Critical Making: Fostering Critical Thinking in Making Processes

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Abstract

Critical Making is an EU-funded project that combines critical thinking with hands-on learning in educational makerspaces for the teacher education of STEM subjects. Bringing together partners from Italy, Sweden, Poland and Germany, the project targets pre-service and in-service teachers of biology, chemistry, computer science, physics and politics. Based on the concept of Critical Making as the connection between conceptual reflection and practical application, we have developed and piloted a scenario called 'City of the Future'. In this scenario, student teachers address socially relevant issues identified by the United Nations' Sustainable Development Goals (SDGs) and participate in a creative process involving imagination, creation, play, sharing and reflection. The central focus is strengthening their ability to detect and tackle misinformation in socio-scientific debates, particularly those concerning sustainability and technology. This paper describes the Critical Making approach's pedagogical design and reports on pre-service teacher training, where participants designed and realised prototypes such as electrochromic windows for light and heat control, and Arduino-controlled automatic windows that open when a CO_2 threshold is exceeded. Despite initial challenges with tools, materials and programming, participants gradually developed flexible, case-based problem-solving strategies, strengthening their digital and critical evaluation competencies in the process, including the critical appraisal of data and media claims. We argue that Critical Making in teacher education can foster creativity, critical thinking, and responsible innovation relating to sustainability and digitalisation. The iterative cycle of making supports continuous learning by encouraging learners to reflect on failures, refine their ideas, and re-engage with complex socio-technical issues while using empirical measurements and prototypes to challenge misleading narratives.

Keywords: *Critical Making, STEM teacher education, Sustainable Development Goals, digital competencies, critical thinking, misinformation*

1. Introduction

The growing digitalisation of everyday life and the urgent need to address sustainability issues require citizens who can engage critically with technology and socio-scientific matters. Teachers play a central role in preparing students for this complexity, yet they often lack the opportunity to experience technology-rich, project-based learning during their own studies.
Critical Making is a promising approach that links the creation of analogue, digital or hybrid prototypes with critical reflection on social and environmental issues, thereby bridging this gap. In the EU-funded Critical Making project, partners from Italy, Sweden, Poland and Germany are collaborating to design learning environments in educational makerspaces that foster critical thinking and creativity among STEM teachers and teacher trainees [1–3]. A key aspect of this work involves addressing misinformation in STEM-related public discussions. By combining empirical experimentation, data collection, and media analysis, trainee teachers learn to contrast technology-related myths and misleading claims with evidence-based reasoning and their own measurement results.
This paper presents the design of a Critical Making scenario implemented in pre-service teacher education under the theme 'City of the Future', and the first experiences with it. Our focus is on how the iterative making process can support the development of digital skills, the critical evaluation of information, and flexible problem solving. We illustrate this with two example projects: an electrochromic window and a CO_2-controlled smart window. Both projects explicitly encourage participants to question assumptions and to critically assess information from the media and online sources.

2. Theoretical Background

2.1 Critical Making as Integrating Thinking and Making

Ratto presented 'Critical Making' as an approach that deliberately combines conceptual reflection with practical work in order to explore the social and political dimensions of technology [1]. 'Critical Making' (CM) is a teaching method that combines self-directed creation of analogue, digital or analogue-digital prototypes — an essential component of the creative process — with critical thinking [1, 2, 12].
As part of the EU-funded Forward-Looking project, 'Critical Making', universities from Italy, Poland, Sweden and Germany are developing learning scenarios to implement Critical Making in the initial and continuing education of STEM teachers. From the perspective of teacher education, Critical Making encompasses practical work, project-based learning and scientific thinking. Each of these teaching methods has its own unique contribution to understanding and complements the others (see Fig. 1). A central prerequisite for Critical Making is selecting socially relevant problems as a starting point. The United Nations Sustainable Development Goals (SDGs) can serve as a framework for identifying such prerequisites and can also become the subject of critical discussion themselves. From the perspective of the maker tradition, digitality is another critical aspect of Critical Making, particularly with regard to misinformation. Subsequent studies have shown that critical making activities can highlight tensions between efficiency, comfort, sustainability and justice. These tensions can then be discussed productively in an educational context [3].

