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Pedagogical infrastructures in multidisciplinary technology education

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Abstract

In multidisciplinary technology education, teachers work together to support pupils in designing with technology. The different forms of support are based on establishing pedagogical infrastructures for pupils' learning of technology. Although previous studies have identified the main forms of pedagogical infrastructure, how they can be leveraged in collaborative technology education remains elusive. This study adopts the perspective of teaching teams in exploring the kinds of pedagogical infrastructures involved in the collaborative planning and implementation of support for learning by collaborative designing (LCD). The data consist of semi-structured interviews with 11 technology education teaching teams. The participants were 21 experienced in-service teachers who worked in primary, secondary, and general upper secondary schools. A multiple case study approach was applied to identify the differences between the teaching teams in the planning and implementation phases. The data were analyzed following the principles of qualitative content analysis. The findings revealed that the application of pedagogical infrastructures varied during the teaching teams' process of collaboration. In the planning phase, support was mainly based on establishing material-technological infrastructures. In the implementation phase, teachers often leveraged scaffolding and epistemological infrastructures. Pedagogical infrastructures were mostly targeted for the early stages of the LCD process, as well as in the stage of experimenting and testing design ideas.

Keywords Technology education · Interdisciplinary approach · Pedagogical infrastructures · Learning by collaborative designing

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Introduction

The value of teacher collaboration in innovating new pedagogical solutions has been widely acknowledged (Vangrieken et al., 2015). Continuous development of pedagogical solutions is deemed especially important in the context of technology education, the status of which remains inconsistent in many countries' curricula (de Vries, 2018). Previous studies have revealed many variations in teachers' expertise (Fahrman et al., 2019), confidence (Jones et al., 2021), and self-efficacy (Nordlöf et al., 2019) related to technology education. Further, teachers have various levels of previous experience in organizing a design process (Antink-Meyer & Meyer, 2016), which is at the core of technology education (Haupt, 2018). Less experienced teachers often struggle to support coherent learning experiences, thus leaving different classroom activities separate and unconnected (Lakkala & Ilomäki, 2015). Collaboration between teachers can balance out individual differences in their expertise (see, e.g., Kafyulilo et al., 2016), thus improving the quality of support for learning.

When designing with technology, pupils learn to develop novel solutions to open-ended problems (Kangas & Seitamaa-Hakkarainen, 2018). Such learning may be conceptualized with the model of learning by collaborative designing (LCD) (Seitamaa-Hakkarainen et al., 2010). The LCD model is applicable in technology education because of its specific focus on learning and knowledge creation by designing and constructing (Kangas & Seitamaa-Hakkarainen, 2018). The model describes an iterative design process in which pupils collaborate to advance their design ideas and artifacts, including sketches and prototypes. To learn from the design process, pupils need support from teachers (e.g., Kangas & Seitamaa-Hakkarainen, 2018; Sawyer, 2015; Yrjönsuuri et al., 2019).

There is still little research on the kinds of support teachers organize for the different stages of the LCD process. This study approaches support for learning from the perspective of pedagogical infrastructures (Lakkala et al., 2008). The framework consists of epistemological, scaffolding, material-technological, and social infrastructures (Bielaczyc, 2001; Lakkala et al., 2008; Riikonen, Kangas, et al., 2020). These forms of support may include support for pupils' knowledge creation and sharing, engagement in the LCD process, materials and technologies for implementing the project, and arrangements for social interaction and teamwork (see Riikonen, Kangas, et al., 2020).

In Finland, technology education is not a separate school subject but is often implemented as a cross-curricular learning activity that requires collaboration between teachers from different disciplines. In the Finnish core curriculum for basic education (Finnish National Agency of Education [FNAE], 2016), the objectives for the teaching and learning of technology are general and integrated across different school subjects. For example, in crafts teaching, the objective is that pupils understand the meaning of crafts, manual skills, and technological development in their personal life, society, entrepreneurship, and working life (FNAE, 2016). The curriculum leaves room for municipalities and schools to define more specific aims and content for technology projects.

To create a foundation for effective support in technology projects, this study aims to explore the kinds of pedagogical infrastructures involved in the collaborative planning and implementation of multidisciplinary technology education. Accordingly, the following research questions are addressed:

(1) What kinds of pedagogical infrastructures are involved in the collaborative planning and implementation phases of multidisciplinary technology education?

(2) How are the pedagogical infrastructures manifested in the different stages of the LCD process?

Theoretical framework

Teacher collaboration in multidisciplinary technology education

Organizing support for pupils' learning in multidisciplinary and cross-curricular technology projects is based on teachers' collaboration with their colleagues. It widens the scope of support for learning to involve several fields of expertise, such as social, pedagogical, and technological, combined with several subject domains (see, e.g., Lakkala et al., 2005). Teacher collaboration refers to the involvement of two or more teachers in planning, implementation, and assessment (Friend & Cook, 2010; Lehtonen et al., 2017). This study focuses on the phases of collaborative planning and implementation because of their critical role in defining the kinds of support targeted at pupils' learning. Further, these two phases differ in terms of the focus of the teachers' interaction. In collaborative planning, teachers focus on the joint preparation of learning activities and resources, and on the anticipation of classroom events (Pratt et al., 2017). In implementation, they share the responsibility for the guidance of pupils, which requires applying and sharing practical knowledge at a fast pace (Rytivaara & Kershner, 2012). Both planning and implementation involve considerations related to assessment. In the planning of teaching, assessment is integrated into determining learning goals, pedagogical approaches, and criteria for assessment (Wolterinck et al., 2022). During implementation, assessment can be applied to provide feedback on learning (Wiliam, 2011).

In collaborative planning, a teaching team sets a stage for the implementation of teaching: They make decisions on curricular goals, resources, and materials applicable for the implementation (see, e.g., Yinger, 1980). Teachers share their expertise focusing on what will occur in the upcoming learning sessions, who will teach which part, which instructional models will be applied, and what kind of support for learning pupils need (Pratt et al., 2017; Pylman, 2019). In the field of technology education research, the planning of teaching has received little attention. For example, Stein et al. (2001) described planning as a two-level activity: On the first level, teachers plan their approach to technology, set the learning task, and ensure there are skills, tools, and other resources available. On the second level, the planning is deepened by focusing on the learning process and support for it. However, Stein et al. (2001) did not include a special focus on teacher collaboration in their study on the planning of teaching. In our previous study (Aarnio et al., 2021), we found that teachers' multidisciplinary collaboration in planning increases the versatility of the possible implementations of technology education.

In the collaborative implementation of teaching, teachers bring their subject-specific ideas and perspectives into an integrated entity that they instruct together (Wenger & Hornyak, 1999). For example, subject teachers can integrate their perspectives of arts, mathematics, and science in a technology project, and implement it collaboratively. During collaborative implementation, teachers need to apply and combine their expertise in new and versatile ways. This is because designing is typically a non-linear activity, in which pupils' needs may emerge unpredictably (Riikonen et al., 2020). The actions of the teaching team can be described as a paradox of balancing structuring and improvisation (Sawyer, 2015). Although teachers cannot fully control the design process or its outcomes, they can work as enablers of pupils' collaboration and activities (Viilo et al., 2011). Teachers' support engages pupils in collaborating and taking collective responsibility for the design activity, which is not self-evident without guidance (Viilo et al., 2011). They need to enhance pupils' knowledge-building and usage of technology as a tool for creativity and innovation (Kangas et al., 2013; Riikonen et al., 2020). Although previous studies have acknowledged the benefits and challenges of teacher collaboration, there is a lack of research on the kinds of support for learning organized by multidisciplinary teaching in technology projects.

