Maker Education: Opportunities and Threats for Engineering and Technology Education

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Abstract Over the past decade, the maker movement and in its slipstream maker education have attained worldwide popularity among educators, politicians, and the media. Makers' enthusiasm for creative design and construction, using old and new tools has proven contagious, and is worth exploration and critical reflection by the community of engineering and technology education (ETE). This chapter describes what has been said about "making" by philosophers and educators; what maker education is, and what is new and not so new about it; why it has gained momentum; what the evidence is about its effectiveness and its possible weaknesses; and how mainstream technology education may benefit from maker education. This chapter concludes with ideas for a research agenda.

1 The Maker Movement and Making in Education

1.1 The Maker Identity

Making has been a defining trait of humanity since the first tools for carving stone and wood were used. The ancient Greeks' attitude towards making was ambivalent: at the one hand, for free men, logic (episteme) was regarded as the highest form of knowledge. On the other hand, the value of the knowledge involved in making was also acknowledged, certainly for the lower classes. A Homeric hymn to Hephaestus, the god of craftsmen, testifies of this.

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> Sing clear voiced Muse, of Hephaestus famed for skill.
> With bright-eyed Athena he taught men glorious crafts throughout the world.
> Men who before used to dwell in caves in the mountains like wild beasts.
> But now that they have learned crafts through Hephaestus famous for his art
> they live a peaceful life in their own houses the whole year round
> (Anonymous)

Hephaestus possessed a combination of techné (knowledge to produce) and metis, which is a form of cunning intelligence, opportunism and experience that was held in high regard. The Greeks' ambivalent attitude has parallels in our present-day educational system, as well as in present-day philosophy. Modern day philosophers who regard making as a highly valuable element of humanity, include Hannah Arendt and Richard Sennett. Arendt acknowledges the liberating power of making by contrasting the "animal laborans," who are occupied with daily chores without any progress, to "homo faber," the making human, who is free to make and destroy things and who, therefore, "*conducts himself as lord and master of the whole earth*" (Arendt, 1958, p. 139). Sennett (2008) admires the advanced skill of the craftsman, which he sees as an embodied engagement that keeps humanity rooted in materiality and which changes an individual's view of the world. This, he argues, is important as a balance in a world that tends to be dominated by mental activities. The liberating power of "making" is also emphasized in the present-day maker movement.

In this chapter, our focus will be on making and the maker identity as they have emerged from the maker movement of the past two decades. It is hard to pinpoint a definitive start of this movement, because people have always made things and there is no sharp boundary between for instance radio electronics hobbyists in the previous century and present-day makers. Moreover, the maker movement is not a single movement, but rather a diverse coalition of (disruptive) entrepreneurs, ethical (and perhaps unethical) hackers, sustainability activists, crafts hobbyists, and so on. Nevertheless, Blikstein (2013) and others do see unique characteristics of the maker movement since 2000. The availability of relatively cheap equipment such as laser cutters and 3D printers enabled individuals to prototype artefacts that could only be made in specialized facilities before. Moreover, the maker movement has been linked to the rising popularity of entrepreneurship. Fablabs, Maker Spaces, and Maker Faires facilitate kick-starter projects for entrepreneurs in previously unthinkable ways. Mark Hatch (2014) characterized the movement in a 9 word summary: Make, Share, Give, Learn, Tool up, Play, Participate, Support, and Change. Among the first features that stand out if one visits a Maker Space or Maker Faire, are the innovative use of tools (Tool up) and the playful creativity. Playfulness can be seen in the type of products that are made, but it is also regarded as an important contribution to a problem solving mindset. The words "share, give, and participate" denote the movements propensity to create networks of makers in which knowledge, skills, and half-products are generously shared. Makers share their ideas in magazines such as "Wired" and "Make," on blogs and forums such as instructables.com and hackable.com. Not only do they share ideas but also they submit complete product designs and software libraries to Github, as part of the Creative Commons.

The ease of sharing knowledge and experiences through the internet has thus been instrumental in the rise of the maker movement, as well as being a fundamental driving force for those many makers who are inspired by techno anarchistic ideals. At a societal level, democratic and entrepreneurial values are attributed to the maker movement, because it gives individuals the capacity to make sophisticated products that can change the world, in a way that was previously unthinkable (Halverson & Sheridan, 2014; Vossoughi & Bevan, 2014). The word "Change," finally, refers to the idea that the act of making is fundamentally human and that "*you will become a more complete version of you as you make*" (p. 31).