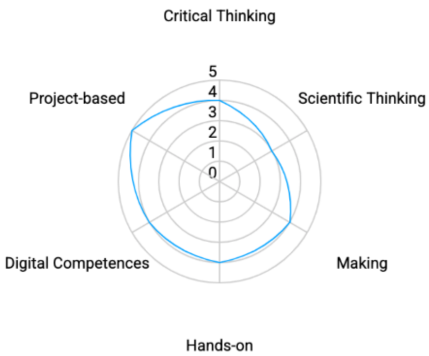


Fig. 1. *Critical Making design criteria. Priorities vary by scenario.*

2.2 Educational Makerspaces and Learning

Educational makerspaces are open learning environments that provide tools, materials, and digital fabrication technologies to support exploratory, project-based learning. Research into learning in makerspaces suggests that they have the potential to foster creativity, a sense of agency, collaborative problem-solving skills and an engineering mindset [4]. However, the open-ended nature of making can make it difficult to structure activities and assess learning.
Recent work on measuring learning in makerspaces has proposed constructs that focus on design process skills, persistence, collaboration, systems thinking and reflective practice, rather than narrow test-based outcomes [4]. These approaches are consistent with the principles of Critical Making, which views learning as the acquisition of technical knowledge and the development of critical and reflective attitudes towards technology and society.
In teacher education, makerspaces can serve as rehearsal rooms in which pre-service teachers experience the perspectives of students undergoing inquiry, facing frustration, undergoing iteration and achieving success. Engaging with new technologies, electronics and software can confront them with their own uncertainties, but it can also open up possibilities for them to reflect on how they would scaffold similar processes for their future students.

2.3 SDGs and Socio-Scientific Issues in STEM Education

The United Nations' Sustainable Development Goals (SDGs) are a widely recognised framework for tackling global issues such as climate change, sustainable cities, health and wellbeing, and responsible consumption [10]. Integrating the SDGs into STEM education can enhance its relevance and meaning by linking disciplinary content to real-world issues.
Socio-scientific issues, such as energy use, air quality and urban mobility, are characterised by complexity, value-laden aspects and the need to balance competing interests. Teaching with these types of issues has been shown to promote critical thinking, argumentation, and decision-making in situations of uncertainty. Combining SDGs and socio-scientific issues with making activities can provide authentic contexts for designing prototypes that embody particular visions of the 'City of the Future', such as energy-efficient buildings or healthier indoor environments.

In our project, the SDGs serve as both a lens through which to select socially relevant problems and a framework for reflection: students are encouraged to consider how their technical designs relate to specific SDG targets, the trade-offs involved, and the perspectives taken into account.