Learning by collaborative designing

In this study, learning in technology projects was approached using the LCD model (Seitamaa-Hakkarainen et al., 2010). LCD is a pedagogical model that focuses on pupils' collaborative, iterative knowledge creation around design artifacts (Seitamaa-Hakkarainen et al., 2001, 2010). It encompasses the idea of collaborative knowledge building (e.g., Scardamalia & Bereiter, 2006) and the progressive inquiry that describes the pedagogical principles of a process where especially scientific knowledge creation can be learned (Hakkarainen, 2009; Hakkarainen et al., 2004). The model resembles a progressive inquiry process with a special focus on learning and knowledge creation by designing and constructing artifacts; therefore, it has been argued to be applicable as a pedagogical model in technology education (Kangas & Seitamaa-Hakkarainen, 2018).

The LCD model describes a complex, iterative design process in which pupils collaborate to advance their design ideas with simultaneously evolving artifacts, such as sketches or prototypes (Kangas & Seitamaa-Hakkarainen, 2018). According to Seitamaa-Hakkarainen et al. (2010), the spiral-shaped LCD process includes eight elements that are not actually separable as design stages: (1) creating design context, (2) defining design task and design constraints, (3) creating conceptual and visual design ideas, (4) evaluating design ideas and constraints, (5) connection to expert culture and data collection, (6) experimenting and testing design ideas (sketching and prototyping), (7) evaluating function of prototype, and (8) elaboration of design ideas and redesign. In the beginning, pupils create a shared conception of the design context and the requirements that affect their working. External experts or end users can be involved in defining the constraints that pupils need to consider when designing. Ideas are then cyclically created, conceptualized, visualized, evaluated, and tested. Pupils seek knowledge and share it socially, which supports a constant deepening of their knowledge. The tested ideas are implemented as prototypes that are evaluated and developed further. Pupils' collaboration and distributed expertise is the core of the model, and its value in every phase is emphasized.

Although few studies have investigated the ways of organizing support for learning in technology education, the need to carefully facilitate pupils' learning at all levels of the LCD process has been recognized (Kangas & Seitamaa-Hakkarainen, 2018; Yrjönsuuri et al., 2019). Teacher-driven activities and collective working as a class have been found to be most present in the first phases of the LCD process, in which pupils need guidance, especially in using the new tools, and in the later phases, the emphasis changes toward supporting pupils' teamwork (Seitamaa-Hakkarainen et al., 2010). In a study by Yrjönsuuri et al. (2019) about Finnish elementary school pupils' collaborative design process, prototyping was found to be especially challenging to young pupils, as pupils build their prototypes in a short time with limited skills and without a full understanding of the purpose of the prototype. The authors noted that young pupils often devote time to building only one prototype instead of several fast prototypes. Therefore, they recommended that teachers pay special attention to how to support prototyping in the planning phase of teaching. The importance of iterating and refining prototypes has been highlighted as a way for pupils to learn to capture their own process of building knowledge (Clapp et al., 2016).

Pedagogical infrastructures in multidisciplinary technology education

In technology projects, teaching teams can organize support for pupils' learning by distributing it across the learning environment. Support for LCD can be integrated into materials, structuring of tasks, teachers' advice, and technologies (see Lakkala et al., 2010). The concept of *pedagogical infrastructures* refers to the underlying conditions for learning activities designed by teachers to meet their pedagogical aims (Lakkala et al., 2008). Aiming to explore the support teachers offer for the LCD process in multidisciplinary technology education, the framework of pedagogical infrastructures (see Table 1) serves as the theoretical base for this study. Previous studies have recognized four pedagogical infrastructures: epistemological, scaffolding, material-technological, and social (Bielaczyc, 2001, 2006; Lakkala et al., 2008; Riikonen, 2020). These infrastructures describe the aspects that teachers can consider in pedagogical design to organize support for learning. In practice, they are often intertwined (Lakkala et al., 2008). In technology education, such considerations can be related, for example, to what kind of materials and technologies to choose for pupils to apply in the projects, or how to organize pupils' teamwork and social interaction.

The framework of pedagogical infrastructures was first introduced by Lakkala et al. (2008) in the field of computer-supported collaborative learning. Lakkala et al. (2008) designed their framework for exploring the progressive inquiry process, which represents the idea of collaborative knowledge creation. The framework was elaborated to better meet the nature of the materially embodied activities of technology education in the context of maker-centered learning by Riikonen et al. (2020). The present study explores the four pedagogical infrastructures in multidisciplinary technology education.

Epistemological infrastructure refers to ways of encouraging pupils to share, elaborate, and create knowledge together (Lakkala et al., 2008). According to Paavola et al. (2002), epistemological infrastructure enables knowledge creation in dynamic and innovative processes among participants with different backgrounds and skills. In these processes, knowledge is embedded in mediating factors, such as conceptual artifacts and shared activities (Paavola et al., 2002). In technology education, pupils' knowledge creation can be made visible through sketches, prototypes, and final products (Riikonen et al., 2020). Epistemological infrastructure supports pupils' learning, especially in long-term projects that enable several iterations in the design, failure, and improvement of ideas and solutions (Riikonen et al., 2020).

Table 1 Pedagogical infrastructures and definitions (Bielaczyc, 2001, 2006; Lakkala et al., 2008; Riikonen, 2020)

Pedagogical infrastructure	Definition of the pedagogical infrastructure
Epistemological	Practices that encourage pupils to share, elaborate, and co-create knowledge
Scaffolding	Support for pupils' engagement in the LCD process
Material-technological	Materials and technologies, and support for applying them
Social	Arrangements for organizing pupils' teamwork and social interaction

Scaffolding infrastructure refers to ways of supporting pupils' engagement in the LCD process. Lakkala et al. (2008) highlighted the cognitive support embedded in scaffolding as an enabler of pupils' gradual learning of knowledge-creation processes. The infrastructure includes conceptual tools, such as guidelines, models, and templates that support pupils in planning, monitoring, and reflecting on their own work (Lakkala et al., 2008). In addition, metacognitive tasks, such as justifying choices and reflecting on the process and its outcomes, may be assigned to pupils (Lakkala et al., 2008). Riikonen et al. (2020) extend the cognitive perspective of the infrastructure with embodied and materially mediated support for pupils' engagement, such as briefing the tasks, setting constraints for the design, and giving guidelines for the process.

