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When design thinking goes to school: A literature review of design competences for the K-12 level

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Abstract
School can nurture critical thinkers, creative individuals, and skilled collaborators and communicators, who are curious about and invested in society. Design thinking is a promising educational approach because it builds on the notion that students learn by tackling problems in the world. However, implementing this approach in a school setting is not straightforward. Our paper synthesizes the findings from the literature on design thinking in the K-12 school context. We explore what competences students apply and develop in the design process and how these competences are described in the literature. Then, we link the discovered competences to the pedagogical context by comparing them with phases of inquiry developed by educational thinker John Dewey. This paper's main contribution is a conceptualization of competences and their relations, which we in closing summarize in our Design Competence Framework. This model can encourage teachers and researchers alike to be attentive to these competences and to assess them.

Keywords Design thinking · Competences · Inquiry · K-12

Introduction

Design researcher Cross (1982) argued that the school system lacks a culture of design. In his view, design involves a theory of learning that has been neglected in general education to the great detriment of both students, whose potential is not fully developed, and society, which misses out on future citizens' problem-solving capabilities. The school system does not value or nurture the abductive ability to come up with ideas—a mode of reasoning at the core of design practice—but, instead, focuses exclusively on deductive and inductive reasoning. Cross claimed that this imbalance stems from the widely accepted categorization of thinking developed by Piaget (1936), who argued that concrete, synthetic reasoning belongs to the earlier stages of cognitive development, which are later surpassed by abstract, analytical reasoning. In line with the high esteem given to deduction by developmental psychologists, analytical styles of learning are highly valued in general education to the disregard of bottom-up, tactile approaches

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that aptly describe how many designers think. In their influential article "Epistemological Pluralism and the Revaluation of the Concrete," the constructionists Turkle and Papert (1992) similarly observed that knowledge construction via material, embodied interaction with tangibles has long been depreciated in the school context. As Papert later concluded in "Child Power: Keys to the New Learning of the Digital Century" (1998), little has changed since philosopher and educational reformer John Dewey expressed his thoughts on pedagogy a century ago. Dewey suggested an epistemology of practice that involved learning through interaction with objects directed at solving issues in the world rather than receiving decontextualized, subject-specific facts from books and blackboard teaching alone. He objected to schools being organized in classes that drill students according to planned curricula. According to the papers that we reviewed, one explanation for the failure to transform the educational system is that Dewey's philosophical concepts are difficult to implement in teachers' everyday practice; accordingly, scholars proposed design thinking as a formalized process to overcome these difficulties (see Retna, 2016; Scheer et al., 2012). Design thinking is a method of learning that may allow educators to introduce learning through construction to schools because when we engage in design processes, we learn by interacting with the world. Design is essentially a dialogue between ideas and the world, a dialogue that lies at the heart of inquiry (Koehler & Mishra, 2005). Design thinking as a teaching method is not based on direct instruction; instead, it consists of suggested phases of inquiry in which the teacher serves as a facilitator rather than a lecturer.

This literature review is the preliminary stage in two Danish research projects that exploit the potential of design thinking as a learning approach. The projects are Game-Based Learning in the 21st Century and Community Drive. The former invites students to learn by building games or by building in games, such as Minecraft (see Ejsing-Duun & Hanghøj, 2019). Community Drive allows students to participate in addressing future urban challenges (see Magnussen & Stensgaard, 2018). Both projects propose design thinking as an approach for inquiring into and tackling problems and gaining so-called 21st-century skills, such as creativity, communication, critical thinking, and collaboration. These skills are based on independent and situated knowledge creation rather than drills or procedures. Moreover, this review's conceptualization of design competences has provided a foundation for the development of an assessment tool (see Rusmann & Bundsgaard, 2019) for the evaluation of the two projects' educational interventions.

At the outset of the projects, we consulted Razzouk and Shute's (2012) review of design thinking, which highlights the educational importance of this mode of thinking. Although the review was helpful, we found its practical usefulness in the pedagogical context to be limited, seeing that Razzouk and Shute's competence model was not clearly based on the reviewed design literature and that not all the presented competences were adequately described in the text. Therefore, we aim to expand on Razzouk and Shute's findings by extracting design competences from the literature and linking them to the educational practice by comparing them with Dewey's phases of inquiry. This focus on the connection between design and inquiry, which has been discussed in earlier studies (e.g., Ejsing-Duun & Skovbjerg, 2019; Johns & Mentzer, 2016 [review article]; Koehler & Mishra, 2005), enabled us to develop a conceptualization that is useful for assessing K-12 students' design competences, both when it comes to formative classroom evaluations and research purposes. The reviewed papers did not follow research designs that would have allowed us to conclude that certain competences can be developed by participating in design activities. Rather, the purpose of this paper was to examine which competences are articulated as central to the design process in the literature and thereby develop a conceptualization that can facilitate future and current implementations and subsequent evaluations of design thinking in K-12 classrooms.

Learning through inquiry and play with materials

Design thinking draws on the philosophy of pragmatism. This section discusses prominent design theorists who explicitly regarded pragmatic inquiry as a theoretical foundation for design and who argued for the relevance of design thinking outside the design field. Schön (1983, 1992a), a design and learning theorist, described design as reflection-in-action and was strongly inspired by Dewey's theory of inquiry. According to Schön, the design process begins when a designer is faced with a situation that does not make sense. However, sense can be created by translating the situation into a problem. The designer constructs the problem by 'naming' the elements of the problematic situation that needs attending, and by 'framing' the context in which these elements can be addressed (Schön, 1983). By naming the elements and framing the boundaries of the problem, the designer can address the problem by interacting with the situation. When engaging in design, the designer is in a reflective conversation with the materials of the situation (Schön, 1992b). The designer sees the materials and manipulates them. The materials "talk back," and the designer sees the result. In reflection-in-action, thinking and doing, or ends and means, are not separate from each other but integral to the designer's inquiry into the problematic situation (Schön, 1983). Inquiry, according to Dewey (1910), is the act of investigating a part of reality to create knowledge for a controlled change based on an experienced problem. When one is investigating reality, one is converting "the elements of the original situation into a unified whole" (Dewey, 1938, p. 105). Then, one evaluates that unified whole—the anticipated solution to the problem—in relation to how it addresses the problem that it is meant to solve (Dewey, 1910). Dewey (1985) was opposed to the idea of education as "being told" and argued, instead, that schools should be "equipped with agencies for doing, with tools and physical materials" (p. 44). Students should use language and materials to engage in shared activities (Dewey, 1985) and work on problems that are related to their everyday lives (Dewey, 1905).

The design theorist Cross (1982) argued that the design approach is underpinned by constructive thinking, a type of reasoning that is concerned with synthesis more than analysis and with solutions rather than problems. Constructive thinking differs from inductive or deductive thinking. Referencing March (1976), Cross noted constructive thinking's kinship with what Charles Peirce, the founder of pragmatism, called abductive thinking, the "provisional adoption of an explanatory hypothesis" (Peirce et al., 1974, vol. 2, para. 544). Abductive reasoning leads to explanatory hypotheses—that is, to ideas. This kind of reasoning suggests questions that require further scrutiny. Deductive reasoning has its source in the known—that is, in verified theories that yield justified assumptions—whereas inductive reasoning is based on fallible observations. By contrast, abductive reasoning points to the future. It is the logic of discovery by means of which new ideas can arise (Peirce et al., 1974, vol. 5, para. 171). It is worth noting that Peirce argued that these new ideas had to be evaluated by deduction—that is, by anticipating the idea's implications—and by induction, as ideas are tested based on predictions (Peirce et al., 1974, vol. 2, para. 634). Therefore, abduction, deduction, and induction are the modes of reasoning that constitute the logic of inquiry. As discussed earlier, Turkle and Papert, in line with Cross, argued that the school system is characterized by a devaluation of the concrete. This disregard of a certain mode of thinking, which includes abductive reasoning, is another possible explanation for schools' failure to unlock the full potential of construction.