2.4 Frameworks and Teacher Education

Critical Making encourages broader reflection on responsibility in innovation processes, taking into account more than just individual projects. For this purpose, Sipos and Åkerman propose a 'Critical Making Responsibility' framework, which can be used to analyse how grassroots democratic practices take aspects such as inclusion, sustainability, power relations and accountability into account [2]. Adopting this approach in teacher education encourages prospective teachers to shift their focus from purely functional questions such as 'Does it work?' to critical and reflective considerations such as 'What are the sustainability implications?' and 'Which resources are affected?'.
This is particularly significant for prospective teachers, as they will later be responsible for developing their students' skills. Experience with innovative critical-making scenarios can help them to understand their role in shaping the discussion, evaluation and implementation of technologies in the classroom. This simultaneously supports the development of competencies required to foster critical digital literacy among students, such as dealing with misinformation, datafication and the environmental impacts of digital infrastructures.
Taken together, these theoretical strands shape our concept: We view the makerspace as a place where pre-service teachers work on critical-making projects explicitly linked to the Sustainable Development Goals (SDGs) and social science topics, where reflection on responsibility is systematically integrated into the design and evaluation of prototypes. 'Critical Making' thus offers a promising framework in teacher education, providing a systematic approach to preparing prospective teachers to foster the development of 21(st)-century competencies in their students.
Building on Ratto's concept of critical making as a combination of physical fabrication and critical reflection on technology and social life, design activities involving new technologies (e.g. microcontrollers, digital fabrication and AI-supported tools) can make problem-solving, future-oriented and digital skills tangible and experiential within authentic design processes.
When learners design their own artefacts, implement them as prototypes, test them and reflect on them, they practise scientific thinking (hypothesis-based approaches, experimentation and iterative improvement) and critical thinking (reflection on the social, ethical and ecological implications of technological solutions), as emphasised in critical-making approaches that focus on responsibility and innovation [2]. Such projects can be embedded in socially relevant topics, such as scenarios related to the Sustainable Development Goals, like 'City of the Future', in which students develop smart houses or sustainable energy systems, iteratively improving their prototypes as they do so. This will be illustrated later in this publication.
In terms of teacher education, student teachers should experience their own competence development through critical making activities, as well as learning didactic strategies to design similar learning opportunities in a school context. Empirical and conceptual studies on critical making in education, on conceptual frameworks of responsibility, and on the assessment of learning processes in makerspaces offer valuable guidance for designing such scenarios. Based on these studies, prospective teachers can boost their students' self-efficacy, encourage cooperative problem-solving, and promote the reflective and responsible use of digital technologies.

3. Project Overview and Design

The Critical Making project brings together institutions from four countries — Italy, Sweden, Poland and Germany — to develop and evaluate design principles, teaching materials and training formats for educational makerspaces. The project focuses on STEM subjects (biology, chemistry, computer science, physics and politics) and emphasises integrating digital technologies into maker projects [1–4].

Our design is guided by the following core ideas:
- the combination of making and critical thinking, with prototyping serving as a means of questioning technological solutions, their underlying assumptions, and their societal impacts.
- SDG-oriented problem framing: learners work on problems that are explicitly linked to the SDGs, such as sustainable cities, clean energy and climate resilience.

- Develop and apply strategies to tackle misinformation in socio-scientific debates by linking media claims to empirical data and your own prototype-based investigations.
- Iterative Making Cycle: Activities follow a playful, iterative cycle of Imagine – Create – Play – Share – Reflect, emphasising experimentation, feedback, and revision.
- Focus on teacher competencies: Scenarios are designed to build teachers' capacity to design, facilitate, and reflect on critical making activities with their own students.

The following presents the 'City of the Future' scenario as a concrete realisation of these ideas.

4. Scenario "City of the Future"

4.1 Learning Objectives

The 'City of the Future' scenario developed as part of the project serves as a concrete example of the critical making approach, explicitly linking it to specific Sustainable Development Goals (SDGs) to highlight socio-scientific issues [10]. The scenario aims to enable pre-service teachers to identify and clearly articulate everyday issues in the context of sustainable cities and communities. Furthermore, they are expected to critically evaluate digital information and distinguish between fake news and evidence-based sources. In terms of digitisation-related competencies, students learn to use digital tools for targeted research, collaborative work, and data-based analyses of urban challenges while considering basic principles of data and algorithm literacy. Based on this, students design and create functional prototypes, often with digital support (e.g. using sensors, programming or simple AI applications), to address specific issues. Throughout this process, they reflect continuously on the ethical, social, and environmental implications of their design decisions, including issues such as data protection, digital inclusion, and accessibility, and consider their future responsibilities as teachers in this field. Finally, they analyse the iterative design process from the perspectives of both learners and teachers in order to make the scenario robust and usable in school contexts in the context of contemporary digitisation-related education [10].

4.2 Sequence of Activities

First, participants are introduced to the concept of critical making and discuss examples of fake news and misinformation relating to sustainability or urban futures. They then work in small groups to select an SDG-related issue, such as energy use in buildings, air quality or mobility, before defining a concrete problem scenario in the context of a future city.