Material-technological infrastructure refers to providing pupils with materials, technologies, and support for applying them (Lakkala et al., 2008). This includes providing various technologies and materials to pupils and ensuring that they are appropriate for the desired activity (Lakkala et al., 2008; Riikonen et al., 2020). It also includes organizing the usage of technologies and materials and giving advice on their usage to pupils (Lakkala et al., 2008; Riikonen et al., 2020). Proper offering and clear organization of materials, tools, and technologies in the learning environment sets the basis for pupils to successfully test their design ideas through material exploration and prototyping (Clapp et al., 2016). In technology education, the material-technological infrastructure can be multidimensional. In addition to materials and technologies, pupils can work on the form, function, and intelligence of the designed solution, as well as on the communications and documentation of their designing process (Kangas et al., 2022; Korhonen et al., 2022). Different technologies, mechanical structures, electronics, programming, and robotics can be combined in novel ways (Korhonen et al., 2022).

Social infrastructure refers to ways of arranging pupils' teamwork and social interactions (Lakkala et al., 2008). The concept of social infrastructure was first introduced by Bielaczyc (2001, 2006) as social arrangements that are inevitable in supporting the successful usage of technology in classrooms. These arrangements enable adhesion to the common task, collective knowledge building of the team, and the use of computer-supported tools for learning (Bielaczyc, 2001). From the perspective of technology education, the social infrastructure is considered an arrangement that supports pupils' teamwork and social interaction in designing (Lakkala et al., 2008; Riikonen et al., 2020). Pupils can be assigned a task in which accomplishment requires them to share responsibility over designing and its outcomes (Lakkala et al., 2008; Riikonen et al., 2020).

Method

Methodological approach

A qualitative research approach was chosen as applicable for the purpose of this study to create a profound picture of pedagogical infrastructures manifested in multidisciplinary technology education. The study follows the constructivist paradigm, which includes an assumption that reality is context-dependent and socially constructed (see, e.g., Mackenzie & Knipe, 2006). The experiences described by the teaching teams in this study are their own, and, therefore, cannot be potentially transferred to other research contexts. The study was inspired by a multiple case study approach (Yin, 2009), which enabled comparisons between the different teaching teams. The teaching teams were first compared based on their background characteristics, including the level of education they taught, team size, and teachers' disciplinary backgrounds. Because this comparison did not reveal differences in how the teams applied pedagogical infrastructures, the study focused instead on the phases of teaching teams' collaboration. Thus, the differences in the application of pedagogical infrastructures between the teaching teams in the planning and implementation phases of technology projects were identified.

Context

This study was situated at a technology education program co-coordinated by two Finnish universities. The program targeted both in-service and pre-service teachers with varying previous teaching experience in technology education. It applied the idea of multidisciplinary technology education with an aim to encourage participants to develop technology education in their own work contexts, and to inspire a wide group of pupils to learn technology. The program was established because there was a lack of institutional professional education in technology education for in-service teachers in Finland, and pre-service teachers did not have opportunities to learn multidisciplinary technology education as a part of their university studies. As an independent academic field, technology education is young in Finland; the first professors were recruited in 2018. However, there is a strong tradition of Finnish research-based teacher education, and qualifying as a teacher requires 5-year university studies.

At the time of the study, which was carried out in 2019–2021, the technology education program was in its pilot phase. The program included three modules, five European Credit Transfer System credits (ETCS) each, where 1 credit equals approximately 27 h of work. In the first module, the participants were introduced to different kinds of innovative solutions for organizing technology education, and they planned their own technology education teaching experimentations. The second module focused on team teaching, and the in-service teachers carried out technology projects in their own workplaces. The theme of the third module was phenomenon-based technology education, and the in-service teachers were encouraged to broaden their cooperation with colleagues, enabling a wider selection of school subjects in the projects.

Participants

The participants for this study were 21 experienced in-service teachers whose career lengths varied between 6 and 30 years. Experienced in-service teachers were chosen as the target group for this study because they were assumed to have enough experience to reflect the collaborative practices situated in the workplace context. The participants belonged to 11 teaching teams, the sizes of which varied between two and seven teachers. The most common size of a teaching team was two teachers. The teachers worked at the primary, secondary, and general upper secondary levels in 10 different schools of 400–1000 pupils located in Southern Finland. They acted as subject teachers ($n=15$), class teachers ($n=5$), and special class teachers ($n=1$). One of the teachers played a leading role in their schools. The teachers' qualifications covered various school subjects, including mathematics, science, music, information and communications technology, and arts and crafts. Both female and male genders were represented: 13 teachers were women, and eight were men. The teachers were committed to long-term collaboration that covered the planning, implementation, and assessment of the technology projects. The teaching teams organized the technology projects at their workplaces, and their collaboration was facilitated in the meetings of the technology education program. Out of the 11 projects, four projects were aimed at primary school pupils, six projects at secondary school pupils, and one project at general upper secondary school pupils.

Data collection

The data collection method of this study was a qualitative research interview (Qu & Dumay, 2011) that enabled collecting in-service teachers' situated experiences of collaborative planning and implementation of technology projects. The data collection was carried out in two stages in 2019–2021. The first author was already familiar with the teachers and had a general understanding of the technology education projects they were planning and implementing because she took part in organizing the technology education program. However, she was not involved in the collaborative planning or implementation of the projects.

In 2019, all 17 in-service teachers, who were attending the first module of the technology education program, were introduced to the study through an interview invitation. Given that the chosen research population of experienced teachers was small, no specific sampling criteria were applied. Six teams (11 teachers) were interviewed about the collaborative planning phase of their technology projects (Aarnio et al., 2021). The interviews focused on the teaching experimentation plans the teams made. The semi-structured interview scheme included five themes: context of co-planning, defining the experimentation idea, evaluation of the experimentation, external resources utilized during the co-planning, and further plans for continuing the experimentations. The interviews were organized in Finnish, either in a university meeting room or in an empty classroom at the teachers' workplace. The length of the interviews varied between 50 and 110 min.

Besides utilizing the existing data from the six planning-phase teaching teams (Aarnio et al., 2021), the data collection was supplemented by asking eight new teaching teams (17 teachers) to participate in the interviews in 2021. The teaching teams attended the second module of the technology education program, and they had reached the implementation phase of the technology projects at the time of data collection. Five teaching teams (10 teachers) were willing to participate, and they were interviewed about the collaborative implementation phase of their technology projects. The semi-structured interview scheme (Appendix 1) followed the LCD model (Seitamaa-Hakkarainen et al., 2010). The teaching teams were asked to describe the implementations of their technology projects and the support they had organized for pupils' learning. The interviews were organized online via Zoom, and their length was 38–65 min. The language was Finnish, except in one interview that was organized in English.

Altogether, the data collection resulted in 734 min of interview data, of which 452 min were collected from the planning-phase teaching teams and 282 min from the implementation-phase teams. The data were transcribed verbatim. To maintain the anonymity of the respondents, the six planning-phase teams were given pseudonyms P1–P6, and the five implementation-phase teams were given pseudonyms I1–I5 in the analysis.