> Reflective question: Who could be the "maker heroes" of our students? A grandparent who makes beautiful textile products? An artist who makes fascinating installations out of scrap materials? A metal worker who modifies a car in a cool way?

1.2 Making in Education

As early as the Greeks, "making" has been taught as a skill, as illustrated by the Homeric hymn above. In our days, making obviously is an important part of vocational and general technology education. Construction workers and electricians learn to make and repair products in vocational education, and so on. These vocations can also be of an industrial kind, whereby artefacts are made in mass production and where students are prepared to contribute to this process by learning to make standardized objects at school. In general engineering and technology education (ETE), where objectives focus on technological literacy, making also has its place. Even though "designing without making" can have a legitimate place in such curricula (Barlex & Trebell, 2008), more often making is an inherent part of the iterative process from conceptualizing an idea based on some human need to realizing and testing the product. Experiencing and reflecting on this process teaches children how the designed world comes into existence and is, therefore, an inherent part of a curriculum that targets technological literacy (ITEA, 2007).

In crafts oriented education, students obviously learn knowledge and skills needed for making. Scandinavian Sloyd is an example of crafts oriented education since 1865, in which the slow and attentive process of manually constructing artefacts is highly valued (Whittaker, 2014) as contributing to personal development. Reformist educational approaches as instigated by Fröbel, Montessori, Dewey, and Malaguzzi (in Reggio Emilia) acknowledged that making is not only valuable in itself but that it can also contribute to development of conceptual knowledge. Making thus has had its well-established place in ETE objectives and pedagogies for many years, so how can be explained that Maker Education has been embraced as a novel phenomenon so eagerly?

2 The Rise of Maker Education

The maker education movement has its roots in universities such as Stanford and MIT, where the first fablabs were established. From there, Gershenfeld, Papert, and Blikstein and others began to explore the educational potential of digital fabrication for extracurricular activities in education, as early as 2003 or the 1980s of the previous century in case of learning to code (Martinez & Stager, 2013). This, in turn, led to the development of new tools for programming and digital fabrication, with varying degrees of openness, that were suitable for use in schools, such as Scratch, MaKey MaKey, Little Bits, and so on. In the meantime, the cost of tools such as 3D printers, laser cutters, and simple programmable computer chips dropped dramatically. In 2019, the cost of a computer chip that can be programmed by secondary school students was below one euro. The availability of digital fabrication tools may have boosted the maker movement and maker education, but a quick glance in any maker space, fablab or makers' blog reveals that low-tech tools and materials are also used in maker classes, often in combination (see Fig. 1).

Fig. 1 Combined high-tech and low-tech products. A computerized art object, a tree that reacts to the seasons (left), and a fun robot with movable parts, sounds, and lights (right). (Credits Arjan van der Meij and Jorg Duitsman)

In the meantime, educationalists started using Papert's (1987) learning theory of constructionism to shape a maker education pedagogy and describe its foundations. Constructionism asserts that embodied experiences and the production of artefacts are central to the ways people learn and that pedagogies should be interest-driven rather than content-driven. The constructionists' idea that education should not stifle children's natural propensity to learn can be traced back to Rousseau and is also prevalent in visions of the early reformists mentioned above.

Papert (1987) illustrates constructionist teaching and learning with a contest in which students make a vehicle of their own idea with Lego bricks. The vehicle runs down a slope freely and it is then supposed to continue across a horizontal floor. Students are challenged to adapt the vehicle so that it runs further than their classmates' vehicles. Papert suggests that this activity, in itself, develops students' understanding of concepts such as mass and friction. It is worth noting that Papert, like Sennett, extends his conception of making to activities such as drawing with the aid of a computer (Barak, chapter "Pedagogical Approaches to Vocational Education").

Martinez, Stager, and Blikstein were among the first to use and extend Papert's ideas to shape a maker pedagogy for primary and secondary education. Martinez and Stager (2013) criticize what they call "design models" as commonly used in schools for containing too much instruction, which would lead to too many interruptions of the learning process (p. 52). The vignette in Table 1 illustrates how such interruptions are typically avoided in maker education. For the sake of contrast, the left column displays a more conventional approach, even though in reality there is no sharp line between such approaches.