Method

This paper is a literature review as described by Grant and Booth (2009). Our search of literature on design thinking at the K-12 level was systematic, and we report our findings conceptually using a narrative form. We did not assess the quality of the reviewed papers because our aim was not to collect evidence on competence development via design practice. Rather, the aim was to develop a conceptualization of competences by synthesizing evidence on the competences that scholars associate with design thinking in school. The purpose of the review was to access peer-reviewed full-text articles on the explicit implementation of "design thinking" in schools. For an article to be included in our set of sources, its title, keywords, or abstract had to include the phrase "design thinking" or "designerly thinking." We established this criterion to ensure that design thinking featured as a prominent theme in the articles. We set the educational context by restricting the search to educational databases (see Fig. 1), and we did not set limits on the year of publication. We conducted the search in mid-2018. During the screening process, we included an article if it (a) dealt with design thinking at the primary or secondary school level and (b) had

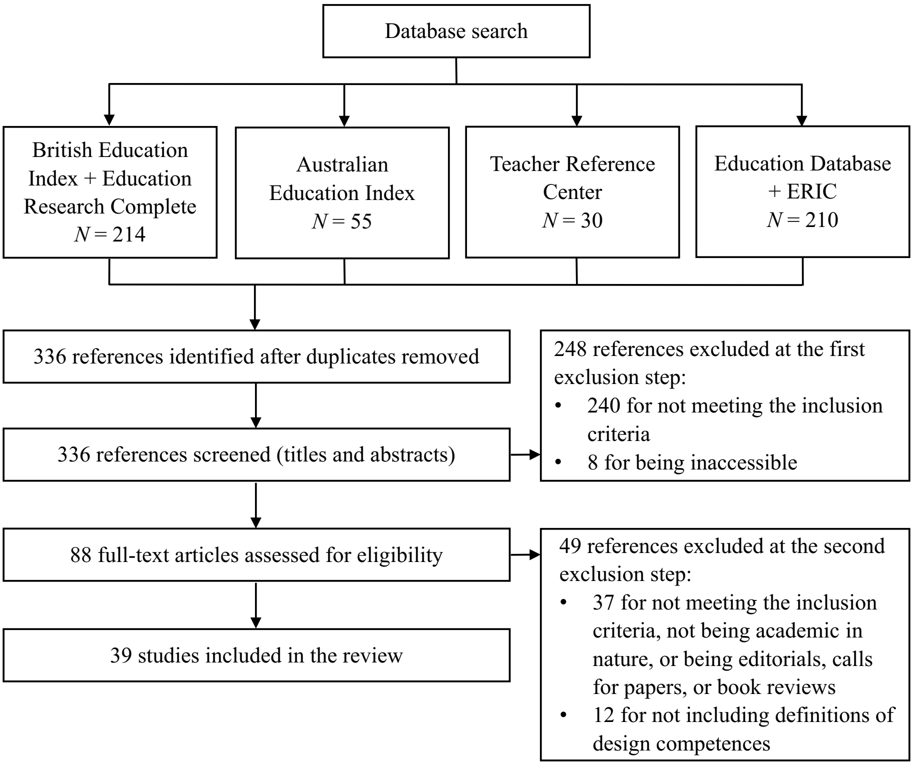

Fig. 1 Flowchart of the source selection process

to do with the use of design thinking by students rather than teachers, principals, school librarians, or other school staff who might use design thinking for school innovations or lesson design. Our final set of sources comprised 39 articles and included both review articles and primary theoretical and empirical studies. The empirical studies mostly consisted of intervention projects, but also involved a few observations of existing pedagogical practices (see Table 1). Sixteen of the 39 papers addressed the US context and seven the UK, of which two papers were collaborations between Canadian and British researchers. The fact that the majority of papers addressed Anglophone countries is obviously in part a result of our search strategy, which was limited to papers written in English. Other countries included, but in minimal numbers, Canada, Australia, New Zealand, a few European countries (Finland, Germany, and Spain), and Singapore; there was also a paper dealing with the Asia–Pacific region. In the UK, the Design and Technology subject has been part of general education since 1988 (Department of Education and Science & the Welsh Office, 1988). The US-published *Standards for Technological Literacy* (International Technology Education Association, 2007) has adopted the stance that design and technology should be embedded in various school subjects. This vision is reflected in the nine instances of cross-curricular research. However, a significant portion of the research on design in K-12 deals with science, engineering, or the umbrella term STEM (science, technology, engineering, and mathematics). A potential pitfall of the selective implementation of design and technology into STEM subjects is a one-sided focus on technical production, which disregards the user dimension (de Vries, 2011). Nonetheless, as our findings below show, the ability to empathize with end users was covered extensively in the reviewed literature.

As noted in Fig. 1 at the second exclusion step, not all articles were explicit about the competences associated with design thinking. Many articles referred to activities that students engage in during the design process. We recorded these activities and steps as competences if they were thoroughly described because the activities that students engage in presumably serve as the performance and development of various aspects of design thinking. Many of the theoretical articles dealt with professional designers' dispositions. We recorded these as competences if they referred to the skills necessary for design, although not all articles distinguished between the skills applicable for novices and those applicable for experts. We did not include skills that were mentioned but were not defined in detail.

The skills, dispositions, and activities associated with design emerged inductively during the initial readings of the articles. We collaboratively organized the multitude of initial codes into six overarching competence areas. Some of these areas had little variation in word usage, such as the well-established phase of empathizing, whereas other areas were characterized by a more varied vocabulary. For instance, we defined ideation as a competence area composed of concepts such as innovation, creativity, and imagination, whereas modeling involved concepts such as spatial reasoning, visual thinking, prototyping, and multimodal literacies used in the context of making. In the following sections, we present the six competence areas separately and discuss them in more detail, elucidating our coding procedure. In every section, a short opening paragraph frames the pedagogical context by relating the given design competence to an aspect of inquiry. This way, we relate the organization and expansion of the inductively coded competence areas to the theoretical framework of inquiry. Aside from these design competences, our reading of the selected sources also revealed general skills, such as collaboration, communication, critical thinking, and metacognition, as skills traversing the design competence areas. We describe their connections to the competence areas throughout the Results section. To introduce our search results, we start by briefly examining the prevalent understandings of design thinking as revealed by the reviewed material.

Table 1 Overview of studies

Study	Study design	Academic level	Country/region	Subject	*N*
Anderson (2012)	Interventional	Primary and secondary	Australia	Cross-curricular	125
Bain and McLaren (2006)	Interventional	Primary and secondary	UK	Technology	54
Baynes and Baynes (2010)	Interventional	Primary and secondary	UK	Cross-curricular	–
Becker (2016)	Theoretical	Primary	Canada	Cross-curricular	–
Bequette and Bequette (2012)	Review	Primary and secondary	US	STEAM	–
Berry (2012)	Theoretical	Secondary	Australia	STEM and Art	6 classes
Carroll et al. (2010)	Interventional	Secondary	US	Cross-curricular	24
Charman (2010)	Interventional	Primary and secondary	UK	Design and architecture	5*
Cook and Bush (2018)	Observational	Primary	US	STEAM	2 classes
Cusens and Byrd (2013)	Interventional	Secondary (and tertiary)	New Zealand	Technology	5 (9*)
Davis (2011)	Interventional	Primary and secondary		Design and technology	–
Francis et al. (2017)	Interventional	Primary	Canada	STEM	18 (19*)
Hill and Anning (2001a)	Theoretical	Primary	Canada and UK	Technology	8 (8*)
Hill and Anning (2001b)	Interventional	Primary	Canada and UK	Technology	8 (8*)
Johns and Mentzer (2016)	Observational	Primary and secondary	US	STEM	–
Kangas et al. (2013)	Observational	Primary	Finland	Design and STEM	3
Kelley et al. (2015)	Theoretical	Primary	US	Science	21
Kelley (2010)	Interventional	Secondary	US	Technology	1*
Kelley (2014)	Interventional	Primary and secondary	US	Technology	–
Kelley (2017)	Case study	Primary and secondary	US	Technology	–
Kimbell (2007)	Theoretical	Primary and secondary	UK	Design and technology	–
Lammi and Becker (2013)	Interventional	Secondary	US	Engineering	12
Lim et al. (2013)	Observational	Secondary	Singapore	Design and technology	2
McLain et al. (2017)	Participatory	Primary	UK	Design and technology	~60
Mentzer et al. (2015)	Interventional	Secondary	US	Engineering	59
Mentzer (2014)	Interventional	Secondary	US	Engineering	47
Noel and Liub (2017)	Theoretical	Primary and secondary	US	Cross-curricular	–

Table 1 (continued)

Study	Study design	Academic level	Country/region	Subject	*N*
Norris (2014)	Practical	Secondary	US	Advisory class	19
Razzouk and Shute (2012)	Review	Primary and secondary	–	Cross-curricular	–
Retna (2016)	Observational	Secondary	Singapore	Cross-curricular	16*
Scheer et al. (2012)	Interventional	Secondary	Germany	Cross-curricular	125 (12*)
Shively et al. (2018)	Theoretical	Primary and secondary	US	Gifted education	–
Stein et al. (2002)	Observational	Primary	Australia	Technology	60
Sung and Kelley (2018)	Interventional	Primary	US	Science	27
Tan and Wong (2012)	Theoretical	Secondary	Singapore	Spiritual education	–
Tsai et al. (2013)	Theoretical	Primary and secondary	Asia–Pacific region	Cross-curricular	–
Underwood (2014)	Interventional	Secondary	Spain	L2	13
Watson (2015)	Interventional	Secondary	US	Art	3
Wells (2013)	Theoretical	Primary and secondary	New Zealand	Technology	–

