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Critical Education

Critical Making Workshops
Sparking Meta-Discussions for Critical Thinking in Vocational Education

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Volume 16, Number 1, 2025

URI: https://id.erudit.org/iderudit/1116740ar
DOI: https://doi.org/10.14288/ce.v16i1.186863

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Publisher(s)

Institute for Critical Education Studies / UBC

ISSN

1920-4175 (digital)

Explore this journal

Cite this article

Sipos, R., Kutschera, A. & Klose, J. (2025). Critical Making Workshops: Sparking Meta-Discussions for Critical Thinking in Vocational Education. *Critical Education*, *16*(1), 49–70. https://doi.org/10.14288/ce.v16i1.186863

Article abstract

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Volume 16 Number 1 February 1, 2025 ISSN 1920-4175

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Abstract

This article explores how critical making - or a combination of critical thinking and making - could enhance and future-proof technical and vocational education and training (TVET). The article reports from a series of multi-stakeholder participatory workshops with educators, caretakers, pupils, and makers. The workshops themselves represent an example of critical making, hereby providing the participants with an immediate understanding of the concept. Through discussions, the stakeholders mapped the viability, challenges, and opportunities for successfully implementing critical making into German curricula. The paper ends with reflections on the general difficulties of updating a curriculum. It proposes a workaround: complementing the technical approach of the existing TVET curriculum with maker tools to foster digital skills and meta-level discussions to foster critical thinking.

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Introduction: Making and Critical Making in Education

Berlin's vocational educators are trained at the Technical University of Berlin's Institute of Vocational Education and Work Studies (IBBA). This study program includes pedagogy and classic production methods, such as woodworking and sewing, as well as digital production and manufacturing techniques, such as 3D printing, laser cutting, and the use of microelectronics like Arduinos and LilyPads. In addition, IBBA has also experimented with a vocational educator training programme called ”Digital Worlds”, a novel school subject aimed at bringing digital maker tools to schools (such as 3D printing, laser cutting robotics, or big data, see Digitale Welten (Voigt, 2017)). These examples highlight how so-called maker tools have enhanced traditional technical and vocational education and training (TVET).

Indeed, making, or the contemporary culture or subculture that can be summarized as a technology-based extension of DIY culture (Doyle, 2013), has been gaining attention in vocational education approaches. One of the main inspirations for the uptake in making has been the course titled ”How to Make Almost Anything” at MIT (Gershenfeld, 2012), and since then, making has spread throughout education. It has been evaluated for its potential to enhance higher education (Bockermann et al., 2021), maker spaces have been cooperating with public and academic libraries worldwide (Willingham & De Boer, 2015), and research has explored educational opportunities in making (Sheridan et al., 2014).

Moreover, experiments in establishing maker spaces in secondary vocational schools have been conducted, e.g., in Austria, where maker classes were integrated into the curriculum for K-12 students. The result was overwhelmingly positive, as maker spaces allowed the students to create their final projects and other creative projects they initiated privately (Sagbauer et al., 2021), further developing their hands-on vocational skills. It has been acknowledged that digital tools, e.g., robotics, can contribute to class projects and thus Career and Technical Education (CTE) approaches, preparing K-12 students for a market demand for tech-based skillsets (McNeel, 2019). The growing interest in how maker spaces and maker activities can transform and future-proof primary and vocational education in the long term is also shown in a report of the European Commission, presenting scenarios on what making could look like in schools in 2034 (Vuorikari et al., 2019). These include making as a learning space, methodology, community and life skill (page 26, ibid.). On the supranational level, UNESCO curated a database of promoting and innovative TVET practices from around the world, many of which feature access to maker tools and skills. For example, the Gearbox maker space in Kenya is providing training in manufacturing or design, as well as other parts of the national innovation ecosystem, with the higher aim to create 5 million jobs in Kenya by 2023 (UNESCO, n.d.).

In addition to making, the authors also consider education that combines different disciplines as a potential method of future-proofing the prospective workforce, meaning that so-called future skills are conveyed (Alexander et al., 2018) successfully. In the past decade, the practice of making has been reconsidered for other, novel educational purposes by a small number of academics looking beyond the mere idea of fabrication or design of products, especially in higher education. This is how critical making came to be: by combining critical thinking and making (Ratto & Hockema, 2009). The term was coined to describe a new type of constructionist scholarly practice for engineering students: “Critical Making is an elision of two typically disconnected modes of engagement in the world: ’critical thinking’, often considered as abstract, explicit, linguistically based, internal and cognitively individualistic; and 'making', typically understood as material, tacit, embodied, external and community-oriented" (p 52, ibid.). This method is an innovative scholarly practice to address and discuss so-called wicked problems Rittel and Webber (1973) by using making to experiment with and develop a collective frame that highlights and resolves disciplinary and epistemic differences (ibid.). Ratto aimed to critically explore the social issues inherent in technical systems, to acquaint students with the possibilities and problems of new physical and ubiquitous information technologies. The goal was also to teach students basic skills in designing, making, and evaluating information systems (Ratto, 2009). In the past decade, critical making has further developed as an interdisciplinary learning method supporting the combination of art, science, and engineering studies with social interventions (Ratto & Hertz, 2019). This notion is especially relevant to our paper, as we will explore how vocational educational activities can support a critical exploration of societal matters.