Instead of regular design models, Martinez and Stager (2013) promote the use of the Think, Make, Improve model. The importance of collaboration and tinkering are foregrounded in this model. Tinkering is described as "*a playful way to approach and solve problems through direct experience, experimentation, and discovery*" (p. 32) that is much more open than recipe-like modes of assembling (Vossoughi & Bevan, 2014). Resnick and Rosenbaum (2013) describe three characteristics of construction kits such as Scratch and Makey Makey that make them suitable for tinkering: Immediate feedback, fluid experimentation, and open exploration. Table 2 lists these characteristics and illustrates how they are part of the programming language Scratch (Resnick & Rosenbaum, 2013).

It is worth mentioning that the use of Scratch, for instance as a programming language for the Arduino, has been criticized on the grounds that it does not resemble professional programming languages and that it is, therefore, unsuitable to teach about (software) engineering. However, text-based and numerical languages used by robotics engineers also evolve in the direction of more user friendliness, for instance by using a more Scratch-like visual architecture (Essers, 2016).

"Think, Make, Improve" (Table 3) is both a design method and an approach to teach designing. A selection of elements within this model as listed by Martinez and Stager (2013, p. 52) reflects common characteristics of maker education.

These key words and examples of maker education assignments that are found in research literature and on blogs illustrate the somewhat anarchistic and playful nature of maker education.

Examples of assignments typically found on maker education blogs and in literature

1. Hack a toy: bring a toy from home and make it move/blink or do other cool things with it.
2. Build a marble track that takes exactly 60 s to complete.
3. Make something you really want to make.
4. Build an object that shows how the liver works.
5. Build a musical instrument. You have to play a song on it that the teacher is able to recognize.
6. Hack your school: build something that improves your or the teacher school life.
7. Build a cardboard box with something locked inside that takes considerable effort to open it up (no force!).

Table 1 Avoidance of interruptions in maker education

Engineering and technology education	Maker education
Teacher: This week you'll design an alarm for the small statue that you've made in your art class. Statues need protection because people might want to steal them, right? You will use a buzzer and a LED as an alarm. It will be set off by a tilt switch in the pedestal, which is made of plywood. We'll first construct the pedestal. The electronics will come later. Carl: What about the size and shape? Teacher: Oh, I forgot. You'll get the design brief listing some specifications and an instruction to construct the pedestal. Other things are for you to choose and work out. Later Teacher: Class, we'll now study the issue of connecting the tilt switch, buzzer, and LED to the battery. Study the handout about series and parallel circuits and then draw a circuit diagram in your design portfolio. Carl: I'm ready, teacher. Can I start soldering after you've checked?	Teacher: What do you want to make this week, Jasmin? Jasmin: I want to make a light box for my aunt. She'll come over after a long time. Teacher: A light box? Jasmin: Yes. With my image engraved and a LED behind it. And it has one of those switches that flips when you turn the box, so my image appears. Later Teacher: Great! I see you made it easy to change the battery. Jasmin: Yes, but it's not bright, so I need more LEDs. Do they have to be in series or in parallel? Teacher: In this case both could be fine but, but if you put them in parallel, you'd somehow have to tinker with the voltage. Check the theory behind series and parallel circuits, and then you'll see that you'd burn them with this 9 V battery. If you need it, I'll explain.

Table 2 Tinkerability in scratch

Tinkerability characteristics	Sub category	Example how this characteristic is built into Scratch
Immediate feedback	See the result	Code is visible through blocks. Clicking on a block immediately shows what the block does to the object that is being programmed
	See the process	Chunks of code are being highlighted as the program is running
Fluid experimentation	Easy to get started	There is a default object that can be tinkered with right away
	Easy to connect	As with LEGO, in scratch it is easy to see which coding blocks can be connected, as a result of the color and shape of the blocks
Open exploration	Variety of materials	Sounds and music, images, backgrounds are available in a library that is easy to access from within the coding environment. Users continually extend this library
	Variety of genres	Scratch can be used to make computer games, animations, stories, music, interactive art, and as input/output computation for a robot or Arduino

Table 3 Think, make, improve according to Martinez and Stager (2013)