Analysis

The interview transcriptions were analyzed by following the principles of qualitative content analysis (see, e.g., Elo & Kyngäs, 2008). The analysis included three main stages, as exemplified in Fig. 1. The first stage of the analysis began by reading through the transcriptions and becoming familiar with the data, after which the analysis units were recognized. A unit of analysis was a meaning unit—more specifically, a coherent data fragment that consisted of a teaching team's description of support for pupils' learning in the LCD process ($N = 225$). Both descriptions of direct and indirect support for learning were approved by the analysis units. Pedagogical infrastructures (see Lakkala et al., 2008) can include teachers' direct support, such as facilitating pupils' interaction or advising in a design task. Also, indirect support for learning can be embedded in the learning environment, for example by providing pupils free access to materials and technologies in the classroom. The focus of the analysis was kept at the level of the teaching team, and each analysis unit included statements from one to two teachers.

The second stage of the analysis was a coding cycle in which each unit of analysis was first assigned one or more descriptive codes by condensing its content briefly. Each unit of analysis was then deductively coded in terms of pedagogical infrastructures (Lakkala et al., 2008; Riikonen et al., 2020), which resulted in the main categories of epistemological, scaffolding, material-technological, and social infrastructures. Recognizing that pedagogical infrastructures could be intertwined (Lakkala et al., 2008), the main categories were not mutually exclusive. Out of the 225 units of analysis, 216 units of analysis belonged to one pedagogical infrastructure and nine units of analysis belonged to two pedagogical infrastructures. For example, the following unit of analysis was involved in both material-technological and scaffolding infrastructure, as it described how pupils can choose materials and build, supervised and guided by teachers:

> We need to see what kinds of structures pupils are going to build. We need to keep their feet on the ground and focus on what they can do and what materials they

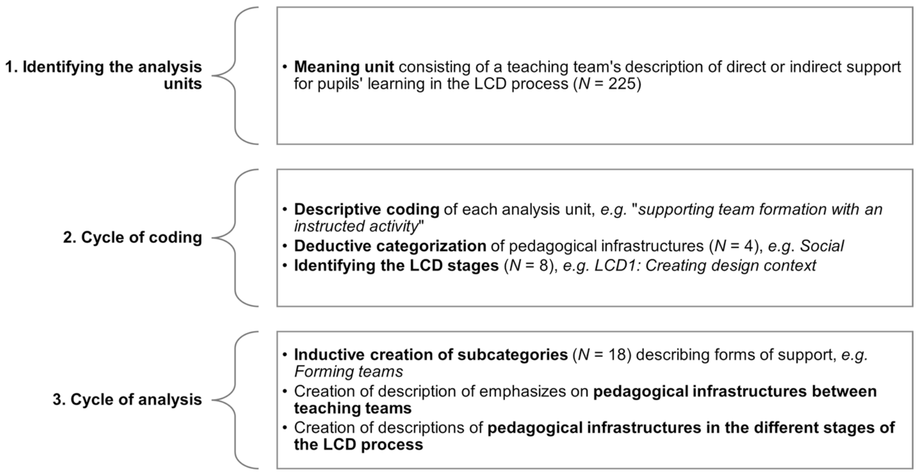

Fig. 1 Three main stages of analysis

can use. We are unlikely to start building giant greenhouses. […] We are trying to finish something in the project. [Teaching team P1, in the planning phase]

The last phase of the coding cycle was identifying the LCD stages (Seitamaa-Hakkarainen et al., 2010). Coding was carried out by applying the frame presented in Table 2, and each unit of analysis was identified into one or two LCD stages. In line with the study's interest in support for learning in the LCD process, such analysis units that described support only in general instead of being related to any LCD stage were excluded from the analysis. For example, descriptions of setting tasks for pupils that were not related to any specific LCD stage but to the technology project in general were excluded. Instead, descriptions of setting tasks to support learning in a specific LCD stage, such as the stage of experimenting and testing design ideas, were included in the analysis.

The third stage was the cycle of analysis. This stage began with the inductive creation of subcategories by comparing the descriptive codes and grouping the analysis units based on the similarities of their contents. Categorization was carried out co-operatively by the first and second authors, and it continued until new subcategories did not emerge. The subcategories were named according to the forms of support identified. This stage produced a coding scheme in which the four existing main categories of pedagogical infrastructures were complemented with 18 subcategories presented in Table 3. Each main category consisted of three to seven subcategories. The subcategories covered all 225 analysis units found in the data. Each subcategory included descriptions of three to nine teaching teams. The average was 5.5 teaching teams per subcategory.

To answer the first research question, each teaching team was studied from the perspective of the kinds of pedagogical infrastructures emphasized in their collaboration. The frequency of descriptions of pedagogical infrastructures varied between six and 45 per teaching team, with an average of 21.5 descriptions per team. Based on team-level information about

Table 2 Coding frame for identifying learning by collaborative designing (LCD) stages in analysis units (based on Seitamaa-Hakkarainen et al., 2010)

Stage of the LCD process	Description of learning activities supported
1. Creating design context	Creation of shared conception of a design context, for example, information about a project theme and technologies, creation of a social context
2. Defining design task and design constraints	Creation of a shared conception of a design task and its requirements, for example, instructions for a project, setting timetables and goals
3. Creating conceptual and visual design ideas	Conceptual and visual idea development
4. Evaluating design ideas and constraints	Evaluating of an idea and its constraints (does not cover evaluating a prototype or a final concept)
5. Connection to expert culture and data collection	Data collection that contributes to defining an idea, for example, seeking information about existing solutions
6. Experimenting and testing design ideas	Building of a prototype or testing an idea in practice
7. Evaluating function of prototype	Evaluating a prototype, sketch, mockup, or some other kind of result created in the learning process
8. Elaboration on design ideas and redesign	Elaborating, redesigning and further development of design ideas (can include elaboration of a prototype, a sketch, a mockup, etc.)

Table 3 Pedagogical infrastructures for supporting learning by collaborative designing in multidisciplinary technology projects (f = 236)

Pedagogical infrastructure	Form of support	*f*
Epistemological (*f* = 77)	Supporting ideation	31
	Providing autonomy	20
	Making advancement visible	16
	Supporting problem-solving	10
Scaffolding (*f* = 68)	Flexible guidance	14
	Increasing motivation	13
	Framing the project	12
	Setting tasks	9
	Ensuring quality	7
	Providing structure	7
	Encouragement	6
Material-technological (*f* = 58)	Supporting the use of technology	25
	Enabling technological creativity	16
	Providing materials and technologies	11
	Hands-on experimentation	6
Social (*f* = 33)	Forming teams	15
	Supporting collaboration	10
	Organizing peer support	8

the manifestation of pedagogical infrastructures, the first and second authors compared and grouped the teaching teams based on their similarities and differences in the appliances of the infrastructures. Because the frequency of pedagogical infrastructures differed between the teams, the comparison was based on the percentages of pedagogical infrastructures in the descriptions of each team. The total frequency of pedagogical infrastructures of each team was converted to 100%. For example, teaching team I2 had 62% emphasis on scaffolding and 38% emphasis on epistemological infrastructure. The between-team comparison resulted in a description of the two main emphases on pedagogical infrastructures. Seven out of 11 teaching teams were characterized by their emphasis on material-technological infrastructure (22–57%). Four teams had simultaneous emphasis on scaffolding (33–68%) and epistemological (27–50%) infrastructures.

