced five insanely fun apps based on their features (e.g., a human-like product that looks nice, makes good choices, and jokes quite often. It can pick up stuff with telescopic hands and tell jokes when it brings food).
> 3. *A plausible solution*: In the third phase, the teams develop one workable solution (e.g., a Miracle Machine, which makes the day's meals and encourages good eating habits). The plausible solution had to fulfill one condition: The object of the invention had to be a product from which teams could build a prototype by using the skills acquired.

Testing and Developing the Chosen Idea

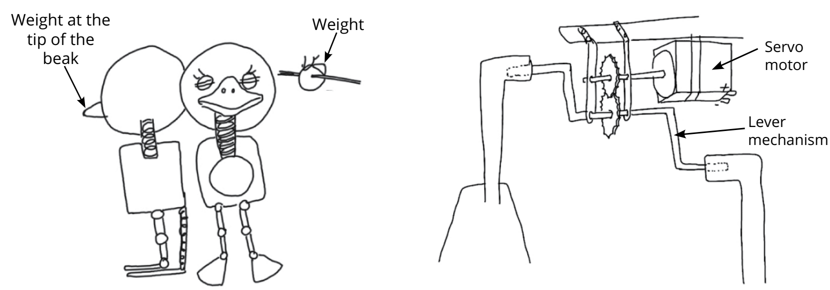
When the team has defined the problem, they evaluate ideas further by experimenting, testing, and redefining ideas. They may have one or more ideas before the group decides on the final subject of the invention.

> The student teachers had to make a design plan for the invention and a prototype to test and develop the idea. The design plan must include a sketch or blueprint and a description of the invention's functions. The teams also had to plan how they would utilize the technology in the product and what materials they would use to make it. Student teachers were encouraged to share tasks (e.g., programmer, designer, and prototype builder). Also, the teacher educator introduced the student teachers to the materials that were available for making the prototype. At this point, the educator also connected the content of technology education from the curriculum as conditions. Student teachers were required to use at least one of the technology dimensions learned in their work (e.g., 3D modeling, electronic and maker kits, simple machines, electricity, or app development software). Figure 9.3 illustrates one student teacher team's invention idea, the Empathetic Reminder, with excerpts from one team member's portfolio entries.

It is worth including digital tools the students are familiar with in the invention project. Otherwise, a large portion of the time is spent learning the basic use of the device. When students are already familiar with the tools, materials, contents, and skills required, they can deepen their knowledge or create something new. Teachers can also include some new elements, but it is necessary to consider what is being practiced or learned and what aspects are to be deepened when drawing up learning objectives. Especially when working with new technology, students benefit from a one-hour introduction to the tool. For example, if the learning objectives involve the creative use of a programmable device, the teacher should carefully teach the students the basic use of the device. As work methods and tools become familiar, it is natural for teachers to expand on the topics and guide the work.

The Empathetic Reminder

The Empathetic reminder blinks the lights and makes funny moves. It reminds me to eat every three hours. The device also talks to other kitchen equipment. For example, it makes food in the future kitchen, that is, fries worms.



Idea sketch: We could make the mock-up with Tinkercad and 3D print it. At school, each student could customize the product's look and think about how to make it move.

Technical drawing: We could mimic walking with a servo motor. It could also dance or shake. We could play Stayin' Alive in the background. This silly and funny reminder gets you in a good mood.

Figure 9.3 A student teacher team's idea sketch and technical drawing of their invention idea.

Evaluation and Approval of the Plan

Students present their idea to other students in a class or experts during the evaluation phase and receive feedback. Based on the feedback, the teams refine the plan of the object of the invention. They also collectively accept the final artifact to be implemented.

> Student teachers presented the plan and prototype of their invention idea to others whom the teacher educator asked to give one piece of positive feedback and one development proposal. Positive feedback was intended to help teams identify workable solutions, while development suggestions helped teams develop their inventions.

The peer feedback given and received during the invention project helps students understand their studying (process) and learning (outcome) and identify their skills and areas in which skills were not yet sufficient. Students also learn to correct their mistakes and develop their work to achieve the goals set for competence and learning. Giving and evaluating feedback can be done verbally or in writing.

Modification, Implementation, and Fabrication of the Artifact

The team makes prototypes, models, or products based on their ideas and plans. These artifacts can be business models, various presentations, or hand-touch products. The value of the models and intermediate outputs is that they make it possible to look at the solution from a new and different perspective. It makes it easier for students to detect the solution's functionality or the need for further development. Often, the invention process does not proceed linearly from start to finish in stages. Especially at this stage of implementation, it can be noticed if the chosen solution does not work, in which case it can be revisited to come up with new solutions and/or modify the plan.

> When working with groups of students, teams would typically set out at this stage to further develop their inventions based on peer feedback. However, because the aim of the invention pedagogy course is to apply the invention pedagogy at schools, the student teachers set out to work on an invention process plan for students, basing it on their own invention process experience. The task was to produce a project plan in groups and a related prototype (i.e., a model of the final output). The student teachers received support materials for planning, e.g., project guidance, project topic selection, student-level brainstorming, planning, design, and technology use. The materials included both literature and inspiration videos or pictures. The student teachers made their project plans on a template, which guided them (e.g., setting goals).
>
> The course ended with an invention fair in which students presented their plans and prototypes to others. One student teacher group elaborated their innovation idea, the Empathetic Reminder further (Figure 9.3), by developing an invention project titled Everyday Eco-machine for fifth and sixth graders.