Think	Make	Improve
Brainstorming, talking it out, predicting, gathering materials, identifying expertise, deciding who to work with, setting goals, sketching, outlining, flowcharting, researching, planning	Play, build, tinker, create, program, experiment, construct, deconstruct, test strategies/materials, observe others, borrow and share code, document process, look for vulnerabilities, ask questions, repair	Conduct research, talk it out, discuss, look at it from a different perspective, use different materials, change one variable at a time, think how you solved similar problems in the past, play with it, find a similar project to analyze, ask a peer or expert, be cool, get fresh air, sleep on it

Such examples illustrate what is perhaps the most alluring quality of maker education: making with a combination of traditional and digital tools is fun. Mitch Resnick uses the metaphor “low floor, high ceiling, wide walls” to explain that maker education should be accessible for novices, challenging for learners and provide a great variety of pathways and projects for learning (Resnick, 2018). Maker education practitioners have also contributed to practical knowledge that helps to establish “low floor, high ceiling, wide walls.” With regard to tools they for instance experienced that a laser cutter is more accessible than a 3D printer, whereas it still provides “wide walls” and a “high ceiling” (Van der Meij, Kloen, Hazelaar, & Van Oven, 2018).

Maker education is often considered as contributing to STEM learning objectives, and its openness and emphasis on student-centered learning resonates with inquiry-based STEM approaches. Knowledge and skills from a variety of disciplines such as physics, chemistry, mathematics, and art are used to make products, but generally it is not explicated what the relation is with these disciplines. Maker education is often located outside schools, for instance in libraries and museums. Where it is school-based, it is often part of extracurricular activities, whereby students voluntarily participate and without high-stakes formal assessment. The learning environment is often called a "maker space." The space and the tools reflect the characteristics of maker education as described above. However, regular technology workshops in schools vary widely and some can doubtlessly be used as maker spaces.

Reflective question: How do technology workshops at schools often look like, and how could they be improved to cater for:
A "low floor, high ceiling, wide walls" pedagogy
Creativity
Tinkering
A culture of sharing of ideas and (half) products

3 Research Findings: Pedagogy and Outcomes of Maker Education

Empirical research on learning outcomes in maker education is sparse and often scattered across journals from different disciplines (Troxler, 2016; Bevan, 2017). Empirical studies have largely been qualitative and descriptive and focused on out-of-school and after-school settings such as activities in museums and school-based maker clubs.

A review by Vossoughi and Bevan (2014) summarizes research findings in three categories. A first category is about how maker education gives young people a chance to develop identities as participants within STEM practices, specifically as makers. Second, the review gives examples of how learning and development can be structured. Third, the review shows how maker education promotes collaboration and fluid roles of novices/experts, rather than fixed roles of teacher and learner. We will use these three categories to elaborate on research findings.

3.1 Maker Identity

An outcome of maker education that is foregrounded in much research is what is called a "maker identity," or self-efficacy as "maker," a change agent in the material world. Participants take on new roles as makers, using computational media and craft technologies and they connect these roles to long-term interests. Blikstein (2013) agrees and illustrates this from his extensive experiences. He emphasizes that this identity is multidisciplinary and in some cases as strongly associated with engineering as with other domains. As an example, Blikstein describes the case of

Max, who made a robotic flute. Blikstein argues that Max learned a lot about engineering, but the main learning outcomes were about music interpretation. In another example, students made a historical model using digital fabrication equipment and learned about history, engineering, and mathematics in the process.

A critical note with regard to this "maker identity" is concerned with maker education's power to bolster this identity across a diverse student population. Scholars from within the maker education community have observed that maker education presents a picture of "making" as a white, middle class and male enterprise (Vossoughi, Hooper, & Escudé, 2016). Blikstein and Worsley (2016) warn that maker education in schools may increase inequality when middle class boys who have had access to maker culture get to do more demanding work in schools than girls and boys from lower-income groups. If no precautions are taken, this can be a result of maker education's tendency to leave decisions about what is being learned and who takes up tasks in a project group to students themselves. In addition, Vossoughi et al. (2016) argue that maker education generally fails to appreciate valuable accounts of making from different cultures. Moreover, they assert that maker education finds its legitimacy one-sidedly in economic value of commercial innovations, which will only strengthen existing economic structures and imbalances of power.