Another novel approach combining critical discussions and making that is interesting for vocational education is the "Wilderness Wireless" workshop by Brett Balogh (School of the Art Institute of Chicago and Illinois Institute of Technology). At first glance, the goal of this workshop is to learn engineering skills by building a solar-powered and wifi-enabled access point and web server, which has been inspired by the free radio movements. However, through the lecturer's prompts, participants also discuss and share thoughts about socio-technical questions, including the commodification of natural resources like radio waves, the sustainability and mining of materials of the physical parts used, questions around renewable energy, as well as open source blueprints and their contribution to the commons, as documented on https://wildernesswireless.org. We call these meta-conversations (a term previously used, e.g., in behavioral ethics by Smith-Crowe & Zhang, 2016) as the discourse goes beyond merely the technology itself, creating an opportunity for critical socio-technical discourses in the classroom, which we will discuss later.

Rationale: Exploring the Viability of Critical Making in German Schools

The approach described in the paper at hand cannot only be analyzed through the opportunities critical making brings with itself for the future of German students, but it must also be explored through the lens of challenges pertinent in general to project- or problem-oriented learning settings. We are not the first to hit institutional walls: Schumacher et al. (2013) describe the difficulties of their empirical approach in attempting to reform teachers training on a project basis. Facing the need for a lot of time to plan and prepare, a lack of information material and training for better orientation and implementation of project work, dependent and not cooperative pupils, a lack of conviction on the part of teachers about learning growth, difficulties evaluating performance in the new framework and institutional obstacles such as a lack of financial means are issues we also have faced.

Recognizing the obstacles but being inspired by the opportunities listed in the previous section, we decided to explore the viability of critical making in German schools. Being a partner in the EU-funded Critical Making project provided us with an opportunity to experiment with bringing critical making to the German school system. We iteratively designed participatory workshops to explore two central questions: First, we wanted to test the hypothesis that critical making was indeed an applicable educational practice within German schools and their curricula.

We tested a novel, co-creative method, which we will describe in the next sections. We held reflexive discussions with makers, educators, caretakers, and children to observe their engagement. These actions also revealed how they interpreted the term, which we use to refine the applicability and develop further meta-discussions.

Finally, we needed to understand the current challenges and opportunities in the German TVET landscape. These built on observations from previous projects and included potential reasons why critical making has yet to be utilized as an educational tool in German schools, and whether and how this could change.

Our goal has been to utilize participatory workshop approaches to open up spaces for socio-technical discourse through making for children, their caretakers, and their teachers. This paper outlines learnings from six participatory workshops we organized so far for vocational educators, teachers, and children between the ages of 10 and 16 with their caretakers.

Pedagogic Background and Participation

How we understand and deploy reflexivity in this paper is based on the work of Dewey (1933), where action is strongly linked with reflection and the solving of problems that fall outside of regular routine (p. 49, Dewey, 1933). Such reflexive activity, or reflexive practice, starts with a confrontation with a new problem, and therefore, new types of actions are required, leading to experimentation with different solutions. Finally, a reflection on how the problem was solved is, as we will outline, a key starting point for the workshop design discussed in this paper. The process was further developed into the project method by Richards, whereby Dewey's project-based learning is further developed from primarily focused on the technical-practical to a broader perspective (Frey, 1984). Another source of inspiration has been a competency-related approach: the "Gestaltungskompetenz"-model of de Haan (2006). This model focused on output instead of input - allowing for the learning content to be flexibly selected, increasing the student's interest in the content and their skills at the same time - confirmed that applying a flexible framework instead of a class in which every minute is meticulously designed is a correct approach to our original goal: enhancing vocational education through maker practices and meta-discussions.

Finally, as critical making in schools can be interpreted as a version of critical pedagogy, building on Freire (Freire, 1970), participatory methods were especially relevant for our actions. Participatory action research (PAR) also has its roots in project-based learning, and making in itself is a group activity where participation is a prerequisite. Hence, with the growing academic interest in involving citizens in various research projects, a participatory-iterative method was deemed adequate. Furthermore, by including meta-discussions in the maker workshop about societal, technological, justice-oriented topics, we also explored the possibility of students engaging in discourses through an artefact, embedding a "critical sensitivity to design" in the pedagogy through critical making (Sheya et al., 2021).