To answer the second research question, the units of analysis were grouped into two according to the teaching teams' phases of collaboration: planning and implementation. The analysis units were mapped to two tables utilizing the main categories of pedagogical infrastructures, the subcategories, including the forms of support, and the coding of the LCD stages. As a result, two separate descriptions were created on the manifestation of the pedagogical infrastructures in the different stages of the LCD process.

Results

Pedagogical infrastructures involved in the planning and implementation of multidisciplinary technology education

The first research question pertained to the kinds of pedagogical infrastructures involved in the planning and implementation phases of multidisciplinary technology education. Out of the 11 teaching teams, seven teams emphasized material-technological infrastructure, and four teams highlighted scaffolding and epistemological infrastructures. Six teams were in the planning phase, and five teams were in the implementation phase of their technology projects. Social infrastructure was the least emphasized pedagogical infrastructure in the descriptions of the teaching teams. The distribution of pedagogical infrastructures in the planning and implementation phases is presented in Fig. 2.

Emphasis on material-technological infrastructure

Out of the 11 teaching teams, seven emphasized the material-technological infrastructure. Besides strongly highlighting the material-technological infrastructure, these seven teams included an emphasis on scaffolding infrastructure. In addition, six of the teams included social infrastructure, and five applied epistemological infrastructure. Five of the teams were in the planning phase, and two were in the implementation phase. The teams are presented in Fig. 3.

The forms of support identified in relation to the material-technological infrastructure were *supporting the use of technology*, *enabling technological creativity, providing materials and technologies,* and *hands-on experimentation* (see Table 3). The importance of supporting pupils in using different technologies and materials was highlighted

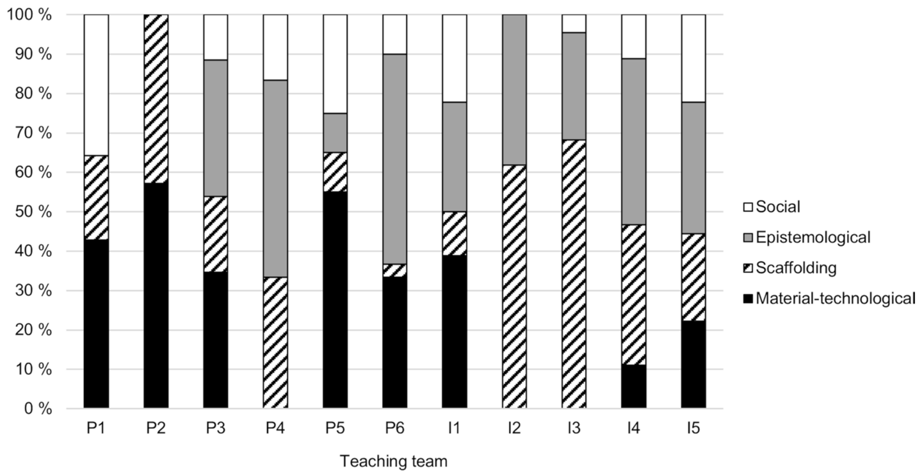

Fig. 2 Distribution of pedagogical infrastructures ($f = 236$) involved in teaching teams' descriptions of the collaborative planning and implementation phases. P1–P6 represent the teams in the planning phase, and I1–I5 represent the teams in the implementation phase

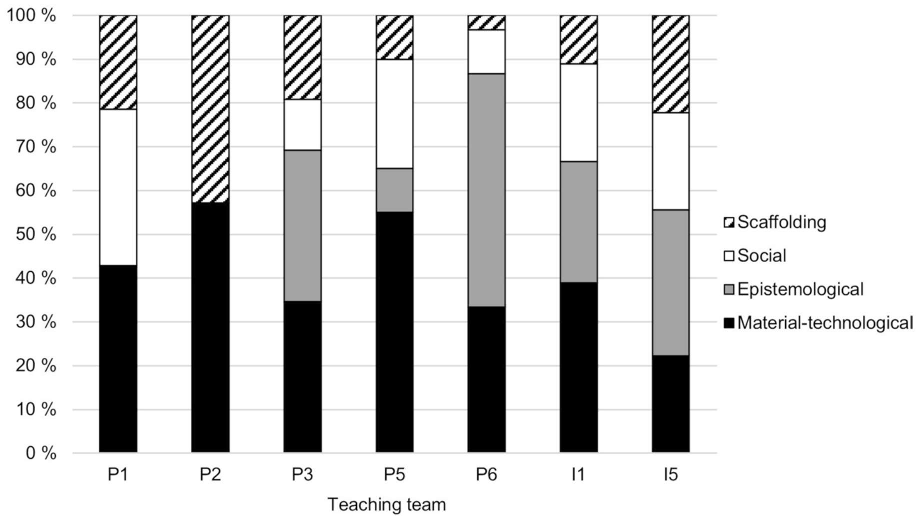

Fig. 3 Emphasis on material-technological infrastructure involved in the seven teaching teams' descriptions of collaboration ($f = 142$). The teaching teams P1, P2, P3, P5, and P6 were in the planning phase, and the teaching teams I1 and I5 were in the implementation phase

by all seven teaching teams. As shown in the following quotation, the teachers emphasized the importance of structuring building activities for pupils:

> We see it important that the building is structured instead of being an open thing. […] During building, pupils learn skills that help them to build and design by themselves after this [project]. This is structured; we do not work freely, so they cannot do and program whatever they want. [Teaching team P2, in the planning phase]

Five of the seven teaching teams described enabling technological creativity to pupils by giving them the freedom to choose technologies and materials and to combine them in novel ways. For example, programming and building could be combined according to the pupils' own ideas. Providing materials and technologies for pupils was described by four teaching teams, who mentioned tools, working spaces, and digital learning environments as resources. For example, access to the school kitchen, chemistry lab, 3D modeling facilities, and prototyping materials were organized. Digital learning environments were often described as support for pupils' cooperation and documentation of learning. Four teaching teams saw hands-on experimentation as an important means to support pupils' motivation to work with technology, and to lower their threshold to participate in the projects.

Emphasis on scaffolding and epistemological infrastructures

Four of the 11 teaching teams emphasized scaffolding and epistemological infrastructures. Three were in the implementation phase, and one was in the planning phase. The teams are presented in Fig. 4.

