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Cross-cultural examination of 3D modelling and 3D printing in STEAM education: comparing results from teachers in Montenegro and Austria

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Abstract

Integrating 3D modelling and printing in STEAM education presents opportunities and challenges for teachers, particularly those in some European countries where its adoption in schools still needs to be improved. This article presents findings from a cross-cultural examination of 3D modelling and printing in STEAM education, showing results from teachers in Montenegro and Austria. The study aimed to gather insights into teachers' perceptions of 3D modelling and printing, ideas for its implementation and the challenges teachers face. Data were collected through questionnaires, interviews and examples of 3D modelling and printing use. They were subsequently analysed to identify similarities and differences in the impressions and use of the technology. The findings indicate that teachers in both Montenegro and Austria expressed interest in using 3D modelling and printing for STEAM teaching purposes and saw potential for connecting to subjects, such as digital literacy. However, they also identified software-related challenges, time constraints and training and financial difficulties when adopting 3D modelling and printing. The slow adoption of 3D modelling and printing in schools suggests that teachers should be better supported in using this technology, considering external and internal influences such as teacher training, local culture and availability of technology. Furthermore, the study highlights the need for suitable measures for teacher training and ensuring access to technologies necessary for 3D modelling and printing.

Keywords 3D modelling; 3D printing; policies; digital literacy; teacher training; STEAM

Introduction

Applying new technologies and using them to enrich teaching may be subject to cultural and financial considerations. To learn more about local or broader challenges that teachers face, collecting data from different countries can be valuable (Nistor et al., 2013). This study aims to understand teachers' use of 3D modelling and printing (3DMP). Comparing data from two countries that still need to offer 3DMP in schools helps to find arguments for supporting teachers regarding their local opportunities. 3DMP describes forming an idea by creating a 3D model for a 3D-printed object. Such activities receive increasing attention in education because of broad opportunities for science, technology, engineering, arts and mathematics (STEAM) subjects. The rise in popularity of 3DMP is often argued with STEAM classes frequently using new technologies for educational purposes (Meletiou-Mavrotheris et al., 2022). The slow adoption of 3DMP in schools suggests that teachers should be better supported in using 3DMP. External and internal influences, such as teacher training, local culture or availability of technology, vary according to the local resources available and cultural aspects inside and outside schools, which affect teachers' use of technology (Rosa and Orey, 2021). Ethnological conditions for teaching science, technology, engineering and mathematics (STEM) subjects are continuously changing in the context of a region's history related to cultural, scientific and technological developments (Rosa and Orey, 2016), and challenges in using technologies may differ from country to country. Therefore, it can be helpful to examine teachers' feedback from different countries – in our case Montenegro and Austria – to identify challenges and gain knowledge of local characteristics and find new ways of support. Neither Montenegro not Austria offers STEAM education or 3DMP to its students, suggesting that these countries could benefit from support for using it.

When selecting countries and contacting researchers for this research, we considered that one of the countries (Austria) is a European Union (EU) member, and the other (Montenegro) is a developing country applying for EU membership. As we wanted to investigate technology adoption, we chose an indicator used in similar studies (for example, Schmitz et al., 2022). The ICT (International Telecommunication Union) Development Index (IDI) measures countries' level of technological development. According to the ICT (2017), 0 is the lowest IDI score, indicating low technological development, and 10 the highest. The IDI score for Austria is 8.02 and for Montenegro 6.44, indicating that both countries differ in technological development, suggesting interesting new viewpoints to discover. We were privileged to introduce 3DMP to over 300 teachers in Montenegro and Austria, and when conducting pre- and post-data collection, we found inconsistencies in expectations about opportunities and challenges of 3DMP. Therefore, we looked at additional collected interview data and project descriptions to learn about their respective perceptions and to answer the questions: What opinions do teachers in the two countries, with different sociocultural backgrounds, have about implementing STEAM exercises using 3DMP? Moreover, what can 3DMP examples for STEAM exercises look like in these settings? We aimed to find common or specific challenges that could be addressed to support teachers in using 3DMP and aspects to consider. We also compared teachers' chosen topics for visualisations or illustrative models to find whether 3DMP could be used for inter- or even transdisciplinary STEAM approaches by non-STEAM teachers. The data were reflected in aspects of policy, knowledge, education and technology to develop ideas for supporting teachers in their specific situations.

Benefits for teachers using 3DMP for STEAM education

Traditional school subjects often have potential for improvement in providing needed knowledge for overcoming future challenges. As task complexity increases, there is a growing demand for innovative solutions. According to the Council of the European Union (2018), active and creative participation in society and working life requires specific key competencies for lifelong learning, including technological and social competencies supporting innovations. These skills include problem solving, critical thinking, collaboration, computational thinking, self-regulation and creativity (Council of the European Union, 2018). Creativity is part of the four Cs of the twenty-first century, alongside critical thinking, communication and collaboration, and it is identified as being crucial to foster (Trilling and Fadel, 2012).

Creativity and other mentioned skills can be promoted by introducing art and design thinking into STEM education (Wittayakhom and Piriyasurawong, 2020). For example, the ethnomathematical perspective in STEM education enhances pedagogical approaches by familiarising students with different ways of thinking, reasoning and developing mathematical knowledge in different sociocultural contexts (Rosa and Orey, 2021). This aspect could also be considered for other STEAM subjects. An interdisciplinary approach incorporating arts can provide STEAM learning exercises (Liao, 2016). According to Leavy et al. (2023), interdisciplinary approaches and new technologies break down boundaries between individual STEAM subjects and create connections between them and the real world. Such STEAM learning exercises can be achieved, for example, by using new technologies such as digital fabrication, including 3D printing (Leavy et al., 2023; Ng, 2017), which is based on previously created 3D models. A 3D model is usually created based on concepts including mathematics, scientific considerations such as physics or engineering, and design (Boy, 2013; Lee and Kwon, 2023). Virtual 3D models are then transformed into physical 3D objects using a 3D printer, applying technological and engineering knowledge and considering constraints related to physics, chemistry, aesthetics, engineering and so on. This process, which we call 3DMP, is successful if concepts from all STEAM subjects, including aesthetic considerations, are taken into account, and personal, unique solutions are part of problem-solving processes, which can be more motivating for students (Bicer et al., 2017).