Methodology: Multistakeholder-Based Design Process

The workshops were aimed at enabling co-design to start a reform to future-proof TVET in Germany. As this venture and our initial hypotheses and questions were quite complex, carefully designing the scientific inquiry and stakeholder involvement was crucial. We decided to conduct

PAR, a method in which researchers and practitioners work together to understand a situation and improve it in recurrent stages (Kindon et al., 2009). However, we needed to modify this approach: the recurrent stages did not take place with the same practitioners, but we derived key learnings from each step and further iterated them with a new group of stakeholders in every workshop to be able to involve as many different viewpoints as possible, approximating community-based design (Abrol, 2005; Bidwell & Jensen, 2019; Rossitto et al., 2021).

In our design process, an initial exploration phase was followed by six workshop events representing two reoccurring research phases continuously shaping the workshop contents (see Fig. 1. and Table 1.).

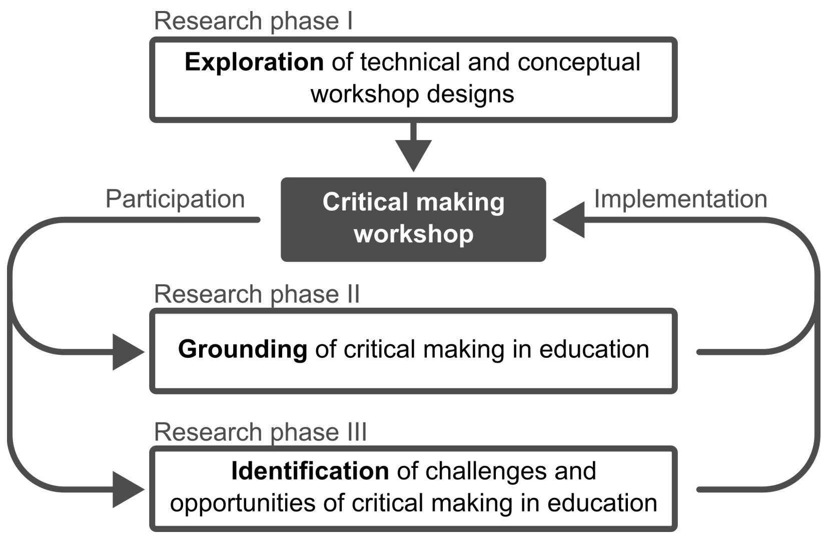

Figure 1. Diagram of the multistakeholder-based design process.

We explored different technical and conceptual designs in the first phase and determined a topic for the critical making workshop. Similarly to Balogh's "Wilderness Wireless" workshop, we developed a concept that is concise and accessible: the hands-on part resembling a TVET class would take a relatively short time and does not require large machinery or deep background skills so it could be done a part of conferences and other events. The making part of the workshop was also kept simple so it would not require full attention and allow for discussions and reflection. That way, the workshop was suitable for pupils and adults alike, and the format could be dually used as a workshop for a school class as well as a meta-workshop with makers, educators and other stakeholders.

In the second phase, the initial concept was tested and discussed with international and German makers and educators already familiar with the practice of critical making (Figures 2 and 3). The goal was to ground critical making in education by identifying parallels, connections, and niches to expand on. Beyond that, practical examples of implementing a critical approach in making activities and school lessons were collected. In addition to the global scope of the research, a special focus was set on how to embed critical making in the German school curriculum.

Figures 2 and 3. Workshop with educators at the network meeting of mobile maker spaces and at a STEM-educators meeting. (Credit: Authors; Körber-Stiftung/Bente Stachowske)

The learnings were taken into the final, third research phase, which we named “Identification.” Here, we introduced the essential findings and concepts developed in previous phases and opened up the findings for further, deeper discussion. An additional layer in this phase was that the educators and stakeholders involved were unfamiliar with the concept of critical making. Instead, they had a better understanding of TVET and education in general and could contribute to identifying challenges and opportunities for critical making in education. These will be contributing to a “Critical Making Manifesto,” which might be published as a poster and added to a box of tools to be shared with maker spaces and schools alike to inspire critical making in TVET and beyond. As this is still in development and not within the scope of the paper, we abstain from detailing the Manifesto here. We are only briefly mentioning it, as it was used as another way of engagement.

Not all workshops combined both critical making and meta-discussion. Some were focused on the practice of critical making (labelled as “critical making” in Table 1), while others were solely based on discussing and reflecting on critical making with education stakeholders (labelled type “meta workshop” in Table 1). We also had the opportunity to evaluate the workshop with a school class in the 4^{th}-grade elementary school (ages 9-10) at an education festival, where we received feedback from the pupils and their teachers. This iterative process thus involved a diverse group of stakeholders. In Figure 1, we depicted the iterative process, which represents a participatory, community-based design approach and a multi-stakeholder and democratic design approach that we will further detail below. The workshops, the respective participants, and the corresponding research phases are listed in Table 1.

Table 1.
Workshops during the participatory action research phase.