Scaffolding refers to supporting pupils' engagement in the LCD process. The forms of support identified in relation to the scaffolding infrastructure were *increasing motivation, framing the project, providing structure, flexible guidance, ensuring quality, encouragement,* and *setting tasks* (see Table 3). All four teaching teams established increasing

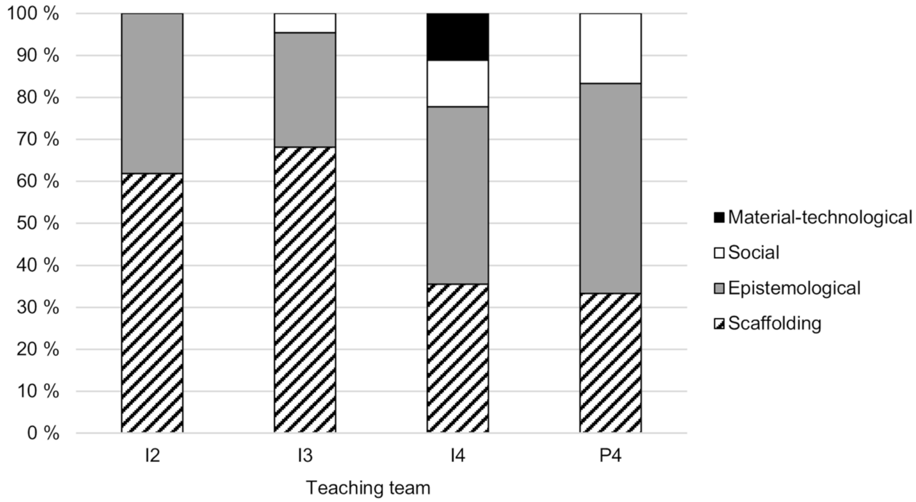

Fig. 4 Emphasis on scaffolding and epistemological infrastructures involved in the four teaching teams' descriptions of collaboration ($f = 94$). Teaching teams I2, I3, and I4 were in the implementation phase, and teaching team P4 was in the planning phase

motivation as a form of support. They described setting pupils' interests and experiences as starting points for the project. Teachers deemed it important to offer options to pupils in working, for example, letting pupils decide the order in which they implement their own projects. Some of them highlighted creating an inspiring atmosphere in the classroom. Further, making compromises and negotiating were described as ways to increase pupils' motivation.

Three of the four teaching teams described framing the project at the beginning of the work. The assignment and the working process were introduced at a general level and discussed together with the pupils. Two teams introduced a project to pupils by showing a video related to the theme of the project, such as future housing solutions. Providing structure for pupils' learning was described by three teams. Teachers created structures for learning by defining the sources for searching for information. They limited pupils' social interactions to ensure their focus on the task. They also kept pupils' working focused on the goals of the project. Two teaching teams described flexible guidance. They supported pupils' own work planning and goal setting and adjusted the guidance and exercises according to pupils' varying skill levels and needs. In the following quotation, the teacher describes breaking a task into small pieces that pupils could carry out more easily:

> We then had to break the task into pieces, as we usually do here at school. We must break the task into small parts and check their accomplishments. We instructed pupils to manage the workload to get things done. [Teaching team I4, in the implementation phase]

Ensuring quality as a form of support was included in the descriptions of two of the teaching teams. The teachers expected quality solutions from their pupils and guided them to document all choices when planning and implementing their own ideas. Pupils were asked to complement their work if they were not doing their work well enough, or if the work was not properly completed. Pupils' progress in the project was continuously followed.

Two teaching teams described encouragement as a form of support. One team approached encouragement as mental support for pupils in testing ideas without fear of failing. Another teaching team highlighted the value of learning instead of focusing solely on the results. One of the four teaching teams mentioned setting tasks as support related to scaffolding. It included offering exercises, platforms, and templates to pupils. For example, exercises supported searching for information about existing solutions before pupils started to implement their own ideas.

In addition to scaffolding, the four teaching teams had a shared emphasis on epistemological infrastructure. It referred to support for pupils in operating with knowledge. The forms of support identified in relation to the epistemological infrastructure were *supporting ideation, providing autonomy, making advancement visible*, and *supporting problem-solving* (see Table 3). All four teaching teams brought up supporting ideation. They mentioned comprehensive ways to support ideation, including asking questions to enhance ideation, encouraging pupils' free ideation, offering examples of ideas, supporting the evaluation of the created ideas, using specific ideation methods, and utilizing pupils' own experiences as a base for ideation. In the following quotation, the teacher exemplifies trying to encourage pupils to adopt a similar attitude to that of Gyro Gearloose, a famous character in Donald Duck comics:

> We pushed the children to think they did not have any borders. They did not have to be worried about some material that was, or was not, invented already. Anything was possible in a way. […] We encouraged them to adopt the attitude of Gyro Gearloose, and we did not shoot [their ideas] down. [Teaching team I2, in the implementation phase]

Four teaching teams described providing autonomy as a form of support related to epistemological infrastructure. The teachers gave pupils opportunities to direct their own working processes and to make decisions freely. Pupils' creativity and ownership of the projects were highlighted. Three teaching teams described making advancement visible. They organized opportunities for their pupils to present results to other pupils and teachers. The descriptions of the two teams included supporting problem-solving. This form of support was related to the difficulties that emerged while pupils were implementing their own ideas. The teachers solved problems together with their pupils. In some situations, pupils had to change their ideas, and the teaching team helped the pupils move forward from the original idea.

Social infrastructure

In the descriptions of all 11 teaching teams, social infrastructure was the least emphasized pedagogical infrastructure. Social infrastructure refers to support for pupils' teamwork and social interactions. The identified forms of support related to it were *forming teams, supporting collaboration*, and *organizing peer support* (see Table 3). Seven teaching teams described support for forming teams. The teachers highlighted the importance of well-functioning teams that aim to reinforce pupils' opportunities to support each other's learning. The criteria for forming teams included, for example, pupils' strengths, gender, and already existing friendship relationships. In the following quotation, the teaching team highlights the knowledge of pupils' strengths as a basis for forming teams:

> We have a picture of the pupils' strengths, which we can utilize in team formation. We can try to include all the strengths needed [in the project] with a good balance. In this way, the teams may do better. [Teaching team P1, in the planning phase]

Five teaching teams described supporting collaboration of their pupils. This often included introducing social practices and rules to pupils to ensure successful teamwork. The teachers also supported pupils in sharing the workload of the projects. Four teaching teams mentioned organizing peer support. The teachers named an 'expert pupil' in the class, a student who took a special role in helping others proceed with their projects. In some cases, peer support was organized by asking pupils from previous classes to tutor younger pupils with their projects. Sometimes, pupils were asked to help each other without any special role as experts or tutors.

Manifestation of pedagogical infrastructures in the LCD process

The findings revealed differences between the pedagogical infrastructures involved in the planning phase and the infrastructures involved in the implementation phase of teachers' collaboration. The differences were further analyzed based on their manifestation in the different stages of the LCD process. Overall, the pedagogical infrastructures were manifested with slightly lower emphasis in the collaborative planning phase ($f=103$) than in the implementation phase ($f=133$) of technology projects (see Tables 4 and 5). In both phases of collaboration, the pedagogical infrastructures were manifested most in the early stages of the LCD process, and in the stage of experimenting and testing design ideas. Support for pupils in evaluating function of prototype was not as emphasized in the teaching teams' descriptions. However, the forms of support targeted at the LCD process differed between collaborative planning and implementation. In the following subsections, the different focuses of the planned and implemented support for the LCD stages are presented.