"Interventional" in the column "Study design" denotes that researchers devised the design challenge; "Observational" denotes that teachers devised the design challenge; "Participatory" denotes that researchers and teachers collaboratively devised the design challenge. "Country/region" is the country in which the empirical research took place or, in case of theoretical research, the country that the paper addresses by, for example, referencing the national curriculum. An asterisk for *N* indicates non-student participants (e.g., teachers, design experts, historical cases)

Results

The reviewed papers involved different understandings of design and design thinking, and some did not provide an explicit definition of design thinking. The theorist most frequently referred to in the definitions of design thinking was Nigel Cross (2001a, 2001b, 2002, 2006, 2008, 2011; Cross & Dorst, 1998; Cross et al., 1981, 1992; Dorst & Cross, 2001), who was cited in 10 of the 39 papers. The second most cited theorists were Kees Dorst (Cross & Dorst, 1998; Dorst, 2006, 2015; Dorst & Cross, 2001; Lawson & Dorst, 2009), Buchanan (1992, 1999), and Herbert Simon (1969), each of whom was referenced in five papers.

Cross (2006) argued that there is a particular set of competences related to design practices and being a designer. He described design expertise as the ability to (a) resolve ill-defined problems, (b) adopt solution-focused cognitive strategies, (c) employ the logic of conjecture, and (d) use nonverbal modeling media (Cross, 2006, p. 12). Dorst co-authored several papers in collaboration with Cross, which, in addition to the other works by Cross, describe design as a form of reasoning or sense-making (Cross, 2006, 2011; Dorst & Cross, 2001). According to a review (Johansson-Sköldberg et al., 2013), the view of design as sense-making fits within Schön's theory of reflective practice that involves connected rather than separate acts of doing and thinking. Buchanan (1992) represented a different albeit related discourse, in which design is regarded as a problem-solving activity centered on the concept of "wicked problems." According to Johansson-Sköldberg et al.'s (2013) review, Buchanan, Cross, and Schön share a practice-based approach to design, whereas Simon (1988) primarily regarded design as the creation of new artifacts for "changing existing situations into preferred ones" (p. 67). In the following sections, we review the selected articles in relation to specific competence areas. Our goal is to provide a better understanding of each area to encourage and support the development of design competences.

Reasoning

Referencing McKim (1972), Davis (2011) argued that frequent oscillation between different kinds of reasoning was a key characteristic of design thinking. In their review, Razzouk and Shute (2012) also found evidence in the literature that designerly behavior is successful in terms of innovation and efficiency when it entails alternating quickly between different modes of inference. Therefore, design inquiry can be said to involve different modes of reasoning that all contribute to achieving a result. The purpose of an inquiry is to gain knowledge—or, in a broader sense, to reduce the uncertainty that gave rise to the inquiry—based on which solutions to the problem can be developed. Inspired by Aristotle, Peirce (Peirce et al., 1974) worked with the concepts of abductive, deductive, and inductive inference. In this section, we discuss how these three fundamental modes of reasoning were addressed in the reviewed papers.

In the design process, an abductive strategy is initially used to make a guess. Based on fragmentary information, the designer guesses which idea may be best for achieving the desired outcome. Referencing Dorst (2015), Noel and Liub (2017) outlined a special case of abductive reasoning, namely "design abduction." A designer not only has to envision the element for achieving the desired solution but also has to frame the problem in a way that identifies the steps toward the solution. Thus, the designer deals with two unknowns, namely the "what" and the "how," which makes the design process more uncertain than other processes of inquiry but also more innovative. Much like the formulation of a hypothesis, which narrows down the scope of an inquiry, synthesis is a convergent process that reduces and clarifies the problem space. Davis (2011) defined synthesis as the activity of combining two or more seemingly unrelated ideas to generate a new perspective from which to view a problem. Such forging of connections facilitates innovation. According to Charman (2010), abduction is a cognitive strategy predominantly employed by designers. In her view, abduction is suitable for ill-defined situations because it involves guesses that can be iteratively altered once new information is acquired. In a paper by Lammi and Becker (2013), individual experience constitutes the source of incomplete information that students draw on to come up with initial ideas. The authors called this strategy "analogous reasoning" and argued that it could help students understand abstract concepts. Similarly, Tsai et al. (2013) referred to Rowland's (2004) observation that design decisions about nebulous problems are made by tapping into one's accumulated life experiences. Given that ideas are elicited by drawing on experience, abductive inference can also be called intuitive inference. Cusens and Byrd (2013) discussed intuition when exploring the origin of design ideas and the development of design thinking across educational domains. By examining how 11th-grade secondary school students and 4th-level tertiary education students addressed a design challenge and consulted an expert panel, the authors found that the difference between novice and expert designers had to do with the ability to "synthesize tacit knowledge, resulting in the correct action performed off-the-bat" (Cusens & Byrd, 2013, p. 242). For novice designers, "solving problems came at a high cognitive cost as they had little (relevant) tacit knowledge to apply to the situation, hence their need for rules and data from experts and stakeholders" (Cusens & Byrd, 2013, p. 242). Wells (2013) also regarded intuition as a source of knowledge and argued that intuition allows students to solve problems creatively instead of correctly.

Once an idea for a design proposal has been abduced, deductive inference can be used to expand on the implicit consequences so that the proposed design can be tested. In a study by Francis et al. (2017), professionals working in various STEM careers observed students aged 9–10 years build robots and commented on the skills that emerged during the students' work. The aim of the study was to extend educators' understandings of spatial reasoning in order to encourage educators to give spatial reasoning more attention in elementary schooling. A medical doctor noticed the students' use of conditional reasoning, which he described as the ability to arrive at a testable conclusion by rationally assessing data. A mathematician also noted the use of conditional (if–then) statements in programming. Two papers co-authored by the STEM educational researcher Todd R. Kelley (Kelley et al., 2015; Sung & Kelley, 2018) employed Halfin's (1973) codes for cognitive strategies, which are commonly used by engineering designers. These strategies include the process of "predicting," which involves using existing knowledge to predict the possible consequences of a proposed idea. When searching for sequential patterns of cognitive strategies among fourth-grade elementary students, Sung and Kelley (2018) found that students rarely used prediction. When this strategy was employed, it precipitated as well as followed the process of generating ideas. This indicated that the abduced idea was the point of departure for the prediction of consequences and from consequences, new ideas could also arise. According to Sung and Kelley's (2018), prediction is a unique feature of engineering design. This notion seemed to be prevalent among educational researchers, as deductive inference was not mentioned in any of the reviewed papers on design thinking in subjects outside STEM. Besides predictions, deduced evidence that enables testing hypotheses can also take the form of design criteria. Mentzer et al.

(2015) studied the differences in engineering-design performance between high school students and expert designers. They explained that in the process of understanding a problem, designers map out the criteria and constraints for their solution. Thus, the evidence on which judgments are based is deduced from the framed problem. The authors found that high school freshmen spent less time than their senior schoolmates or experts on attempting to understand problems. Therefore, they had less evidence to guide their decision-making and, as a consequence, could not arrive at a solution that would live up to all necessary functions. Kelley (2010) used the term "analysis" for the prediction of results and "optimization" for guidance via constraints and criteria. He considered both strategies superior to the trial-and-error approach and suggested the use of design notebooks and decision matrices for improving students' optimization skills. In a later paper, Kelley et al. (2015) regarded the identification and handling of constraints and criteria as the analytical phase. Drawing on Halfin (1973), Kelley et al. (2015) offered a more general understanding of analysis as the process of clarifying a problem by identifying or isolating its basic components. Contrary to their expectations, they found that students spent a remarkable amount of time in the problem space. Likewise, Davis (2011) considered analytical ability to be the skill of breaking down a problem into its constituent parts to identify which ideas should be developed further.

Having considered the implications of the proposed design and defined criteria and constraints, the designer can test if observations agree with these deduced results to ensure that the proposal is the best possible solution. This experimental part of the design inquiry is based on inductive inference. Bain and McLaren's (2006) study assessed the design skills of students aged 11–13 years using a rubric. The students were evaluated in terms of several skills, including their proving skills, which involve testing and reflection. The authors found that students were more adept at generating ideas than proving them. Similarly, Kelley et al. (2015) found that elementary school students typically neglected prototype testing. Referring to Halfin's (1973) study of high-level designers, Kelley et al. (2015) defined testing as the process of determining the feasibility of a model. The outcome of the test is the attainment of information that either elucidates the deduced design specifications or reveals the need to revise the specifications. If revised, the model can be tested again. As outlined above, Mentzer et al. (2015) found that high school freshmen spent less time than their senior schoolmates or experts defining a problem in terms of requirements for the solution. Consequently, they made fewer judgments regarding the feasibility of their design than high school seniors and expert designers. Referring to Schuun (2008), Lammi and Becker (2013) also defined optimization as the iterative process of "balancing constraints, trade-offs, and requirements" (p. 56).