Date	Event	Participants	Number	Type of workshop	Process phase
10.06.2022	Re:publica conference (international conference on digital society)	International makers, educators, activists	17	critical making & meta workshop	grounding
02.07.2022	Mobile maker spaces' network meeting	makers, educators	12	meta workshop	grounding
18.07.2022	Open workshop day at Goodlab (makerspace focusing on sustainability)	children, caretakers, parents	16	critical making	identification
16.09.2022	MINT-Barcamp (network meeting of STEM educators)	educators, stakeholders	ca. 30	meta workshop	identification
30.09.2022	Bildung, Bits und Bäume (conference on digitalisation and sustainability in education) Day 1	teachers, school classes teachers, educators, stakeholders	ca. 35	critical making	identification
01.10.2022	Bildung, Bits und Bäume Day 2	teachers, school classes teachers, educators, stakeholders	ca. 20	critical making & meta workshop	identification

Critical Making Workshop Design

Torch as an Entry Point into Making and Socio-Technical Discussions

To make the workshop comprehensible for anyone, we chose a universal topic. In addition to critical thinking skills and socio-technical discourses in the classroom, we wanted the participants to think about the power of technology and highlight something they are very used to but which is not necessarily given all over the world. Here, we reflect on unreliable or damaged energy infrastructures and black-outs, hence why we chose light as a topic. It provides a suitable level of depth and discusses how recent technological developments can simultaneously have positive and negative implications and impacts. On the positive side, LED lights are highly efficient compared to other light sources and have a lower energy consumption per lumen

(Pimputkar et al., 2009). On the negative side, their manufacturing requires resources with limited global deposits (Lim et al., 2011). Beyond that, the excessive use of inexpensive LED lighting has an environmental impact, disturbing ecosystems through light pollution (Schulte-Römer et al., 2019).

For this purpose, we created a design for a small, functional torch. We focused on keeping it simple to demonstrate that also simple technical solutions can have a great impact and solve problems. The workshop was developed in an open source manner, with all materials and source files available online (https://github.com/vektorious/cm-flashlight). The documentation essentially allows for the hands-on, TVET part of the workshop to be reproduced anywhere, by anyone. In the following, we describe the technical and conceptual design of the workshop in detail.

Figure 4. The torch kit, containing everything needed, in paper bags and sealed with a DIY sticker saying "Light is Power."

Technical Design of the Workshop Kit

Paper circuits are a method using conductive materials such as conductive ink or conductive foil on paper substrates to create electric circuits by hand. Due to their accessibility, paper circuits are often utilized for electronic design in making education especially, but not exclusively, when working with young people (Qi & Buechley, 2014). While paper circuits proved to be mainly an educational method for electronics and the possibilities are theoretically endless, they are usually used to build small ornamental objects such as postcards or posters and seldom have practical use. However, paper circuits strike through their ability to simplify the process of building an electronic circuit, which is often perceived as complex and is thought to require very specific skills, such as soldering.

That is why we based the technical design on the principles of paper circuits and utilize their simplicity to demystify electronic design hidden in everyday objects. We use copper tape for easy wiring without soldering to build the circuit. However, we replaced the paper with laser-cut plywood pieces as a substrate to further improve the durability of the object and to allow for a multilayered circuit design with a sliding switch. The design of the torch kit was further improved based on the feedback from workshop participants. The final design consists out of only 15 parts, and the costs of producing them is relatively low. The main body is laser-cut but can be easily produced in maker spaces and schools; all the other components are off-the-shelf. The final design consists of only 15 parts (such as the laser cut body, copper tape, a 5 mm LED, a CR2032 coin cell, four M3x13 screws, and four M3 nuts), and the costs of producing them are relatively low. The main body is laser-cut but can be easily produced in maker spaces and schools; all the other components are off-the-shelf. We engraved the footprints of the parts into the main body and added the numbering of the building steps (see Figure 5). This enables people experienced with the materials to build the torch without additional instructions.

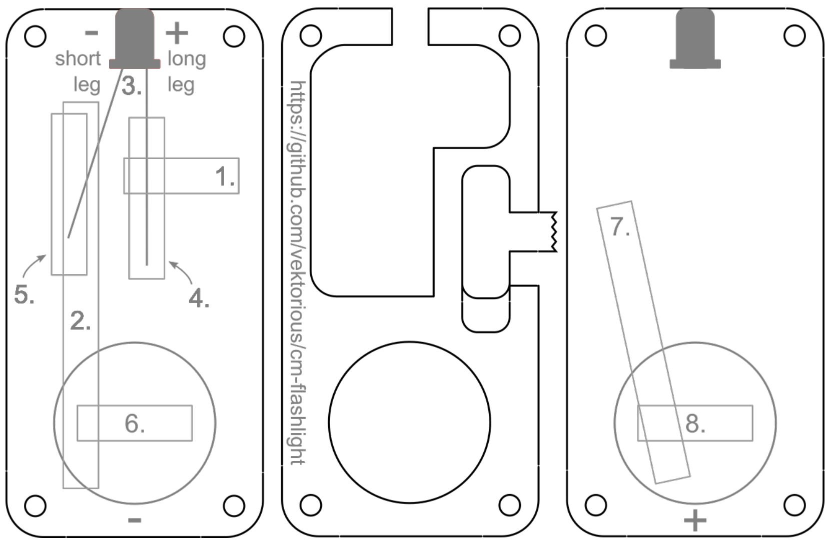

Figure 5. Torch design for laser cutting. Numbers and markings indicate the building steps and application of copper tape.