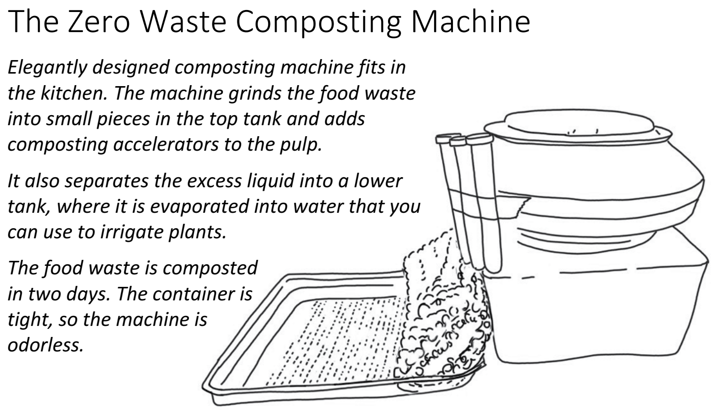


Figure 9.4 The prototype of sixth graders' invention solution: The zero waste composting machine.

> "The idea is that student teams design the future machine that can solve food and environmental challenges. The machine prototype is built from recycled materials. In addition, one or more functions or features are modeled on the prototype on the Adafruit Circuit Playground. A portfolio is compiled of the stages of the work. Finally, teams will present the inventions at the Invention Fair."
>
> (Student teacher's portfolio entry)

The teacher-student team's invention solution for the project is presented in Figure 9.4. Pictured is a drawing of artifacts made from students' recycled materials and an excerpt from one team member's portfolio entry.

An invention fair is an event at which students present the invention and its phases to the audience and receive feedback on their work. The audience can consist of other students in the class or school, parents, experts, or teams from other schools in bigger invention fairs. Before the fair, student teams plan the presentation, prepare an inspiring presentation, and practice presenting it. The invention process portfolio helps teams in this process. The invention fair can be held either during or at the end of an invention project. When the fair is held during the project, the presentation will focus on presenting the prototype of the invention. At the end of the project, student teams will present both the process and the finished inventions at the fair. The fair also provides a natural endpoint for the project.

Conclusion

The education of future creators and inventors emphasizes open-ended learning tasks in which students apply learned knowledge and skills to learn more in collaboration with their peers. The teacher's most important responsibility in these learning projects is to realize transdisciplinary learning. The goal is that no subject alone guides the learning process, but they are seamlessly combined into a holistic unit that is strongly connected to the real world. Often, transdisciplinary learning projects are driven by a pedagogical model developed in the context of a single subject or discipline. However, our goal has been to create a pedagogical model that supports the learning of today and the future in which activities that disrupt subject boundaries are possible. This chapter introduced the invention pedagogy process model based on the project-based engineering process and LCD models highlighting knowledge creation, science, engineering, and design practices. The end goal is to support the teacher and student teachers in designing pedagogically meaningful learning activities and engaging and getting the first experience of an explorative and open-ended process.

According to Smith et al. (2016), teachers have insufficient understanding of complex design processes and awareness of digital technologies and tools, and consequently, they experience a loss of authority and control of the teaching (Andersen & Pitkänen 2019; Härkki et al., 2021). We have developed a model of transdisciplinary cooperation in which the disciplines provide an inspiring context. The invention process model makes it easy for the teacher to lead the learning process in the classroom and provides the possibility to change traditional teaching methods in the school. When organizing workshops and courses related to invention pedagogy, we have aimed to empower teachers and student teachers to increase their understanding of invention pedagogy and related technologies in a way that strengthens their capability to try and take control of unfamiliar and unexpected aspects of the design process and to feel more confident applying it in their teaching. Also, the research-practice partnership (Coburn & Penuel, 2016) has allowed us to involve more teacher practitioners that were initially unfamiliar with the maker technologies and principles of nonlinear invention pedagogy. This opportunity has made it possible to support teachers during the invention projects we have initiated together.

It is self-evident that there are plenty of other design or maker-centered learning process models, such as design thinking (IDEO), that emphasize participatory and emphatic designing with users (see Chapter 5 of this book). We strongly encourage teachers and student teachers to familiarize themselves with these models and learn to find suitable tools to apply in their invention projects. Similarly, we support the teachers and student teachers in using various design materials and technologies in the design process.

Guiding open-ended learning assignments is often challenging for teachers, especially if they are leading the project for the first time. Although the invention challenge should be connected to the curriculum, at the same time, students should be given opportunities to work in the direction of their vision. A range of pedagogical models facilitate the teacher's designing and orchestration of work and help to anticipate challenges that students might encounter. Especially for teachers guiding a nonlinear learning process for the first time, the model helps outline the learning entity. For this reason, student teachers must gain firsthand experience with open-curricular learning tasks and nonlinear learning processes in teacher education.

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