As the reviewed studies have shown, design reasoning comprises abductive, deductive, and inductive modes of reasoning. Abduction is initially employed to conceive a range of possible solutions by drawing on prior experience and the incomplete information that makes up the problem space. Then, these proposed solutions are developed using deduction—for example, by tracing their logical implications and establishing requirements in terms of functionality, aesthetics, and so on—to arrive at a testable solution. Lastly, the developed design proposals are tested inductively. This way, deductive and inductive processes serve to validate the highly fallible initial guesswork. Although the different modes of reasoning are associated with certain phases of the design process, they can also provide occasions for reiteration—for example, when deductive elaboration results in new ideas or a test outcome requires the revision of specifications.

Problem setting

According to Carroll et al. (2010), who studied the application of design thinking in teaching, "students need both the skills and the tools to participate actively in a society where problems are increasingly complex and nuanced understandings are vital" (p. 38). This insight resonates with one of the main arguments of pragmatism, which, as argued earlier in this paper, is also at the root of design thinking—namely, that inquiry should be driven not by mere curiosity but by problems relevant to people. By means of the design inquiry, one should gain new knowledge for solving the problem at hand and make a change by applying this knowledge to the problem. This section discusses the ability to set the problem—that is, to find, understand, and frame the issue—and outlines how the reviewed papers described design competences with regard to approaching and scoping problems.

Carroll et al. (2010) studied the implementation of design thinking in a middle school classroom. When evaluating design thinking as a teaching method, a middle school teacher emphasized the improvement in students' competences in relation to problem solving as the students reflected more on their approaches to problems: "We're not just going to think about a problem, but we're going to think about how to think about a problem" (Carroll et al., 2010, p. 47). Being able to critically think about and act upon issues is important in a world where issues accumulate, and design thinking challenges students to become the "change agents" who find "answers to complex problems" and develop "multiple viable solutions" (Carroll et al., 2010, p. 38). Carroll et al. (2010) emphasized this view of students as empowered actors in the world: "Design thinking is an approach to learning that focuses on developing students' creative confidence. Students engage in hands-on projects that focus on building empathy, promoting a bias toward action, encouraging ideation, and fostering active problem-solving" (p. 38). Accordingly, Cook and Bush (2018, p. 94) referred to Plattner (2010) when stressing that design is an inquisitive approach that allows students to be "empathetic toward others, identify problems, and generate creative solutions." This mindset was said to include eschewing familiar patterns of problem solving by questioning the problem and the framing of the design situation (Cook & Bush, 2018). Furthermore, students had to accept that a solution cannot be "right" or "wrong." Dealing with wicked problems for which no single solution is possible, students had to consider "multiple viewpoints, synthesizing data, and generating solutions that invoke their creativity, collaboration, critical thinking skills, and communication skills" (Cook & Bush, 2018, p. 101). According to Cook and Bush (2018), this process required an open mindset and the ability to tolerate ambiguity.

Carroll et al. (2010) based their understanding of problem solving on Passig's (2007) notion of melioration (that is, making better), which they considered to involve "choosing the appropriate chunks of information, and applying them to the solution of problems in different time and space-dependent situations" (p. 38). They claimed that this process was important in design but tended not to be prioritized by novice designers. Furthermore, Carroll et al. (2010) stated that expert designers had a well-developed ability to look for relevant information to understand a given problem. This finding also emerged when Mentzer et al. (2015) compared the design processes of novice designers (high school freshmen and seniors) to those of experts. A comparison of the time allotted to problem scoping, which covers problem definition and information gathering, by the high school students and experts revealed that experts spent significantly more time on information gathering. Experts focused on “understanding the design problem before attempting a solution” (Mentzer et al., 2015, p. 428). The authors emphasized that problem scoping is critical for design thinking because it “sets the foundation for developing solutions” (Mentzer et al., 2015, p. 429).

Sung and Kelley (2018) explored the thinking behind problem solving by studying fourth graders’ cognitive activities in relation to an engineering task and identifying common problem solving patterns in that process. The students had to solve a design problem while thinking aloud, which enabled the researchers to follow their thought processes. Sung and Kelley then calculated the time that students spent on seven different cognitive activities. Their findings showed that fourth graders spent significantly more time on designing, modeling, and questioning than defining and analyzing the problem, managing the process, and predicting implications, which confirmed Mentzer et al.’s (2015) findings.

Kelley et al. (2015) also found that students in grades five and six spent significantly more time on designing than other activities in their problem solving process. They discovered that students who carefully framed the problem over multiple iterations were generally more efficient designers and made better design suggestions than students who spent less time in the problem space. These students had a teacher with extensive experience in a design-based approach to teaching. Kelley et al. (2015) claimed that this teacher may have scaffolded the students’ systematic approach to defining the problem space, which suggests that K-12 students need support in learning this skill. Nevertheless, the researchers also found that all students spent more than a fifth of the total design time in the analytic phase trying to identify and address the constraints and criteria related to the problem. Sung and Kelley (2018) suggested that this analytic phase is part of problem scoping and emphasized that students engaged in defining the problem space when designing. Sung and Kelley (2018) also argued that this first stage of the design process was, indeed, analytic because the (student) designers engaged in “identifying, isolating, taking apart, or breaking down the given problem” (Sung & Kelley, 2018, p. 12).

In summary, problem solving through design thinking is biased toward action. Students who work with design thinking in class may become more reflective when approaching problems. Engaging in design thinking can foster creative confidence because students can become change agents who learn to tackle complex problems and develop multiple viable solutions. Design thinking is an inquisitive approach that requires students to be empathetic toward others and to take the views and needs of others into account. When faced with an issue, designers need to eschew familiar patterns of problem solving by questioning the presented problem and its framing. This requires an open mindset and the ability to tolerate ambiguity. Skilled designers collect relevant information on the problem and then analyze and frame it, which enables them to understand the problem before attempting to solve it. Learning to work with problems in such a systematic and analytical way requires scaffolding.

Empathy

To begin the design process, the problem at hand must be framed, as outlined above. To achieve this, the designer needs to become immersed in the social context of the problem. This stage involves the skill of empathizing, which is about understanding the needs and perceptions of others. Empathy was discussed in many reviewed studies, and in this section, we extract the most salient aspects of the ability to empathize in the design process.

To produce a meaningful design, it is necessary to map out end users' criteria for a solution. End users can have a variety of conflicting interests, which makes it even more important to recognize these interests. As Davis (2011) noted, end users are often a heterogeneous group with competing values and priorities. No design can satisfy everyone, and part of designing a solution involves resolving these conflicting user needs while recognizing that such prioritization of needs is biased. Following Sheppard et al. (2009), Mentzer et al. (2015) identified "reflective judgment" as a proper term for the cognitive approach in design thinking. Drawing on King and Kitchener's (1994) developmental stages of reflective thinking, the authors argued that becoming adept at design thinking entails a shift from regarding knowledge as certain to recognizing that some problems are poorly structured and that certainty requires judgments. In the K-12 context, Davis (2011) highlighted the need to make students aware of this ambiguity instead of presenting them with simple problems. Tsai et al. (2013) also emphasized that the human dimension of design makes design a normative process. The fact that design has implications for people in the real world introduces an ethical dimension. Citing Rowland (2004), the authors argued that this dimension of the design process teaches students to empathize with others, accept ambiguity, and take responsibility for their actions.

Shively et al. (2018) claimed that the emphasis on empathy in the design process forces students to critically consider an issue from other people's perspectives. Norris (2014) investigated the connection between design thinking and Freire's (1970) critical pedagogy—a dialogical approach with emphasis on addressing problems in society through reflection and action. Citing Watkins (2012), Norris argued that the design process fosters critical thinking because students are required to look at a social environment with an inquiring attitude. In her study, she also concluded that students gained a critical awareness of themselves as they discovered how their gendered and racialized identities influenced their designs. Tangible designs facilitated students' critical awareness of their reality. As these studies have shown, students exercise their critical thinking when they empathize with others and when they become aware of their own positions.

Some studies divided the skill of empathy into cognitive empathy and affective empathy. Citing Chen et al. (2015), Noel and Liub (2017) identified the need for cognitive and affective empathy in various professions. Cognitive empathy means understanding others' points of view, whereas affective empathy involves relating to others' feelings. Carroll et al. (2010) defined empathy as the ability to intellectually recognize or vicariously experience the feelings, thoughts, or attitudes of others.