Furthermore, the torch is designed in a way so that it can be built without tools. Scissors, screwdriver, and a multimeter for troubleshooting are optional.

Conceptional Workshop Design

The overarching idea of the workshop concept was to practice ”learning by doing” and explore potential novel concepts hands-on, which is inherent to maker-education (Blikstein, 2013; Hsu et al., 2017). Beyond that, we set a focus on “reflecting by doing” which is one of the core principles of critical making. For some of the workshops with bigger groups, we used a presentation to guide the participants through the workshop. One or two facilitators usually carried out the workshops, depending on the group size. We started our workshops with a general introduction to the Critical Making project and explained our research interests. We opened up the topic of the workshop and started conversations with the participants by asking questions we designed to stimulate meta-discussions, e.g.:

- How do we produce light, and what do we need it for?

- When was the last time you used light?
- What would you do without light?
- Is light available everywhere in the world?

Through this, we intended to raise awareness around living situations where light is not readily available, as in countries with less reliable infrastructures, remote areas and in natural or man-made catastrophes and crises such as war. Once each participant received a torch kit and unpacked it, we went through the different components, discussed the materials used, and how and where they are produced. By this, we aimed to initiate a reflective atmosphere before diving into the actual building part of the workshop. The simple design and straightforward build allowed for side conversations in the workshops with adults, which we further facilitated by asking individuals questions for their thoughts about relevant topics, such as the current energy crisis, and invited them to share a personal account if they felt comfortable.

To build the torch, participants either received printed build instructions or we showed them as part of the presentation. In the workshops with the pupils, we went through the instructions together and built the torch synchronously, step by step. We always encouraged the participants to help each other and troubleshoot together, but we were also available to help.

Curriculum-Specific Mapping and Competency Framework

Competence frameworks shape the lens through which we evaluate learning practices. In Germany, competencies for TVET are structured in the concept of "Handlungskompetenz" which roughly translates to "competence to act". It is split into four dimensions: technical expertise or knowledge, methodological expertise, social competence, and self-competence. To analyze accessible learning objectives, we utilized the "Handlungskompetenz"-framework while integrating relevant aspects of "Gestaltungskompetenz"-model of de Haan (2006) to add more depth. Learning objectives were gathered by educators in a participatory manner during the workshops. The final learning objectives and the respective competencies are listed in Table 3).

Table 3

Learning objectives and superordinate competencies according to the participating educators

Overarching Competencies	***Concrete Learning Objectives***
Technical knowledge	Students can name used components and their functions.
	subtitle of article.
	Students can explain the electric circuit and how the LED lits up.
	Students learn how to do troubleshooting for easy electrical circuits by testing conduction.
	Students can name electricity production sources.
Societal and environmental knowledge	Students can describe differences in the living conditions of people with and without steady power supply.

Overarching Competencies	*Concrete Learning Objectives*
	Students learn about the advantages and concerns related to LED technology, including affordability, low energy consumption, pollution through production, light pollution, and limited recycling.
	Students learn about the advantages and concerns related to copper tapes, including its practicality and functionality, mining practices, pollution through production and limited recyclability.
Methodological competencies	Students learn to use copper tape to build an electrical circuit.
	Students learn how to follow step-by-step instructions.
	Students can follow thinking routines for meta-discussions.
Social competencies	Collaboration, i.e. students ask for help and provide help when needed.
	Students pause their work to assist others in tasks they already completed and learned.
Self-reflection and critical thinking skills	Students can reflect on the role of light and technology in their daily lives.
	Students are open to rethink their assumptions about the world, and integrate alternative points of view regarding technologies, light, and resource limitations.
	Students show empathy and solidarity with others who lack access to a steady power supply.
	Students develop endurance in troubleshooting of technologies.

Beyond that, we discussed integration opportunities in their existing school curricula with the participants. Due to the legal frameworks around education, in Germany, each state has its own curriculum. During some workshops, integration opportunities into the school curricula of Bavaria, Baden-Württemberg, Bremen and Berlin/Brandenburg were provided as an example and discussed (see Table 4 for details). This constitutes an example of how flexible critical making can be fit into existing curricula.