3.2 Structuring Learning

With regard to pedagogy, Vossoughi and Bevan's review (2014) highlights how maker education provides meaningful contexts for learning STEM concepts, particularly the STEM that is grounded in a socio cultural approach to action learning. Although the argument seems plausible, there is little concrete evidence about how the STEM-learning could be implemented from such context. Details with regard to sequencing of activities, the choice for specific making assignments, sources for students, teaching materials etc., have also not been provided thus far. Blikstein describes possible drawbacks of a maker education pedagogy, an important one being the "*keychain syndrome*" (p. 8). He shows how students' success in making keychains with the aid of a laser cutter came at the cost of their willingness to "invent." Students valued product over process, a problem that is exacerbated due to the very nature of the machine that facilitates the production of flashy products in a relatively simple way. The machine becomes "*a Trojan horse*" unless the educational designer intervenes (Blikstein & Worsley, 2016, p. 9).

3.3 Roles

With regard to the roles that teachers and students can take on in maker education, much of the research describes these roles as fluid. Teachers are role models as "learning makers," but at times they can also adopt roles as coaches or instructors.

In this latter role, they also make knowledge explicit. Words that are also used for teacher's roles in Vossoughi and Bevan's (2014) review are "sparking" (interest), "sustaining" (participation), and "deepening" (participation). The latter role resonates strongly with Martinez and Stager's (2013) emphasis on improvement of students' products, as far as possible. But also there, students' agency in the way their product could be improved is given priority.

In addition to what has been said thus far, Smith, Iverson, and Veerasawmy (2016) described the following challenges for teachers to adopt a role that fits the ideas behind maker education: bridging the gap with formal curricula, emphasizing the learning process over the product, and nourishing a design language, the latter being a general challenge in technology education (Van Dijk & Hajer, 2017).

4 Some Doubts from the Learning Sciences

In this section, we provide a few links with insights from the learning sciences that could help to identify opportunities and threats for technology education, as we try to learn from maker education.

Nowadays, school-based maker education is often part of extracurricular activities. In this case, students follow compulsory science and technology classes and voluntarily come to "maker activities" after regular hours. In this context, the fun factor of maker education can be fully exploited and regardless of pedagogy, some students will certainly learn many things. However, where maker education is adopted as a replacement for more traditional science and technology lessons, a discussion about pedagogy is paramount. In this section, we raise two issues that are of concern when maker education becomes part of regular curricula: the role of teacher guidance and problems with transferability of skills. The issue of content will be dealt with in Sect. 6.

Martinez and Stager's (2013) argument for less teacher instruction, fewer interventions, and fewer interruptions resonates with radical constructivists' view on learning as well as with Papert's constructionism (in particular its child-centeredness). Publications by other proponents of maker education follow the same lines and it is hard to find any publication about maker education where guidance and explicit instruction are being advocated (Stockard, Wood, Coughlin, & Caitlin, 2018). Constructivism and constructionism, however, are certainly not uncontested, in particular for learning new content (Andersen & Andersen, 2017; Klahr & Nigam, 2004; Kuhn, 2007). Mayer (2004) reviewed a body of research on constructionist' methods of teaching to code in the LOGO language. He comes to the conclusion that "*author after author noted the role of guidance in learning to program*" (p. 17), which explains the failure of "discovery oriented" environments for learning to code. Furthermore, evidence is inconclusive with regard to the equity effects of student-centered and constructivist pedagogies: while some authors found that open and child centered pedagogies tend to widen the gap in learning outcomes between high and low SES students (e.g., Andersen & Andersen, 2017), others report beneficial effects particularly for low SES students (Mehalik, Doppelt, & Schuun, 2008). This issue deserves careful attention if we consider implementing Martinez and Stager's advice for less instructions in formal curricula.

For learning to design and make, whole task approaches that are prevalent in constructivist pedagogies have been explored by Van Breukelen (2017). He asserts that many design-based learning approaches involve too many objects of integration (skills, practices, attitudes and content) for students, "*that often remain underexposed in the case of unexperienced practitioners*." Content is often overlooked as a result (Van Breukelen, 2017: p. 102). This too raises questions about claims that "making" in itself is a powerful vehicle for learning conceptual and procedural knowledge for all children. This does not mean that maker education as a whole can be disqualified on research grounds. In some cases, publications that criticize constructivist teaching approaches can also be used to highlight strengths of maker education. Clark, Kirschner, and Sweller (2012) for instance emphasize the effectiveness of learning with the aid of "worked examples." Following the "share" principle, the maker education community has found many ways to make "worked examples" easily accessible for students. The Scratch platform, for instance, provides students with many examples of chunks of code, whereby it is easy to see how the code works (Table 2).