Needs can be explicitly articulated by the intended end users, but they can also be discovered by designers' analysis of unspoken or unconscious wants. Scheer et al. (2012) discussed users' hidden needs, which designers had to discover by understanding the relations between the problem and its social context, and Carroll et al. (2010) argued that needs can be either latent or manifest. Kelley (2014) identified focus groups, interviews, and surveys as techniques for getting inside users' heads. Shively et al. (2018) claimed that observations, interviews, and spending time in the users' everyday milieus are the most fruitful ways of collecting user information, while Cusens and Byrd (2013) identified observation as designers' primary inspiration. Kelley (2014) regarded students' analysis of multiple data sources as expert design behavior with respect to the skill of empathy, whereas Shively et al. (2018) focused on the quality of the collected data. Davis (2011) introduced the construction of scenarios and personas as a method for analyzing typical users' interactions with designed objects.

In the school context, empathy is directed not only at the user for whom a solution is designed but also at the peers with whom students collaborate when designing a solution.

Citing Goleman (1999), Wells (2013) argued that students learned multiple skills when they interacted with their peers. Among other skills, students were said to develop an awareness of their own position and the ability to sense others' needs and respond to these needs. According to Wells, building social intelligence through design processes also entailed learning how to be sensitive, respond appropriately, and resolve conflicts. Apart from enabling group work, other studies regarded empathy as a formative skill that promoted selflessness and tolerance. For instance, Tan and Wong (2012) considered the pedagogical purpose of design thinking to be the development of empathy toward people who are different from oneself. In Retna's (2016) study, teachers were found to be especially attracted to the emphasis on empathy in the design process. More specifically, teachers hoped that learning to think about others' needs could counterbalance the negative effects of growing up in an individualistic culture. According to Tsai et al. (2013), collaborating on the design of a product improves students' self-awareness and reflexivity. Similarly, Davis (2011) related empathy to the ability to meta-cognitively assess one's own learning. What these abilities share is the awareness of others' and one's own perspective among multiple possible perspectives.

In sum, empathy in design involves acknowledging the subjective nature of design decisions. Empathy may be directed at both end users and peer collaborators. In the design process, empathizing with others is essential because designers create solutions for people with given wants and with characteristics different from their own while often working in design teams composed of people with different skill sets and interests. Designers must collect user data to identify end users' values and needs, either cognitively or affectively, and prioritize these needs to design a specific solution. Designers also have to become aware of their own position to recognize how subjective values affect their prioritizations of interests.

Ideation

Once the problem has been framed, the designer continues the inquiry process by conceiving ideas for solving the problem. The reviewed studies highlighted ideation as a central competence in design processes. As outlined previously, ideas are the results of abduction and are later qualified or revised by deductive and inductive reasoning. As neither the problem nor the solution is fixed but rather has to be iteratively defined, the ideation phase of the design process is nebulous, and students must embrace its ambiguity to arrive at innovative design proposals.

According to Charman (2010, p. 34), students' proficiency in ideation rests on their ability to "tap into memories or associations" or "draw analogies from their experience." Razzouk and Shute (2012) also argued that initial ideas are drawn from the designer's existing knowledge of the subject and claimed, in line with Dörner (1999), that such knowledge can be a source of analogies. Referencing Hammer and Elby (2002), Tsai et al. (2013) developed a knowledge-creation model based on the notion that initial ideas are formed by activating "initial epistemological resources, which refers to prior knowledge and everyday ways of knowing" (p. 85). Lammi and Becker (2013) called attention to the fact that analogies are limited because students come from different backgrounds and have different experiences. However, the authors highlighted the usefulness of analogies for students in high school or in lower grades.

Most studies treated quantity as an aspect of ideation. Kangas et al. (2013) used the term "horizontal ideation" to refer to the generation of multiple ideas, as opposed to "vertical ideation," which is the development of selected ideas. Using the six design steps elaborated by Hasso Plattner Institute for Design, Carroll et al. (2010) defined ideation as a stage in which quantity is encouraged. In a study conducted by Berry (2012), students were instructed to come up with numerous ideas, and McLain et al. (2017) noted and valued students' productivity in devising ideas. Noel and Liub (2017) and Hill and Anning (2001a) regarded the generation of multiple ideas as expert design behavior, and the importance of multiple ideas was also discussed by Scheer et al. (2012), Watson (2015), Kelley (2014), and Anderson (2012). Davis (2011) and Shively et al. (2018) used "fluency" to refer to abundance of ideas, respectively drawing on E. Paul Torrance's (1959) work on developing tests for assessing creative thinking and Guilford's (1950) definition of creativity. In relation to idea proliferation, Cook and Bush (2018), Noel and Liub (2017), and Shively et al. (2018) all identified an aversion to settling for the first idea. This aligned with Csikszentmihalyi's (1988, p. 168) definition of the creative person, referred to in McLain et al. (2017), as someone who "is able to delay closure: she avoids jumping to conclusions, and waits for the new idea to mature instead of forcing it prematurely into the shape of an already existing one." Mentzer (2014) and Mentzer et al. (2015) argued that by devising alternatives to the initial idea, students are forced to evaluate differences between ideas and to reflect on final decisions. According to McLain et al. (2017), moving beyond the initial idea can also make students focus on a problem's social and affective aspects rather than the technical aspects alone.

For competing alternatives to stimulate reflection and critical thinking, ideas should not only be plentiful but also semantically different. In developing a rubric for creativity, Shively et al. (2018) drew on Guilford's (1950) definition of creativity, which referred to a diversity of ideas as "flexibility." Referencing Staw (2006), Mentzer et al. (2015) and Carroll et al. (2010) claimed that diversity of ideas is essential for innovation. Retna (2016) argued that exposure to real-world issues enables students to address a problem from different angles and devise various solutions, while Watson (2015) identified an "imagine" step in the design process during which students come up with and try out different ideas. Originality and novelty were said to be related to diversity, and Shively et al.'s (2018) paper on developing a creativity rubric was also based on Guilford's (1950) definition of creativity, which included originality—that is, the uniqueness of ideas. Davis (2011) referred to the generation of new ideas based on the work of E. Paul Torrance (1959) on developing tests for assessing creative thinking. According to Anderson (2012), developing new ideas is a prerequisite for innovation. Summarizing their findings, Razzouk and Shute (2012, p. 343) noted that by applying ideation techniques in a design process, students learn how to "think outside of the box" and "come up with innovative solutions."

Multiple articles defined the ideal classroom environment as one that stimulates ideation. This environment was said to be one in which students do not judge each other's ideas before numerous ideas have been produced. Carroll et al. (2010) emphasized the importance of ensuring a supportive milieu for students to feel confident to come up with fantastic ideas. Kimbell (2007) argued that while unrealistic ideas may not offer any immediate practical solutions, they can form the basis for the most innovative designs, which can later be adapted to accommodate functional requirements. Referencing Stables (1992), Kimbell claimed that this open mindset required in design processes is especially suitable for children due to their imaginative power. With reference to Kubie (1958), Wells (2013) argued that illogical ideas are the first and essential stage of any creative process and generate material for the second, evaluative stage. Like numerous, diverse ideas, illogical ideas have the didactic purpose of stimulating critical thinking as they "allow pupils to engage with a discourse and make value judgments" (McLain et al., 2017, p. 34). Consequently, "design thinking fosters the ability to imagine without boundaries and constraints" (Carroll et al., 2010, p. 52). Baynes and Baynes (2010) argued that such designerly imagination can invent products that may not be plausible today but can become real in the future. By contrast, some researchers believed that creativity is facilitated by imposing constraints on the design process. In Charman's (2010) view, constraints narrow the solution space, which helps students focus on suitable ideas, while Davis (2011) identified constraints as a way of ruling out conventional ideas. In line with Haught-Tromp's (2017) work, Shively et al. (2018) supported the idea of the creative potential of constraints.

In opposition to the production of multiple ideas, which can be regarded as a divergent process, combination is a convergent part of ideation. In their review of scholarship on design thinking, Razzouk and Shute (2012) concluded that designers are characterized by the ability to synthesize different concepts into entirely new concepts. According to the two authors, combining concepts allows designers to create new products and ideas. Noel and Liub (2017) claimed that innovation and creativity have to do with combining two or more dissimilar ideas. Citing Rosenman and Gero (1993), Davis (2011) explained that constructing a new conceptual configuration from existing ideas allows for a creative leap and produces a different frame for evaluating the problem at hand. In classroom settings, combination was seen by Watson (2015) as a technique for initiating creativity in the idea generation phase and by Lammi and Becker (2013) and Cook and Bush (2018) as a way of combining the design team's ideas to arrive at a final group solution.