Table 4 Manifestation of pedagogical infrastructures in the collaborative planning phase of multidisciplinary technology projects ($f=103$)

		Learning by collaborative designing (LCD) process							
		1	2	3	4	5	6	7	8
Pedagogical infrastructure	Form of support[a]	Creating design context	Defining design task and design constraints	Creating conceptual and visual design ideas	Evaluating design ideas and constraints	Connection to expert culture and data collection	Experimenting and testing design ideas	Evaluating function of prototype	Elaboration of design ideas and redesign
Epistemological ($f=30$)	Supporting ideation			≥ 9	1–4				
	Providing autonomy		5–8			1–4			
	Making advancement visible				1–4			5–8	
	Supporting problem-solving		1–4			1–4	1–4		
Scaffolding ($f=16$)	Increasing motivation	1–4					1–4		
	Encouragement						1–4		
	Providing structure	1–4					1–4		
	Flexible guidance						1–4		
	Setting tasks					1–4	1–4		
Material-technological ($f=40$)	Enabling technological creativity		5–8				5–8		
	Providing materials and technologies			1–4		1–4	5–8		
	Supporting the use of technology						≥ 9		
	Hands-on experimentation			1–4			1–4		
Social ($f=17$)	Forming teams	≥ 9							
	Supporting collaboration	1–4	1–4						
	Organizing peer support	1–4					1–4		

[a]Frequencies:

1–4 5–8 ≥ 9

Table 5 Manifestation of pedagogical infrastructures in the collaborative implementation phase of multidisciplinary technology projects ($f = 133$)

Pedagogical infrastructure	Form of support[a]	Learning by collaborative designing (LCD) process 1 Creating design context	2 Defining design task and design constraints	3 Creating conceptual and visual design ideas	4 Evaluating design ideas and constraints	5 Connection to expert culture and data collection	6 Experimenting and testing design ideas	7 Evaluating function of prototype	8 Elaboration of design ideas and redesign
Epistemological ($f = 47$)	Supporting ideation	1–4		≥ 9	1–4		1–4		1–4
	Providing autonomy		5–8	1–4	1–4		1–4		
	Making advancement visible				5–8			1–4	1–4
	Supporting problem-solving				1–4		1–4		1–4
Scaffolding ($f = 52$)	Framing the project	5–8	5–8						
	Flexible guidance		5–8	1–4	1–4		1–4		
	Increasing motivation	1–4		1–4			1–4		
	Setting tasks			1–4		1–4			
	Ensuring quality			1–4			1–4		
	Providing structure		1–4	1–4		1–4			
	Encouragement						1–4		
Material-technological ($f = 18$)	Supporting the use of technology		1–4	1–4			≥ 9		
	Enabling technological creativity		1–4				1–4		
	Hands-on experimentation	1–4							
Social ($f = 16$)	Supporting collaboration		1–4		1–4		1–4		1–4
	Forming teams	1–4					1–4		
	Organizing peer support			1–4			1–4		

[a]Frequencies:

1–4 5–8 ≥ 9

Planning: enabling technological creativity as support for defining design task and experimenting and testing design ideas

In the planning phase of technology projects, pedagogical infrastructures were identified in all stages of the LCD process, except in the elaboration of design ideas and redesign. Most of the support was targeted to the early stages of the LCD process, as well as to the stage of experimenting and testing design ideas. The planning-phase teaching teams focused on the material-technological infrastructure. The most highlighted form of support in this infrastructure was enabling technological creativity, which was identified in defining a design task and its constraints, and in experimenting and testing design ideas (see Table 4). Overall, the material-technological infrastructure manifested itself most often in experimenting and testing design ideas. At this stage, the manifestation of forms of support was diverse. In addition to enabling pupils' technological creativity, it involved supporting the use of technology, providing materials and technologies, and organizing hands-on experimentation.

The planning-phase teaching teams also emphasized epistemological infrastructure, aiming to support pupils in operating with knowledge. The most emphasized form of support was supporting ideation, which was present in creating conceptual and visual design ideas. Epistemological infrastructure was often manifested in defining a design task and its constraints, where the most highlighted form of support was providing autonomy. Evaluating function of prototype was supported by making advancement visible. In the planning phase collaboration, social and scaffolding infrastructures were less emphasized than material-technological and epistemological infrastructures. The social infrastructure was mainly targeted at creating a design context in which the teaching teams highlighted support for forming teams. Scaffolding was largely related to experimenting and testing design ideas. In this stage, diverse forms of support were identified: encouragement, flexible guidance, providing structure, increasing motivation, and setting tasks.

Implementation: framing the project as support for creating design context and defining design task

In the implementation phase of multidisciplinary technology education, the entire LCD process was supported. Most support involved in the teaching teams' descriptions was related to the first half of the process. Support for learning at the beginning of the process was comprehensive, as all four pedagogical infrastructures were included. The implementation-phase teaching teams emphasized scaffolding and epistemological infrastructures in their collaboration. In scaffolding infrastructure, framing the project was the most highlighted form of support. It was identified both in creating the design context and in defining a design task and its constraints (see Table 5). Flexible guidance as a form of support manifested itself with the strongest emphasis on defining a design task and its constraints. The strongest overall manifestation of scaffolding infrastructure was identified in experimenting and testing design ideas, in which the forms of support involved flexible guidance, increasing motivation, ensuring quality, and encouragement.

In relation to epistemological infrastructure, supporting ideation was highlighted in creating conceptual and visual design ideas. Providing autonomy to pupils as a form of support was manifested, especially in defining a design task and its constraints. Making advancement visible was emphasized in evaluating design ideas and their constraints. Material-technological and social infrastructures were only slightly manifested in the implementation phase of the teaching teams' collaboration. The material-technological infrastructure was most identified in experimenting and testing design ideas, in which the teaching teams emphasized supporting the use of technology. Social infrastructure was also emphasized in experimenting and testing, where support included organizing peer support, supporting collaboration, and forming teams.

Discussion and conclusions

This study explored the kinds of pedagogical infrastructures involved in multidisciplinary technology education. The findings revealed that pedagogical infrastructures were mostly identified in relation to the early stages of the LCD process, and their manifestation differed between the phases of collaborative planning and implementation. In the planning phase, there was a clear focus on supporting pupils' technological creativity, autonomy, and teamwork. In the implementation phase, support was more diverse, as it included all four pedagogical infrastructures.

During collaborative planning, teachers focused on supporting pupils in applying materials and technologies as part of their design projects. Previous studies have identified similar activities of planning for suitable technologies, and other material resources as a base on which teachers can plan the learning process and the support for it (Stein et al., 2001; see also Pratt et al., 2017; Yinger, 1980). Planning suitable materials and technologies may be an easier starting point than, for example, planning support for pupils' designing and problem-solving activities in which teachers may lack prior experience (see Antink-Meyer & Meyer, 2016).

During implementation, the teachers in this study focused on framing and structuring the projects, as well as providing enough freedom and structure for ideation. In a previous study on creative teaching and learning (Sawyer, 2015), the difficulty of balancing structuring and improvisation has been described as an instructional paradox. This paradox is present in learning environments that aim to foster pupils' creativity. Collaboratively organized instruction can be considered as reacting to pupils' unpredictably emergent needs during designing (see Riikonen et al., 2020). Instruction as a reactive response to classroom situations may explain the strong emphasis on scaffolding and epistemological infrastructures, which shadowed the other infrastructures. To ensure the involvement of all pedagogical infrastructures, teachers could more explicitly share their responsibilities for instruction. Such practical collaboration with colleagues can support teachers' professional development in technology education (Gill, 2019).