Following a brief introduction to project management and available tools, the groups will brainstorm solution ideas and sketch initial prototypes, considering technical feasibility and social impact. During the core phase, participants engage in iterative cycles of building, testing, and refining their prototypes, following the 'making' cycle: imagine, create, play, share, reflect. They document their process, share intermediate results with their peers, and incorporate their feedback.

Finally, the session concludes with presentations of the prototypes, followed by a structured reflection on the learning outcomes, challenges, and transfer opportunities for school practice. In this implementation, two groups worked on prototypes related to building technologies and indoor climate, namely an electrochromic window and a smart window controlled by CO_2 levels.

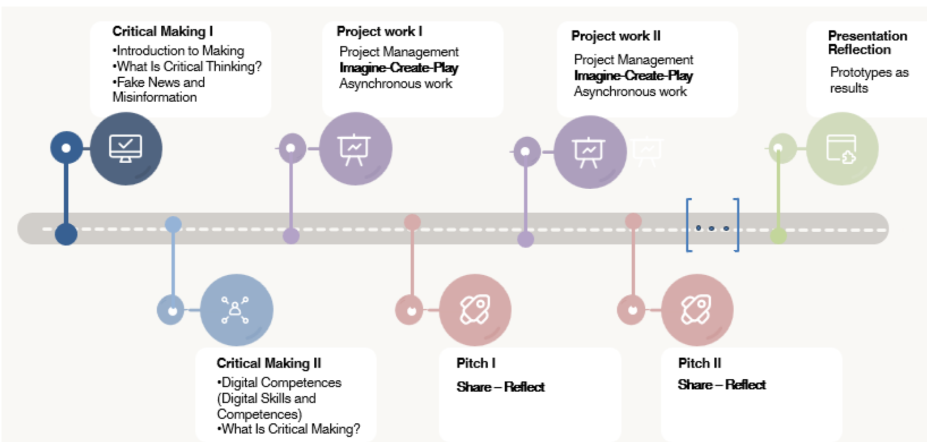


Fig. 2. *Pre-Service Teacher Training Session Plan*

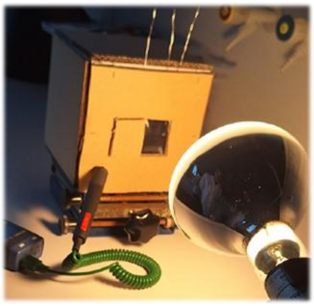
5. Examples of Prototypes

5.1 Electrochromic Window for Light and Heat Control

One group designed an electrochromic window that uses Prussian Blue-based redox reactions (Fe^{2+}/Fe^{3+}) with ion insertion to regulate light and heat in buildings by reversibly changing the tint. The electrochromic layer consists of Prussian blue on transparent, conductive electrodes, combined with a potassium nitrate-based electrolyte to enable ion transport.
The student teachers produced a PVAL-based gel containing 1 M potassium nitrate, coated the window using a stepwise procedure, and connected the system to a power supply. Several iterations were necessary; an initial trial with insufficient potassium ions yielded an inadequate colour change, necessitating an adjustment to the electrolyte concentration. Subsequent modifications, such as the use of a rolled graphite electrode, increased the active surface area and improved the switching behaviour. Stable colour change was finally achieved at approximately 1.7–2.0 V.

Fig. 3. Electrochromic window that can be used to regulate light and heat in buildings. It uses redox reactions (Fe^{2+}/Fe^{3+}) based on Prussian blue and the incorporation of ions to change its colour reversibly. Foto: Scharmann, Lehmann

A measurement setup was used to investigate whether the window could help keep a house cool. A lamp at a fixed distance was used as a heat source (see Fig. 3). During the experiment, the students critically discussed potential sources of error, such as heat storage in the gel, and considered how these might affect the interpretation of the data.
From a sustainability and SDG perspective, the prototype enabled the reduction of energy demand for building cooling to be addressed, as well as the broader role of smart glazing in sustainable urban infrastructure. Students identified advantages such as energy savings, high chemical stability, and diverse applications. However, they also critically examined disadvantages such as high production costs and challenges related to the disposal of cyanoferrate-containing materials.
Several challenges arose during the making process, including selecting a topic, designing the window within the model house, producing a stable gel and constructing the multilayer window system. These challenges provided opportunities to enhance communication, collaboration, and resilience in the face of experimental setbacks.