Table 4
Examples for potential inclusion of the torch workshop in German curricula

Federal state	*Level*	*Subjects*
Baden-Württemberg	Primary school	General studies
	Secondary level I	Science and technology, physics, engineering
	Secondary level II	Science and technology, physics
Bavaria	Primary school	Local history and general studies, handicraft
	Secondary school 1	Science and technology, engineering, economics, vocation
	Secondary school 2	Handicraft, physics
	Secondary school 3	Science and technology, physics

Federal state	*Level*	*Subjects*
Berlin / Brandenburg	Primary school	General studies
	Secondary level I and II	Economics, vocation and technology, life science, physics
Bremen	Primary school	General studies
	Secondary level	Science

Participants' Reflections

In the workshops with the making element, we observed the participant's interactions and behavior. A final reflection session was held after participants finished building their torches in which they reflected on what they learned that day, and how it is useful to them in their daily life. General feedback was also collected.

In the workshops with a meta-discussion element, we started a discussion around what critical making means to the participants and what general implications they think there are for education. We asked them how they think they could encourage more reflexivity in their own workshops, activities, or school lessons. Finally, they were encouraged to share experiences and give best practice examples. The feedback from the participants was either exchanged and discussed in a group conversation and/or collected on a poster framed as "The Critical Making Manifesto". which, as previously mentioned, is a work in progress and will be shared with stakeholders as a physical poster.

Results

Pillars of Critical Making in Education

In the first research phase, we identified core concepts for critical making in education and reviewed, discussed, and improved them as part of our design process in the second research phase (see section 4 and figure 1). The participants suggested that the following key principles inherent to critical making should be promoted in educational activities:

Critical thinking, according to the participants, means asking questions to yourself and others. In the context of critical making, this implies looking into which technology we actually need to solve a problem or whether technology creates new problems. Novel technologies are often promoted as saviors which will change our lives for the better. Therefore, it is important to show young people to look beyond buzzwords and question imprudent use of technology, e.g., facial recognition in surveillance systems (Van Noorden, 2020). In this case, making is a tool to uncover, explore, and display potential negative implications that are overlooked (confer section 5.1). This is important because in critical theories about technology, both technosolutionism (Lindtner et al., 2016) and the black-boxing of technology (Hertz, 2015; Latour, 1987; Oliver et al., 2011; Ratto & Boler, 2014) are recurring topics that, in our opinion, should be discussed in schools.

Reflexivity is closely linked to critical thinking and to the practice of responsible research and innovation (see e.g. Tassone et al., 2018). Aptly, making has been explored as a tool supporting mindful and responsible innovation (Thomas et al., 2024). According to the participants, taking different perspectives on a problem and looking into different ways to solve it raises awareness.

By demonstrating the various levels one can think on, educators can encourage their students to expand their horizons and to think outside the box. Making opens up new perspectives by creating and interacting with physical objects and promotes reflection on the benefits and risks of technology by doing. This grounding experience aids to better understand the adequacy of technology and to gain mindfulness in dealing with it.

Prosumerism describes the trend of a dissolving distinction between consumers and producers in an economy. People alter, repair, and improve existing products or even produce them themselves. Re- and upcycling also play an important role in dealing with overconsumption and working towards economic as well as ecological sustainability. Critical making is a way to reflect on how we consume and to give young people an understanding of prosumerism. Creating a physical artefact empowers them and raises awareness about the implications of production in an economy. Beyond that, the actions support the development of individual skills, which might in turn inspire to start making by oneself. Combined with critical thinking and reflection, this opposes the classical "making" which celebrates the creation as an end in itself. Technological literacy, repairability, and "prosumerism" (Anzalone et al., 2015; Baier et al., 2016; Fonseca, 2015; Paltrinieri & Esposti, 2013; Srai et al., 2016) are also recurring topics in research that could be discussed in the classroom.

Social innovation is another key element inherent to critical making, which distinguishes it from generic making activities. Making education is a powerful tool to find solutions for a better future, using "tech for good". It is about being able to help minorities and using appropriate technology to solve neglected problems. Critical making can encourage young people to develop and use their skills to help others, by showing them what they are capable of, and that they can make a difference. In this context, critical making also means reflecting together on the social impact innovations can have and pointing out antisocial innovations and developments. Indeed, social innovation (MacCallum, 2009; Moulaert et al., 2014) and grassroots innovation (Smith et al., 2016) are seen as potential directions to develop alternative futures, especially in non-Western settings (Kaiying et al., 2019), and can provide interesting frameworks in the classroom to think about citizen empowerment.

Transparency and openness, according to the participants, is reached by creating things ground up, experiencing how they work by doing, and sharing knowledge with others. Educators can change how their students experience technology by opening black boxes, disassembling objects and recreating technologies. This practice of critical making promotes technical and digital literacy in young people. Furthermore, students should understand that sharing lessons learned, experiences and ideas supports prosumerism and social innovations. However, this also applies to the educators themselves, sharing educational material and exchanging resources openly (see e.g. Mruck et al., 2013).