The learning sciences are also useful to shed light on the issue of transferability of skills. The rhetoric in maker education is abound with claims that students learn skills such as creative thinking and problem solving that they will need in life, perhaps for different things than making. A quote from Mitch Resnick, LEGO Papert Professor of Learning Research at MIT and long standing and influential developer of maker education tools for learning (Scratch, MaKey MaKey) illustrates this idea.

> As people learn to code, they think systematically. They start to identify bugs and problems and fix them in ways that carry over to other activities. You learn basic strategies for solving problems, designing projects and communicating ideas. That will be useful to you even if you don't grow up to be a programmer, but a journalist or a marketing manager or a community organizer. We sometimes say, it's not so much about learning to code, but coding to learn. As you code, it's helping you learn other things (Resnick, in Barshay, 2013).

However, research has shown that "thinking systematically," creativity, and skills generally develop in interaction with domain knowledge (Bransford, Brown, & Cocking, 2003). In case of creativity, Lucas, Claxton, and Spencer (2013) have described this in general and Christiaans and Venselaar (2005) have done so for ETE.

5 The Potential of Maker Education for Engineering and Technology Education

In the previous sections, we have described features, strengths, and weaknesses. Now, we will consider how these features can be used to strengthen our ETE agenda. Maker education has been able to exploit the "fun factor" of making, in particular

Table 4 ETE concepts according to Rossouw, Hacker, and de Vries (2011)

Main concept	Sub-concepts
Designing ("design as a verb")	Optimising, trade-offs, specification, invention, product life cycle
Systems	Artefacts "design as a noun", structure, function
Modelling	
Resources	Materials, energy, information
Values	Sustainability, innovation, risk/failure, social interaction, technology assessment

with the aid of accessible high-tech tools in combination with traditional tools and materials. ETE can benefit from maker education's potential to develop "maker identities" by attracting more students and keeping them engaged. In order to utilize this potential, we need a clear understanding of similarities and differences. This will not amount to a simple addition – some elements can strengthen each other, but other elements may be at odds.

Making has always had a prominent place in ETE. However, there is not only overlap between maker education and ETE (Bell & Quinn, 2013), but there are also important differences. Rossouw, Hacker, and De Vries (2011) used a Delphi study to identify five key concepts in ETE, each with associated sub-concepts (Table 4). The concepts were chosen by experts from technology education (secondary education, technology teacher education, and associated research), engineering education (tertiary education and engineering associations), philosophy of technology, design methodology, and science and technology communication.

Of these five, designing is often used as an overarching concept. Design in ETE is goal directed, meant to arrive at the best possible solution for a problem, within technological and other constraints. The goal is usually some customer need or other human desire that guides an iterative process of setting requirements, specifications, construction, testing and evaluation of different solutions (Björnberg, 2013). Maker education does not necessarily regard making as part of a design process that is meant to identify and solve authentic problems in the world outside schools (Bevan, 2017). Many of the examples of maker education tasks in this chapter testify of this difference, for instance "*make something that you really want to make*" and "*hack a toy*." This reflects the emphasis on the personalized fun factor of making in the maker movement,[1] rather than an emphasis on design in an ETE sense.

Differences are also easy to find if we zoom into the ways learning to design is scaffolded with the aid of functional or structural design models (Mioduser & Dagan, 2007), as stated earlier. Such models, however, serve as scaffolds for novices to learn to work systematically during designing, for instance to regularly check whether the process is still on track to meet user requirements and technical requirements. Thinking is terms of systems is another important aspect of learning about technology (Hallström & Klasander, this volume). This helps students to gain

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[1] A YouTube search on '*useless machine*' will result in many examples.