5.2 Automatic Co₂-Controlled Window for Smart Homes

A second group developed a CO_2-controlled window for smart home models. The prototype incorporates a CO_2 sensor, a microcontroller, a servomotor and a laser-cut window construction. The central idea is to use the concentration of CO_2 indoors as an indicator of air quality, triggering the automated opening of the window once a defined threshold is exceeded.

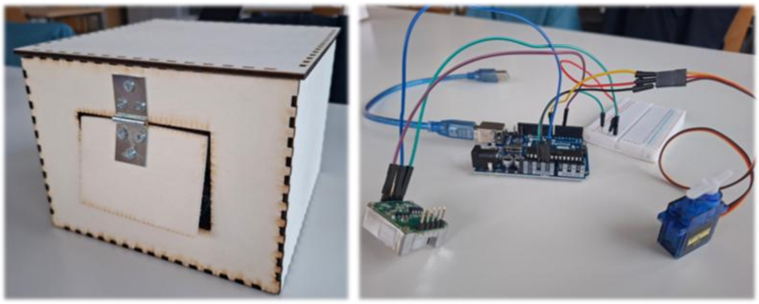


Fig. 4. Automatic window opening when CO_2 threshold is exceeded (Arduino controlled). Foto: Zelenak, Nitsche

During the theoretical phase, students identified key aspects of indoor air quality. They discovered that CO_2 is a colourless, odourless gas whose concentration in enclosed spaces depends on factors such as the number of people and animals present, the size of the room, the ventilation situation, and the level of physical activity. They then related their design to existing guidelines, which state that CO_2 levels of up to 800 ppm are desirable for infection control, levels of up to 1,000 ppm are considered hygienically

acceptable, levels of 1,000–2,000 ppm are noticeable, and levels above 2,000 ppm are unacceptable. The effects of elevated CO_2 levels, such as fatigue, reduced concentration and diminished performance, were also discussed.
The implementation process involved several steps, beginning with safety training in the makerspace. This was followed by designing the window box using a graphics programme and then laser-cutting the housing. The students then selected suitable components and planned the circuit. They then tested the sensor and servomotor using example code, before integrating the components on a breadboard. Finally, they assembled the window mechanically using hinges.
During testing, the group initially defined a CO_2 threshold of 1,200 ppm, but found that lower thresholds caused the window to open almost constantly. They also noted several practical limitations, such as the fact that CO_2 values were displayed only on the connected computer, the window did not close properly and it was not currently possible to permanently embed the electronics into the small house model.
In their reflection, the students identified learning gains at multiple levels: personal (planning, perseverance and solution orientation); social (recognising that asking for help is normal and productive); methodological (systematic testing of individual components, stepwise programming, error analysis and threshold calibration); and subject-specific (a deeper understanding of CO_2 as an indicator of indoor air quality, and of the interplay between measurement technology and building design). They concluded that the prototype fulfilled its intended function, effectively combining technical and manual work with scientific reasoning about indoor climate and health.
Students also compared their prototype with commercial smart glazing solutions and visualisations of energy flows, discussing scalability and realistic performance expectations [11].
In addition to electrochromic and CO_2-controlled windows, the 'City of the Future' scenario can be expanded to include further smart house modules. Within this system, students can integrate solar cells and miniature fuel cells as renewable energy sources, investigating how different energy mixes could contribute to more sustainable urban neighbourhoods. They can also compare wall and insulation materials (e.g. phase change material wallpapers, foams and reflective foils) under simulated day–night cycles, discussing how such building envelopes could be scaled up to entire city districts.
Building on the concept of the smart house as a micro-laboratory, further modules could incorporate hydroponic and aquaponic systems as prototypes for urban food production. Learners can examine the interaction between water quality, nutrient cycles and plant growth in closed systems, as well as how such installations could be incorporated into the façades or rooftops of future cities. Adding algae-based components (e.g. simple photobioreactors in transparent panels) allows learners to address microbiological aspects that are energetically and climatically relevant, such as CO_2 uptake, oxygen production, biomass generation, and shading effects. Sensor stations measuring temperature, humidity, light intensity and CO_2 enable learners to monitor the influence of these biological subsystems on indoor climate and energy demand. Thus, the smart house model serves as a test bed for exploring how buildings in the 'City of the Future' could provide housing, energy services and food production simultaneously, linking concrete measurements to broader questions of urban planning, climate mitigation and education for sustainable development.