Interpretation Informing Applicability

In the third research phase, the key principles of critical making were introduced to teachers, educators and stakeholders. Possible implementations in the school curriculum were discussed, identifying challenges and opportunities (see section 4 and figure 1).

Based on the educators' input, we can summarize that in the existing curricula, the principles of critical making were already present in their foundation but are often neglected or only covered superficially in practice. While making is not specifically addressed, critical making principles resonate with the sustainable development goals (SDGs) and contribute to an education for sustainable development (ESD) (Alexander et al., 2018; United Nations, n.d.). The German government is part of the UNESCO program "Education for Sustainable Development: Learn for our planet. Act for sustainability". The school forum implements the goals of the National Action Plan on ESD for the education sector school and formulates recommendations for action to structurally anchor ESD in schools and school policy (Holst & Brock, 2020). The strategic paper on digital education of the Conference of German Cultural Ministers describes a similar goal, with a focus on digital literacy (Kultusministerkonferenz, 2016). Interdisciplinary education, project- and/or problem-centered learning are already integrated in the German states' school curricula and teacher education. It is clear from the interpretations described in the previous section that critical making can enhance TVET in order for education to be better equipped and future-proofed for children, as well as to serve the goals it is required to serve.

Both strategies provide several connection factors for critical making, which, could serve as a link between ESD and digital education in the curricula. Participants in our workshops confirmed the compatibility of critical making and teaching. They considered and valued critical making as a practical approach to digital and technological literacy in young people. However, our own experiences and discussions with stakeholders as part of our design process indicate that the implementation of ESD and changes in the approach towards digital education are often missing in practice. Our research revealed a lack of literature describing a successful realization of ESD and the digital strategy in school teaching. Therefore, we looked deeper into this apparent gap between theory and practice to identify action fields and entry points for a successful implementation of critical making in education.

Pertinent Challenges

As part of the research, we elucidated possible challenges with participants that might hinder the introduction of critical making into education. Analyzing the outcomes, it can be deduced that most of the identified obstacles to overcome are not specific to critical making but generally valid for changes in school teaching, as outlined in detail above (Schumacher et al., 2013).

Teacher involvement has been identified as a major field of action. Multiple makers and people involved with maker spaces offering educational workshops reported that it is hard for them to reach and involve teachers as an out-of-school institution, especially for extracurricular activities. They heavily criticized the lack of openness. This observation was explained by the school system rewarding the focus on main subjects and grading while discouraging teachers from trying out new ways of teaching and learning. The current priority on promoting projects in STEM (science, technology, engineering, and mathematics) education leads to the emergence of top-down organized lighthouse projects that eventually become empty ivory towers. As a participant put it, other projects initiated by teachers are abandoned when the initiator leaves the school. However, best practice examples were also demonstrated, highlighting the importance of the school governance structures for the successful implementation of projects. Extracurricular interests and competencies of teachers, such as working, teaching, and thinking in an interdisciplinary manner, are especially important for such endeavors and need to be encouraged and rewarded accordingly.

Multiple participants with an educational background mentioned the perceived lack of time and space for experimentation in the school routine. There is high pressure to cover the necessary topics of the curricula, and almost no unscheduled time is left. Often the contrary is true, and time for a subject is consumed by cancellations of classes. Simultaneously, implementation of, e.g., ESD and project-based learning is viewed as an extra burden and thus is avoided. We experienced a similar situation when we were faced with a tight schedule for our workshop with a school class at an education festival. The reflecting part of the workshop was neglected to the benefit of finishing in time with working torches.

In the workshop with the school class, we also observed initial skepticism of the teachers and chaperones (parents), which dissolved during the workshop. In the beginning, they expressed worries of overwhelming the pupils with the tasks without further background on that matter. The teachers have been used to first sharing background information on how the tool is supposed to work, essentially sticking to a rigid method of first educating and then doing. They were proven wrong by the kids effortlessly building their torches and enjoying the workshop. When asked if they would implement critical making in their lessons, they denied, saying that they lack the necessary knowledge and skills.