Students should also understand that creativity can be a collective effort. Wells (2013) cited Robinson's (2001) argument that solitude is not a requirement for being creative. On the contrary, the most creative outcomes arise from the exchange of ideas among people with different areas of expertise and skill sets. The creative potential of multidisciplinary teams was also addressed by Tsai et al. (2013) and Carroll et al. (2010) and supported by Tan and Wong (2012), who cited Brown's (2009; Brown & Wyatt, 2010) definition of design problems as cutting across different disciplines. To make students "T-shaped" people—a term popularized by Edwards (2008) for describing people who can see possibilities in combining their competences with those of others—teachers need to design projects that invite students to value people's differences and ideas. In the classroom setting, Hill and Anning (2001a, 2001b) observed students propose ideas based on their fellow students' designs, and Bain and McLaren (2006) carried out an intervention project in which students were asked to ideate based on peer evaluations of their initial ideas. Scheer et al. (2012) also discussed the advantages of brainstorming in teams, which, they argued, helps students build on each other's ideas.

Collaboration not only helps students generate ideas but also helps them improve their ideas. In McLain et al.'s (2017) study, a teacher noticed that students naturally worked together to modify each other's ideas. Tsai et al. (2013), citing Oshima (1998), explained that articulating ideas results in interaction because students may have different understandings of a problem, which helps refine ideas. Citing Stager (2013), Becker (2016) emphasized that collaboration among students who connect with each other's ideas should be mutually beneficial. Bain and McLaren (2006) argued that, in addition to facilitating collaboration, sharing and evaluating ideas develops students' communicative skills and that presenting ideas involves learning how to sell one's ideas to a potential client. According to Mentzer (2014), collaboratively developing ideas exposes students to critical thinking as questioning each other's ideas prompts feasibility considerations.

This second, evaluative phase, which Kangas et al. (2013) called "working vertically," follows the first phase of producing numerous ideas, which they referred to as "working horizontally." With reference to Runco and Jaeger (2012), Shively et al. (2018) claimed that usefulness was another aspect of ideation because students must understand the social context for which they ideate solutions. According to Davis (2011), the evaluative activity of considering the usefulness and quality of ideas is often forgotten when assessing students' ideation skills. In line with Csikszentmihalyi (1996), Sternberg (1999), and Schwartz (1987), Davis (2011) criticized scholars' unilateral focus on non-judgmental skills, arguing that the disregard of evaluation overlooks the essential analytical skill of critical thinking.

To conclude, the ideation phase is characterized by ambiguity because solutions and problems are developed interactively. Designers should embrace this indeterminacy by ideating from multiple perspectives and thus concocting ideas that are manifold and diverse. Ideas are derived by drawing analogies between personal experience and the problem at hand, and originality can be achieved by combining ideas into entirely new concepts. A classroom environment conducive to ideation is one in which peer judgment is deferred during collective brainstorming and in which teachers can introduce constraints to guide students towards appropriate ideas or to rule out obvious ideas. Based on the pool of generated ideas, some ideas can be selected for further collaborative development by assessing their usefulness. During this process of comparing the value of different ideas, designers can arrive at a proposal worthy of further exploration through modeling.

Modeling

The construction of models was an often-mentioned ability in the reviewed articles and should be an essential part of design thinking in schools. This is in line with Dewey's (1985) learning-by-doing approach, according to which playing with physical materials facilitates the transformation of learning from passive absorption to an active and constructive process. According to Schön (1992a), designers engage in a conversation with the materials by being attentive to the "backtalk" that emerges from the constructed artifact. Modelled ideas can then be explored further by listening and responding to the situational feedback.

Transforming a construct from a mental product into a physical form involves conducting a conversation with oneself. Davis (2011) supported the position of the School Examination and Assessment Council in Great Britain (Kimbell et al., 1991), according to which sketches and models are a way of giving shape to ideas and thereby making them available for exploration and manipulation. Sung and Kelley (2018) argued that representations stimulate thinking by encouraging the exploration of links between the mental and the physical model; the authors empirically documented this process by considering the relations between cognitive strategies in design adopted from Halfin (1973). Their data showed that modeling often led to the questioning strategy, which involved challenging elements of the design. Becker (2016) pointed out design thinking as one of three pedagogical discourses important for the creation of maker spaces and identified their common elements. Referencing Brown (2009), Becker (2016) found that mind maps are an effective way of externalizing purely mental models.

When an idea is represented, it is not only externalized for individual exploration but also made available for public scrutiny. Representation enables end users and group members to offer feedback. Ideas are tested and developed, and the group achieves consensus on how to proceed. Carroll et al. (2010) called this process a culture of prototyping. According to Kangas et al. (2013), modeling facilitates collaboration because when students work collaboratively on a physical object, their actions are mediated by the artifact and made visible to the students. The authors argued that proficiency in design depends on materially mediated communication; to produce an effective solution, students must be able to use materials and tools as well as words to communicate their ideas to others. Cusens and Byrd (2013) also argued that students should learn to communicate their ideas multimodally, and Francis et al. (2017) similarly defined visualization as the construction of designs that convey information.

Besides enabling ideas and information to be communicated, modeling involves the ability to interpret the ideas that are being communicated. Davis (2011) employed McKim's (1972) tripartite concept of visual thinking to claim that schools emphasize observation at the expense of imagination and making. According to Davis, students read diagrams in textbooks, but they do not imagine and construct their own representations of data—that is, they are not taught to critically consider representations. For instance, students are not generally asked to assess what type of diagram is best suited for a given data type or to consider whether a gradient color palette is the appropriate way of representing increasing proportions. In addition to decoding representations of information, Francis et al. (2017) argued that students should be able to read representations of three-dimensional objects. This skill was documented in their study, in which professional designers commented on a video of children building robots. The experts' written statements documented the skills that emerged during the children's work and that the experts deemed important for the design profession. One of these skills was the ability to interpret the conventions used in depictions, such as shape, scale, orientation, size, and light and shadow, to understand two-dimensional representations of three-dimensional objects.

In some papers, sketches and 3D figures were considered to be representations, whereas in others, representations strictly referred to non-textual, two-dimensional descriptions of how to build a (typically three-dimensional) solution. Mentzer et al., (2015, p. 424) described a coding scheme adopted from Atman et al. (1999), in which modeling was defined as "detailing how to build the solution (or parts of the solution) to the problem."

Bequette and Bequette (2012) saw modeling as graphical communication insofar as representations offer pictorial descriptions of how 3D models are built. However, some scholars argued that text need not be completely absent from representations. According to Halfin's (1973) codes for designers' cognitive strategies, adopted by Kelley et al. (2015) and Sung and Kelley (2018), a representation can be a graphical, physical, or even written generalization. Text can also be incorporated into pictorial representations via annotations, labels, or a key for explaining symbols (Kelley, 2017). Francis et al. (2017) considered the comparison of two-dimensional pictures or written instructions with a three-dimensional physical object to be a key aspect of modeling.

Planning the construction of a solution entails both a technical aspect and an aesthetic aspect. Kangas et al. (2013) described design as movement between two problem spaces, one visual and one technical. According to the authors, the composition space is related to the organization of visual elements, such as shape, pattern, and color, whereas the construction space is related to the organization of technical elements, such as structure, material, and production methods. Razzouk and Shute (2012) reviewed a study by Seitamaa-Hakkarainen and Hakkarainen (2001) that examined the differences between novice and expert weaving designers. The authors found that experts focused equally on visual and technical elements in the design process, whereas novices mainly focused on visual aspects and seldom explored how the latter could be implemented in the solution. The importance of considering both spaces was supported by Hill and Anning (2001a, 2001b), who found that professional designers believed that it was important for school students to learn about aesthetic concepts, such as proportion. However, the designer interviewed in Hill and Anning's study emphasized the importance of considering these aesthetic aspects in relation to the built environment. According to Mentzer et al. (2015), the consideration of visual and technical elements, such as size, shape, and scale, is what separates (engineering) design from other problem-solving strategies. Likewise, Kimbell (2007) argued that the ability to handle fantasy and reality in unison is an essential skill for designers. Baynes and Baynes (2010) claimed that aesthetic elements, such as shape, form, and color, form the basis of designerly thinking and that understanding mathematical harmonies, such as pattern and proportion, enables a designer to communicate an idea clearly both to themselves and to others.

In summary, models, whether two- or three-dimensional, allow designers to communicate ideas to themselves and to others. When directed at oneself, externalization makes an idea available for exploration and facilitates the visual organization of information. Exploring an idea involves considering both its visual and technical aspects with the aim of communicating one's idea as clearly as possible. When communicated to others, representations of ideas can be improved through feedback. Furthermore, representations enable others to help build the depicted model. The modeling ability involves constructing, improving, and understanding representations of ideas and information.