6. Observed Learning Processes

Empirical insights into learning processes within the Critical Making scenario can be gained from observations and student reflections on the two prototype projects. In the electrochromic window project, students reported facing a series of technical and organisational challenges. These included selecting a topic, designing the window for the model house, producing a stable PVAL–potassium nitrate gel, and assembling the multilayer electrode structure. These challenges necessitated repeated group coordination and iterative adaptation of their approach. The making process involved several experimental cycles, fostering experimental reasoning as students had to interpret unexpected outcomes, hypothesise causes, and design targeted modifications. A subsequent measurement phase brought questions of measurement uncertainty and validity into focus.
In the CO_2-controlled smart window project, learning processes unfolded along technical, conceptual, and socio-emotional dimensions. Students had to familiarise themselves with the makerspace, select and test components, plan and implement the circuit, and integrate the code. They repeatedly troubleshot issues such as unstable threshold values and mechanical imperfections, thereby developing their methodological competencies and engineering design thinking skills. In their reflections, the students highlighted their learning gains in the areas of the personal, social,

methodological and subject-specific dimensions, and they linked their prototype to specific issues relating to health and learning conditions in schools.
In both prototypes, the scenario supported the development of flexible, case-based problem solving and strengthened collaborative and communication skills. It also promoted digital and experimental competencies, as well as encouraging critical reflection on sustainability, indoor climate, and the conditions for teaching and learning.

7. Discussion and Conclusion

The Critical Making project shows how educational makerspaces can link STEM subjects with socio-scientific issues in teacher training. The 'City of the Future' scenario shows that, when embedded in a broader framework of SDGs and critical reflection, prototyping becomes more than a technical activity; it becomes a space for exploring responsible innovation and democratic participation [1–3].
The playful, iterative cycle of imagine – create – play – share – reflect encourages learners to view failure as a resource, incorporate feedback, and refine their ideas. This approach fosters continuous learning and can contribute to the development of more resilient and reflective teaching practices. At the same time, however, the scenario highlights the need for careful scaffolding: pre-service teachers require support in managing open-ended projects, dealing with technical frustration, and explicitly linking design decisions to the SDGs and questions of responsibility.
Future work on the project will involve refining the assessment tools used to capture learning outcomes in critical making environments, extending the scenarios to different subject areas and school levels, and elaborating further on the role of responsibility frameworks in guiding design and reflection [2, 4]. We also intend to examine how Critical Making can be incorporated into school curricula in a way that can be realistically implemented, taking into account time, resource and assessment constraints.
In conclusion, integrating Critical Making into STEM teacher education can help future teachers develop the competencies needed to design meaningful, critically informed learning experiences for their students in an ever-changing, digitally mediated world. A key strength of the 'City of the Future' scenario is that it fosters technical and design skills while equipping student teachers with concrete strategies for tackling misinformation in socio-scientific debates. By linking empirical measurements, prototype-based investigations, and critical media analysis, this approach supports the development of evidence-based classroom practices that encourage pupils to question misleading claims about sustainability, technology, and urban futures.

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