Opportunities for a Successful Implementation

While the introduction of new ways of teaching can be hindered in many ways, participants also shared success stories demonstrating that change is possible. In our workshops, teachers, educators and stakeholders exchanged experiences and ideas how to overcome the challenges and obstacles they face. Furthermore, suggestions for in-depth changes in school policy were collected, which are necessary to allow for change. One of the suggestions was to focus on engaging with school headmasters to allow for more participatory design of curricula, and essentially a change of governance in schools - which had been previously identified as a general obstacle (see section 6.3). Although identified as a challenge as well, teachers should be implicitly involved in the activities, especially when the implementation of a larger project is planned. Exchange and transfer of knowledge inside and beyond institutions can ensure that projects become more sustainable. Furthermore, the final target group should be remembered. Students should be included in shaping activities and project because they are usually the best multiplicators. Allowing for bottom-up projects to grow leads to collective ownership and, thus, sustainable and resilient implementation. Critical making should not feel like a burden but should add value for every party involved. In general, when practicing critical making, the following should be prioritized in the interaction with young people: The activities should be aligned with the students' skills, take their personal situations into account, and expect less from them to reduce any implicit pressure to perform. In critical making, the process is important, with a focus on experimentation (see, e.g. Ratto, 2009), and not the product. Thus, giving students an understanding of this and clarifying the expectations is crucial, as also observed by, e.g. Schumacher et al., (2013); they are not used to such freedom in learning. Support through communication, e.g., asking questions to trigger critical thinking and reflection, is especially important in the beginning, but also throughout the process of a making activity. Activities should also stay close to the practical needs of young people and should focus on matters relevant to their daily lives. Beyond that, critical making also has a social component, which can be promoted by allowing for fun and potentially leading to creative projects that support the self-directed learning process (Sagbauer & Ebner, 2021).

Closing Thoughts and Outlook

While the design of these workshops was originally motivated by the need to further develop existing vocational educational offers in Germany to educate citizens of the future who can think critically and are socially responsible, the participatory workshops illuminated several unexpected challenges and opportunities.

We wanted to test the observation that currently, in many German classrooms, critical thinking skills are not being transferred. The hypothesis was that this might be a shortcoming of the educators, as it depends mainly on whether they allow discussions to happen and how deep these can go. The working theory was that it also depends on their existing knowledge beyond the curriculum and willingness to do further research or participate in training. This has not been the first experiment of IBBA to improve TVET through making and other digital skills. We knew that there was interest, having designed and conducted the previously mentioned vocational educator training "Digital Worlds". However, we also knew from the project evaluation that challenges existed. First, gaining new and complicated skills often led the educators to focus only on the technology and its troubleshooting. Second, a lack of funding for and a lack of time to attend such trainings also translate to the everyday life of teachers. Understaffing and rushed teaching of large amounts of educational material cause a lack of unstructured, creative time that could lead to experimentation, the opportunity to fail and learn from it, and deeper socio-technical conversations (as summarized in the last point in the previous section). By designing some of the participatory workshops specifically for vocational educators, providing them with a simple tool that does not require a lot of troubleshooting, and allowing them to experience how to have meta-conversations while making, we wanted to understand whether these challenges could be addressed.

Although adding "Digital Worlds" to the curriculum in select schools in Berlin has been possible, it would be unrealistic to expect that the vocational curriculum on a national level will include a new set of subjects soon. Such processes are highly political and take a long time. Due to the issues described above, we also cannot recommend adding new courses on top of the existing curricula. Thus, instead of changing the system with the workshops described above, we essentially propose replacing or adding some elements to complement the existing curriculum. As there is, e.g., a predefined set of classes to teach children about electronics (see Table 3), with critical making, teachers would not need to change the whole subject. Instead, they could add discussions about the process not only on the factual level but also on the meta-level. This way, they could create space for exchange on the sociotechnical topics proposed above while pupils build their circuits. Essentially, the teaching style is updated to add significantly more value to the classes. This requires neither further funding nor more time spent in the class.

As a final thought, we would like to briefly reflect on our own shortcomings. The original goal was to make the workshops participatory, not only when building the artefacts, but also in terms of knowledge sharing. While we assumed that 90 minutes would be enough to build and discuss, our focus shifted from the knowledge exchange and meta-discussions to an internal pressure to give away something "finished" at the end of the workshop. Thus, in one of the workshops, we made the mistake of focusing on making only, due to the time pressure. Reflection - maybe because the facilitators' background was in making, not reflexive practices - became of secondary importance. In this workshop, the facilitators seemingly forgot the possibility that the artefact itself could be finished at home or during another event, freeing up time for discussion. Learning from this, if educators were to follow up on our recommendation and design their classes to add criticality to making, they need to keep in mind to be reflexive of how much they need to achieve both in terms of critical thinking as well as making during the allotted time. This is a question of experience, background, and also individual priorities: a focus on the process rather than the output. Having the focus on the process of making and understanding it as something that includes reflection in addition to working on a project might be a useful pathway to facilitate this split between time pressure and output-centered education.

Acknowledgements

We would like to thank Susanne Grunewald for the brainstorming and cooperation, Lisa Mo Seebacher and Barbara Kieslinger for their thorough revisions and contributions, and Julian C. Heyder for his support with the curriculum references. During the development of this paper, the authors were employed at the Institute of Vocational Education and Work Studies, Technical University of Berlin and would like to thank the Institute for its support.

Disclosure statement

No financial interest or benefit has arisen from the direct applications of this research.

Funding

The Critical Making consortium has received funding from the European Union’s Horizon 2020 Research and Innovation programme under grant agreement No. 101006285.

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