The absence of social infrastructure in the collaborative planning and implementation of technology education in this study was unexpected, as previous studies have emphasized the importance of teachers' support for pupils' collaboration in designing activities (Song, 2021; Viilo et al., 2011). Support for pupils' teamwork and social interaction enables them to share responsibility over the whole process of designing and its outcomes (Bielaczyc, 2006; Riikonen et al., 2020). Therefore, a more systematic consideration of social infrastructure is called for both in the phases of collaborative planning and the implementation of technology education.

The variance in support between planning and implementation may be traced back to the different aims related to these phases. The forms of support included in the planning phase may indicate the aim of educating pupils to act as autonomous designers of creative technological solutions. Although collaborative planning has been described as forming a shared agreement on how the instruction will be carried out (Pratt et al., 2017), in technology education, planning of all resources may be challenging if teachers' aim to leave room for pupils' own choices in design. In implementation, diverse support may refer to the aim of helping pupils get a good start on their projects. Allowing pupils the freedom to apply resources that are not yet familiar to them may create a need for comprehensive support at the beginning of the implementation (see Seitamaa-Hakkarainen et al., 2010).

A wide variety of pedagogical infrastructures were related to experimenting and testing design ideas. The teaching teams may have acknowledged the importance of this support due to their previous experience teaching young pupils. Experimenting and testing design ideas has been previously recognized as a challenging stage of designing for young pupils because of their limited skills and understanding of why they build prototypes (Yrjönsuuri et al., 2019). The stage of experimenting and testing was emphasized more than its preceding or following LCD stages, which may reflect a strong focus on supporting the construction of one or several prototypes. Prototypes are centric in promoting pupils' design thinking and reasoning skills (Thuan & Antunes, 2024). However, it must be noted that designing requires several types and directions of reasoning and constant shifting among them, as well as moving back and forth between different stages (see Hultmark et al., 2024). Thus, this study suggests that teachers need to pay attention to providing adequate and consistent support at all LCD stages.

Whereas creating, experimenting, and testing of design ideas were supported in the beginning and in the middle of the LCD process, forms of support for evaluating the prototype or elaborating the ideas were less common toward the end of the process. This finding is contrary to previous studies that emphasized the iterative and open-ended nature of design processes (e.g., Dorst & Cross, 2001; Wynn & Eckert, 2017). Iterating and refining prototypes has been found to be a prerequisite for pupils to become aware of their own knowledge-building during designing (Clapp et al., 2016). Therefore, this study highlights the need to strengthen teachers' expertise in supporting iterative design in technology projects.

Limitations of the study

This study was limited to 11 teaching teams, and the results cannot be transferred directly to other educational contexts. Due to limitations caused by the COVID-19 pandemic, data collection as a follow-up procedure was not possible. Further, during the remote school periods caused by the pandemic situation, the implementation-phase teaching teams had difficulties implementing their original plans for their technology projects. As the datasets were collected from different populations, this study did not aim to explore the causal factors between the stages of collaborative planning and implementation. Further studies are needed on teacher collaboration as a comprehensive process, adding the phase of assessment to the picture. The data collection was based on self-reporting. The results provide a theoretical and empirical basis for further studies that include classroom observation as a methodological approach.

Contributions of the study

As a theoretical contribution, this study shows the applicability of pedagogical infrastructures (Lakkala et al., 2008) in exploring support for learning in the context of technology education. The study provided insight into 18 forms of support related to the epistemological, scaffolding, material-technological, and social infrastructures. In previous studies, the framework has been applied to study teachers' support for the progressive inquiry process (Lakkala et al., 2008) and to study knowledge-creating practices in the context of maker-centered learning (Riikonen et al., 2020). This study creates a basis for further studies on supporting pupils' learning in technology projects approached with the LCD model (Seitamaa-Hakkarainen et al., 2010).

Considering the educational contributions of this study, the findings revealed differences in how the pedagogical infrastructures were involved in the planning and implementation phases of the teaching teams' collaboration. Further, differences were found in how the forms of support were targeted at the different stages of the LCD process. These findings can be applied by teaching teams to plan and implement more comprehensive support for pupils' learning in technology projects. Local school leaders can apply the findings to target resources for developing teacher collaboration. The findings can also be applied by teacher training institutions to organize pre- and in-service teacher education in the field of technology education.

Appendix 1: The group interview framework

- How many years have you worked as a teacher? (*Ask everyone.*)
- You have now implemented a technology education project together. How are your feelings about the project? (*Try to get everyone to respond right at the beginning!).*
- Briefly review the idea of your project. Tell in your own words:
  - What was the project about?
  - What were the objectives of the project?
    - Were there any technology-related goals in the project?
  - Did the students work in groups or individually?

Note: If the students were working individually, ask the teachers to think about the class in general. If the students were working in teams, then ask the teachers to describe the teams.

- Next, let's go through how the implementation of your project progressed step by step.

Creating design context

- How did you introduce the project theme to the students?
- Did you organize any orienting activities, such as workshops of new tools?

Defining design task and design constraints

- What kind of (design) task did you give to the students?
- Did you set any constraints on the project? For example, constraints related to materials or tools?

Creating conceptual and visual design ideas

- How did the students create ideas?
    - Individually, in pairs, in groups, whole class?
    - Sketching, drawing, discussing, writing, making models, etc.?
    - Did you use any specific ideation methods? What? Why?
    - Did you use any other form of support?
- How much time did you use for ideation?

Evaluating design ideas and constraints

- How did the students know if it was a good idea or not?
- Did anyone else participate in the evaluation in addition to the students? Who? How?

Connection to expert culture and data collection

- How and from where did the students search for the information needed in the project?
    - Who provided the information sources?
    - Did the students use external resources (e.g., information from the Internet or expertise beyond the project/school/group?
- Was the information gathered during the project documented? How?

Experimenting and testing design ideas & evaluating function of prototype

- When the students had chosen their final idea(s), did they experiment and test it? How? Why?

    - Did they try out various technologies, materials, structures, functionalities, etc.?
    - Did they build models or prototypes?

- If the students ran into problems while experimenting, how did you support them?
- Were the students eager to start experimenting and testing? What happened? Why?

Elaboration of design ideas and redesign

- During the project, did the students elaborate their ideas / change or develop the idea? How? How many times? Why?
    - Were the students eager to elaborate? Why / why not?
- How did you support their idea elaboration?

Distributed expertise

- How did you support the students' collaboration?
    - Within and between teams?
    - Exchange of information or expertise?
- How did you, as teachers, share your expertise during the project?

When thinking about the project as a whole

- Was your plan implemented as you had thought?
    - How well did you achieve the goals you set for the project?
    - Were there any unexpected situations?
- Best and worst parts/moments?
    - What made it good/special?
    - What did you do when challenges arose?
- If you did the project again, would you change something?

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Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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