Process management

In this section, we analyze the reviewed papers' understanding of process management. Decisions narrow the solution space and are a way of managing the ambiguity of the design process described in the previous sections. Schön's (1983) view of design as a reflective practice entails reflecting on one's design decisions. From a Deweyan perspective, it is through such decisions—that is, through actions and their consequences—that students construct meaning. Like reasoning, the skill of process management is needed at every step of the design process.

Kangas et al. (2013) argued that "success in the design field … depends on the management of the whole design process in all its components, from idea generation to the mastery of techniques. Students need to manage the procedures of planning and making" (p. 30). In their study of design pathways among fourth graders, Sung and Kelley (2018) employed Halfin's codes (1973) for cognitive strategies. In Halfin's (1973) study, "Managing" was defined as "the process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system" (p. 196). Sung and Kelley (2018) found that managing followed the activity of defining and analyzing the problem and preceded the modeling stage. Moreover, Sung and Kelley also found that managing followed the cognitive strategy of "questioning", which indicates that managing is employed at various steps in the design process. However, Sung and Kelley also found that managing was one of the least frequently used cognitive strategies among the participants. As Sung and Kelley noted, this empirical finding confirms Crismond and Adams' (2012) argument that novice designers regard design as an end product or stage, whereas expert designers see design as a managed, iterative process.

In Halfin's (1973) dissertation, managing was broken down into operations such as determining and prioritizing goals, generating and evaluating alternative solutions based on specified criteria, identifying required resources, evaluating feasibility, assigning time schedules and tasks to project participants, and determining sequences of events. Halfin analyzed the writings of high-level technologists to establish operational definitions of technologists' processes of inquiry. Based on his analysis, he concluded that managing was a higher-level activity than the other skills covered in his study, such as modeling. He proposed that the operations that belong to managing are skills on the same level as modeling and that these multiple skills covered by managing should be explored further.

Based on Halfin's operations of assigning time schedules and determining sequences of events, one can infer that time management is an aspect of managing. In their review of design competences, Razzouk and Shute (2012) included "manage time" in their competence model, but they did not elaborate on the details of this skill. Likewise, Lim et al. (2013) simply stated that time management is important. Kimbell (2007) offered a more comprehensive description of management. He referred to design tasks as wicked problems and argued that students need complex management skills, which include both managing and optimizing. According to Kimbell (2007), time is one factor that needs to be managed, alongside "cost, materials, production processes, technical performance, and much more" (p. 190). In this sense, managing means handling the ambiguity of wicked problems by making design decisions.

When discussing engineering design, Kelley (2010) defined optimization as the systematic process of making decisions about design based on the identified constraints and the specified criteria. In Kelley's view, this vital skill of being able to make informed decisions is often missing at the middle and high school levels. Referring to Schunn (2008), Lammi and Becker (2013) also defined optimization as the balancing of constraints and requirements, which, as they noted, are often in conflict. To manage this conflict, as well as the variety of end users' values and needs, prioritization is necessary. Lammi and Becker (2013) stressed that optimization should be employed continuously throughout the design process by revisiting the design for further improvement. According to the authors, educators should motivate students to balance technical functionality with variables such as cost and aesthetics iteratively to teach them to make informed decisions. In their study of the differences in design processes between high school engineering students and expert engineers, Mentzer et al. (2015) highlighted the importance of making design decisions by comparing various possible solutions based on a dimension, such as cost. The authors referred to eight design processes identified by Mosborg et al. (2006), of which the following three pertain to the skill of making decisions: feasibility, evaluation, and decision-making. When assessing feasibility, students pass judgment on a solution; when engaging in evaluation, they compare different solutions based on a set of dimensions; and when making decisions, students choose a solution, having assessed its feasibility and compared two or more design alternatives. Mentzer et al. (2015) claimed that these skills are essential for the engineering design process. However, they found that high school students spent significantly less time judging functionality and evaluating alternatives than did the experts.

In a collaborative design process, such negotiation of criteria and possible solutions supports a shared meaning-making process (Kangas et al., 2013). Halfin's (1973) operation of task delegation is a people-oriented aspect of managing. Distributing responsibility is particularly relevant as design problems are often solved in teams. In their study of the collaborative and embodied nature of design at the elementary-school level, Kangas et al. (2013) focused on the skill of collaboratively organizing a process. In their view, students should not only learn to coordinate the process but also develop and maintain a shared understanding of their endeavor. In this sense, the skill of empathy is a prerequisite for a team to be able to organize their joint design activities.

Davis (2011) described how rapid technological changes in the twenty-first century have emphasized the need for a new approach to organizing the design process. With reference to Dubberly (2008), Davis claimed that an organic process has replaced the earlier mechanical process, which was managed from the top down and aimed for almost perfect solutions. Today, designers supposedly manage their process from the bottom up and strive for adequate rather than perfect solutions, which can also be improved later if required. As Sung and Kelley (2018) and Lammi and Becker (2013) have noted, design is an iterative process in which designs are continuously revisited for improvement. In their review, Razzouk and Shute (2012) included a study by Ho (2001), which found that both novice and expert industrial designers employed a bottom-up, working-backward approach. Wells (2013) was also opposed to the linear, top-down approach and criticized the current technology-education curriculum for its highly structured content. He argued that a uniform, restricted approach to design hinders creative problem solving and that by employing a formulaic design process in class, students miss out on opportunities for building awareness of their own learning processes. Carroll et al. (2010) and Cook and Bush (2018) also emphasized the metacognitive rewards of design thinking. They stated that the design cycle teaches students to be aware of their design decisions—that is, why and how they make certain decisions and which decisions they should make to move forward in the process. Bain and McLaren (2006), Berry (2012), Kelley et al. (2015), Shively et al. (2018), and Underwood (2014) have all emphasized the fact that design supports students' reflections on their own learning via process documentation, such as portfolios. Scheer et al. (2012) attributed this metacognitive potential to the multidisciplinary and project-oriented nature of design, which enables self-regulated, collaborative, and authentic problem solving in schools.

In accordance with the bottom-up, iterative approach to design problems, Hill and Anning (2001b) found that second-grade students did not plan all details of their design in advance. Rather, they let their ideas emerge by experimenting with materials and sketching. This finding reveals one reason why design thinking should be integrated into education: namely, because the materiality of the method suits tactile and kinesthetic learners very well. This finding was supported by Davis (2011) and Kangas et al. (2013). However, a paper by Cross (2004), referenced in Razzouk and Shute's (2012) review, showed that novices and experts differed in their process-management skills. Whereas experts started by decomposing the problem, novices tended to dive directly into exploring sub-solutions and lacked an overview of the process. Thus, it can be concluded that although a design process should evolve gradually instead of being planned entirely in advance, designers should start by obtaining an overview of the problem.

In the school context, not all scholars believe that students benefit from being allowed to freely experiment with no teacher intervention. From a STEM perspective, Johns and Mentzer (2016) claimed that students working on a design task can profit from scaffolding while still having opportunities to make design choices. Kangas et al. (2013) also defined effective learning environments as those that enable engagement with real-world inquiry but which, at the same time, are highly constrained. Likewise, Stein et al. (2002) found that although students gained much from experimenting on their own, it was beneficial for the teacher to draw attention to various reasoning strategies to help students go beyond the trial-and-error approach.

In conclusion, design concerns indeterminate problems, which need to be defined to advance the design process. The uncertainty of the design process is handled by making judgments informed by analysis and synthesis—that is, by identifying the components of the problem, such as constraints and requirements, and balancing them to frame the problem and establish design criteria. Judgments narrow the problem and the solution space or re-expand the spaces if an iteration is deemed necessary. Necessary decisions emerge during model making and have to do with the prioritization of constraints and criteria, which enables judgments on feasibility. Time management is also a factor and can be addressed by determining the order in which tasks should be solved and assigning schedules. Delegating tasks to collaborators is another way of managing the complexity of the design process.

Summary and discussion

This review was motivated by our recognition that design thinking as a teaching method has the potential to improve students' learning. When school students are assigned tasks that involve repetitive drilling, they do acquire skills. However, in this form of learning, the predetermined correct responses convey to students a view of knowledge as being absolute. Furthermore, practicing isolated skills in drills decontextualizes these skills from their real-world applications. By contrast, as this review has shown, design thinking proposes an ambiguity-based learning process that enables students to reflect on the subjective nature of knowledge and that addresses problems relevant to students' lives.