insight in working principles, input and output, and the way systems work together to realize a function, a type of transferable knowledge that is particularly important because technologies evolve very rapidly (Hallström & Klasander, this volume). Systems thinking is not only of importance to be able to design, but also to maintain and repair consumer products as well as industrial assets. For these reasons, systems thinking is usually explicitly addressed in ETE. Systems thinking can perhaps be developed through maker education activities, but there are few examples that demonstrate how this is done explicitly, with guidance by the teacher. This is the case for the remaining core concepts (modelling, values, resources) too. The relation with values, for instance in case of sustainability, is particularly interesting. Maker education enthusiasts claim that they can make a contribution to sustainability, because they can help reduce waste by teaching how to reuse materials, to repair broken products, and to become active participants in the search for technical solutions to sustainability. Also, learning to design and make in local communities can decrease carbon footprints because less transportation is needed, it is claimed (Kohtala & Hyysalo, 2015). However, one could also argue that making rather useless fun products at school adds waste unnecessarily and it does not raise awareness of the limits that we face in our use of energy and materials. Furthermore, the maker education literature does not yet demonstrate how values such as sustainability can be addressed explicitly. In contrast, the literature about ETE is rich with regard to values and sustainability (Keirl, this volume). A more overarching concern with regard to sustainability is that participants in the maker movement as a whole are often unaware of major environmental implications of their work, such as toxicity of materials, or they do not even regard sustainability as key issue for future maker spaces (Kohtala & Hyysalo, 2015). Whether this problem with knowledge, beliefs and attitudes transcends from the maker movement into maker education is unknown.

As a conclusion, we assert that replacement of a regular technology, engineering and science curriculum with a radical form of maker education is likely to result in a misfit with generally accepted learning objectives. This has been acknowledged from within the maker education community (Smith et al., 2016; Christensen, Hjorth, Iversen & Blikstein, 2016), and we have attempted to specify this risk a little further. Nevertheless, maker education can potentially strengthen more traditional forms of ETE. As a starting point for further discussion, Table 5 identifies three principles to achieve that.

However, each of these principles is likely to result in trade-offs for both maker education and ETE. Depending on national and local contexts, decisions can be made to arrive at a responsible and feasible balance in the applications of the principles.

Reflective question: What possibilities do you see, to use the three strengthening principles in one technology education practice that you know well?

Table 5 Principles for strengthening ETE curricula

Strengthening principle	Examples of interventions in ETE curricula
Maker education projects as curricular add-ons for increasing students' ownership Allocate time for free, and collaborative making and tinkering, whereby students set their own agenda. Include "making challenges" that fit well with different cultures and gender identities.	Include "making without designing" challenges. This means that a user's needs and other constraints (e.g., technical) do not always have to be specified. "Step-by-step design methods" are not necessarily explicated before or after the process
Frontloading conceptualization and procedural understanding in "making challenges" Set "making challenges" that can only be met if scientific and technical conceptual and procedural knowledge is applied	Start a project with a brief such as: *You are going to make a cool "class promotion board" that interacts with sounds and movements in the environment. It has pulsating LED's and moving "old school" meters with arrows that indicate current and voltage as the Led's pulsate. Next year's class must be able to adapt your product and they can only do so if you provide a written explanation of working principles of your system, which includes calculations of power, voltage, current, and resistance* Give instruction and guidance to enable students to meet the challenge
Backtracking for conceptual and procedural understanding in making challenges Use a product from a maker class or maker faire as an artefact to be understood in terms of regular ETE and science concepts	Ask questions such as: *How do the subsystems in the fun robot work together? How can we visualize that with a diagram to arrive at a better understanding about why it worked so well in the end? What are potential environmental problems with the production and disposal of this fun robot? Which procedures were useful to follow when you needed to find out why a subsystem was not working? How does that relate to formal procedures that engineers use?* Give instruction and guidance to enable students to answer such questions

6 Towards a Research Agenda

Learning by making is alluring, but what is being learned in terms of regular and credible ETE objectives? Van Breukelen's study (2017) shows that conceptual development through designing and making is possible, if students are provided with teacher-led scaffolds that put science content central, such as direct instruction. This was accomplished in a class were students all worked on the same design task, which made it possible for the teacher to give instruction and guidance that was relevant for all students. Moreover, the design task was set in such a way that science content was indeed needed. In a student-centered maker pedagogy this is harder to achieve. The issue of hybridization of maker education and ETE curricula, i.e., explored in Table 5, is worth further research. Such research should also take diversity in student populations into account.

And perhaps we should not just search for hybridization. Extracurricular maker activities deserve a place in their own right, unhindered by demands that would undermine their successes, as long as they do not jeopardize legitimate ETE curricula. In any case, it will be worth the effort to learn from maker education practitioners how they manage to "teach" so beautifully in the spirit of Hephaestus, who rightfully acknowledged that *mankind is a making kind*.

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