Our review study has been partially motivated by our interest in the epistemology of inquiry, whereby tentative knowledge is generated through interactions with the world and its objects whose purpose is to arrive at adequate rather than true solutions to problems. To engage in a dialogue with the world, the framed problem that has initiated the inquiry must be perceived as relevant. We believe that design thinking, as described in this review, offers a practicable approach that adheres to both the materiality and the authenticity of inquiry.

Inquiry begins by wondering about something in the world. Translating a puzzling situation into a problem enables seeking for a solution and making sense of the indiscernible situation. The ambiguity of design problems, which has been discussed at several points in this review, can seem paralyzing at first, but it is what renders design problems authentic. Design problems are the stuff of everyday life, and it is for this reason that they are messy and ill-defined, which places them in stark contrast to the well-structured problems of mathematics and other school subjects. If real-world problems are to be introduced into schools, students must learn to tolerate ambiguity and thrive in it. This means not forcing a premature solution before fully grasping the problem at hand, as we have discussed in the Problem Setting and Ideation sections. Furthermore, process management refers to the process of reducing ambiguity by making informed design decisions. Accepting ambiguity means recognizing that all ideas stem from personal experience and subjective values and that, consequently, there are no right or wrong solutions. We have discussed this topic in relation to empathy, problem setting, and ideation.

Designers act upon the world by conceiving possible solutions and endowing them with physical form, which reveals the designer's understanding of the problem. Solutions can be modeled either digitally or using tangible materials. As we argued in the Modeling section, a prototype serves as a vehicle for personal exploration as well as a channel through which an idea can be communicated to others. In this way, design promotes a material epistemology, which can be understood as "thinking through things," either individually or collaboratively. Such a material learning approach can be useful to certain students, as we mentioned in the Process Management section, and expresses the mode of thinking that Turkle and Papert regarded as depreciated in schools. Cross (1982) linked this devaluation of the concrete to schools' disregard for the culture of design. The dominant cultures of sciences and the humanities chiefly operate with numbers and words respectively, whereas design culture involves a bias towards thinking and communicating through the creation of sketches and other models and relies on switching between abduction and the more commonly accepted modes of reasoning, namely induction and deduction. Abduction is the mode of reasoning that underlies students' guesswork and is qualified via deduction and induction. The role of abduction in design thinking is evident in the Reasoning and Ideation sections, in which we described students' abductive thinking in full. Seeing that assessments can have an impact as signifiers of what is educationally important (see Pellegrino & Wilson, 2015), the development of a conceptualization of design competences can help cultivate an appreciation of a school culture based on material epistemology; rather than valuing what we can easily measure, we should attempt to construct measures of what we consider valuable. We hope that our conceptualization of design competences will work as a steppingstone for future attempts to assess design competences, including teachers' classroom assessments comprising constructive feedback to students on their design progression.

Apart from benefitting a specific group of learners, design thinking also nurtures the competences that are commonly believed to be necessary for all 21st-century students, such as collaboration, communication, metacognition, and critical thinking. Our detailed literature review has shown that critical thinking is associated with empathy, as the latter involves assuming another person's point of view and, consequently, critically considering a subject from a different perspective. Similarly, when students engage in problem setting, they learn to be more reflective when approaching problems. Moreover, when evaluating ideas, critical thinking is required to find the best solution. Communication is part of modeling as externalizing an idea involves a multimodal representation of one's thinking, which invites peer feedback. Modeling also facilitates collaboration in teams because interacting through a shared object makes members' actions and decisions visible to the team as a whole. During ideation, collaboration can provide inspiration by enabling students to draw associations between one other's ideas and develop them further. Collaboration is also closely tied to empathy, a skill that involves considering not only end users but also the other members of a design team. To collaborate successfully on a project, students need to understand each other's perspectives and negotiate different understandings. By interacting with others, students become aware not only of other people's but also of their own positions and competences. This self-awareness makes students capable metacognitive learners—by recognizing competing viewpoints, students learn to take responsibility for their subjective actions.

To summarize, design thinking in the K-12 context is considered to foster competences that are typically regarded as 21st-century skills, such as communication, collaboration, and critical thinking. In addition, metacognition and personal responsibility are both included in various frameworks for 21st-century skills (Binkley et al., 2012; Voogt & Roblin, 2012). These general competences traverse the different design competences that we have extracted from the reviewed articles. Although the design competences are intertwined, which makes it difficult to clearly demarcate competence areas, we believe it is beneficial to categorize design thinking into competences as the defined competence areas provide teachers and researchers with a conceptualization that is useful for implementing and evaluating design thinking in schools. From the practice perspective, our aim was to identify the competences that teachers should focus on when using the design approach in teaching and to understand how these design competences materialized in students' practices—that is, what teachers should look for when assessing students' design proficiency.

Based on existing literature, in Fig. 2, we have illustrated how the competences relate to one another. Reasoning is central and supports all design activities when the latter are framed as inquiries into solving a problem. Abduction is utilized when ideating and relies on the fragmentary information gathered via problem setting and empathizing. When modeling the proposed idea, constraints for the solution are established deductively, and

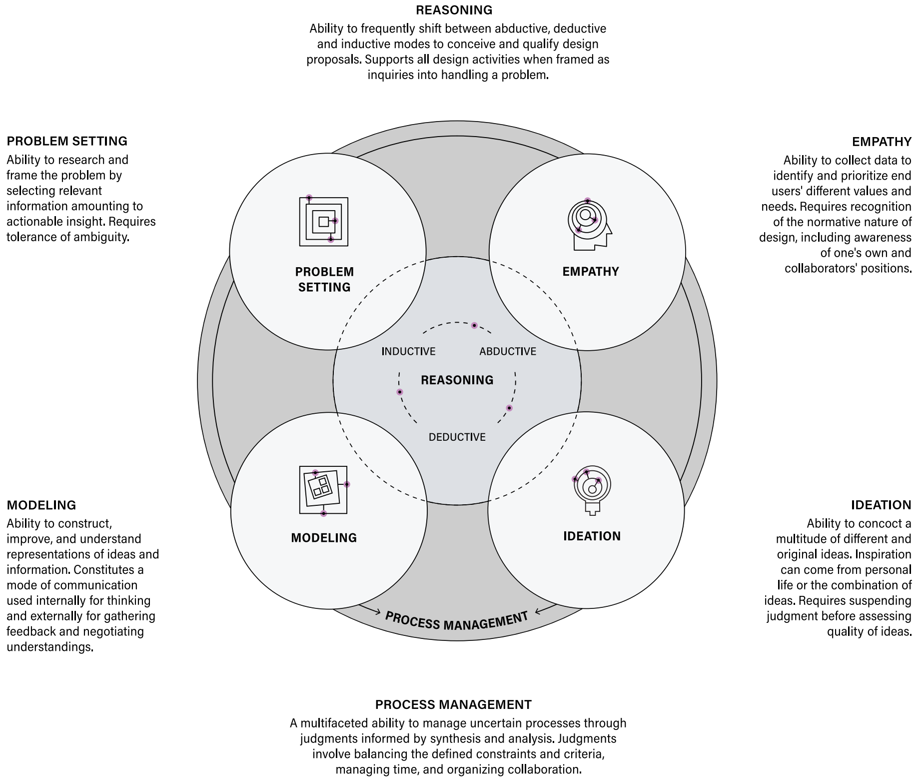

Fig. 2 Design competence framework

the model is tested against these criteria by induction. Design competences include the ability to set the problem, empathize, generate ideas, and model relevant suggestions and develop models for reducing complexity. These four competences are more closely related to specific phases of the inquiry, whereas reasoning and process management are present throughout the process. The design process is iterative, as illustrated by the double-headed arrow underlying the activity-related competences. These back-and-forth transitions between the different activity-related competences are driven by various judgments on which idea to further develop, which criteria to test against, and so on. The iterative nature of design is also illustrated in the icons whose centers are encircled by multiple lines, symbolizing the recursions that are required throughout the process. The flashing nodes illustrate the insights that enable the designer to narrow the problem and solution space further, thus moving closer to a resolution of the problematic situation.

Due to our interest in competence development and assessment, our literature review was focused on students. However, implementing design in general education also makes demands of teachers. In accordance with Dewey's (1985) ideas, when students inquire into a problem, the teacher does not possess the answer. Rather, students and teachers must jointly work toward a solution, and, like the students, teachers must tolerate the uncertainty inherent in the design process while exercising patience to facilitate and guide students' iterative play with material. As we noted in the Process Management section, teacher interventions do not deprive students of opportunities to make their own design decisions and freely experiment. Rather, only with the help of teachers can design thinking foster students' reflections on actions and knowledge, thereby making them resourceful critical thinkers who can apply the subject knowledge and skills learned in school to the challenges that they will meet in their lives.

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