The process of 3DMP also offers potential for transdisciplinarity because of its complexity and possibilities to extend learning experiences beyond classrooms. Haas et al. (2023) explain that 3DMP can connect STEAM subjects to students' lives by, for example, recreating a real-world object in project-based settings. Kit Ng et al. (2022) write about pedagogical settings where teachers use 3DMP in project- and problem-based learning, maker- and design-based learning and collaborative learning. These projects can be extended to solving complex challenges that students bring to classrooms, extending towards more transdisciplinarity (Meletiou-Mavrotheris et al., 2022). Diverse educational applications of 3DMP include teaching mathematical modelling, creating science class models, expressing art through visualisations and developing aids for students with disabilities (Asempapa and Love, 2021; Buehler et al., 2016; Menano et al., 2019; Tanabashi, 2021). Therefore, transdisciplinary STEAM exercises should overarch two or more STEAM subjects, contain a certain level of complexity by connecting to problem-based learning and offer inclusivity. Following this thought, a transdisciplinary 3DMP exercise supports training technical and social competencies, such as key competencies for lifelong learning and the four Cs of the twenty-first century. It includes opportunities for innovation and creativity through problem-based aspects in the 3D-modelling and 3D-printing processes.

However, many process steps in complex technology-based processes can be challenging for teachers, such as the availability of facilities and software usability (Holzmann et al., 2018). Many aspects, such as availability, familiarity with technologies, connections to STEAM subjects for meaningful applications and support from decision makers, can influence school adaptations of 3DMP, which is why investigations to understand challenges and opportunities are essential. Like many non-EU Eastern European countries, the school system in Montenegro has untapped potential to support students in developing critical lifelong learning competencies (Cortoni and Perovic, 2020; Šorgo, 2014). Schools have to rely on state-developed programmes and must request funding, which is rarely granted; they were therefore invited to apply to the programme in which we participated to offer opportunities for schools from financially weak areas or with a focus on inclusion. We then returned to Austria with a developed workshop structure and turned it into a non-mandatory course for pre-service teachers in their final semesters. Pre-service teachers were then introduced to 3DMP, because in neither Montenegro nor Austria are STEAM or technologies such as 3DMP commonly part of teacher training at the moment. We concluded that Austria too had potential to better support students in developing key competencies. When collecting data on opinions of 3DMP in questionnaires before and after workshops and courses, we realised that there was a mismatch between expectations and opinions. Hence, we chose to investigate further, looking at these two teacher groups more systematically.

Policies in Montenegrin and Austrian school systems

The Organisation for Economic Co-operation and Development (OECD) has developed a way to analyse technology-based school innovations using the attributes of:

- policy choices, such as freedom for teachers within curricula
- knowledge choices aiming at knowledge being available, distributable and usable
- pedagogical choices, such as teaching strategies
- technological choices, such as access to technical infrastructure (Oystein and Francesc, 2010).

We leant on these four attributes at specific points when comparing the Montenegrin and Austrian school systems. We also examined the collected data, such as questionnaires and interviews after teacher training through workshops and courses, to find connections to these four aspects.

Starting with an overview of policies, according to Eurydice (2023), the Austrian school system consists of compulsory primary school for four years; compulsory general lower secondary school for four years, followed by a choice of either a one-year pre-vocational or a secondary school; and a variety of secondary schools with either a general or a vocational character.

In 2021, a new Digital Literacy subject was introduced to support media literacy and technology skills (Federal Ministry of Education, Science and Research of Austria, 2021). STEAM, as such, is not part of the curriculum, while mathematics, informatics, natural sciences and technology (STEM) can be a specialisation that a school can choose. After graduating from general or teacher training universities, Austrian teachers mandatorily attend 15 hours of teacher training per year (Federal Ministry of Education, Science and Research of Austria, 2023). This includes training teachers in digital skills based on a 2018 plan to promote digitisation, including curriculum changes, teacher training adjustments and the availability technology hardware in schools (Federal Ministry of Education, Science and Research of Austria, 2018). Teachers about to graduate can already work in schools due to the STEM teacher shortage, and our study includes such teachers.

In contrast, according to Eurydice (2023), in Montenegro, the school system covers a different year span, from compulsory primary schools, including students from 6 to 15 years, and secondary in Gymnasiums for four years, or two to four years in vocational schools. From fifth grade (age 10–11 years), students attend the subject Computer Science for Technology, which is compulsory until ninth grade (age 15 years), where they acquire basic digital skills for using information and communication technologies and learn about their benefits (Anđić et al., 2018, 2022a). There is little research on STEM, let alone STEAM education in Eastern European countries such as Montenegro (Šorgo, 2014), and STEM subjects are not always included in the Montenegrin national curriculum. Lower primary schools in Montenegro cover science, technology and informatics subjects such as biology, physics, chemistry, engineering and computer science as part of the Nature module. In upper primary, STEM content is taught in biology, physics, chemistry, technology, engineering and computer science. Mathematics is always taught as a separate subject. In secondary schools (ages 15 to 19), STEM content is taught separately, in non-integrated subjects. However, recommendations for an interdisciplinary, integrative and future-oriented STEM approach to teaching are included in the curriculum and teacher handbook to link these STEM subjects. Teachers acquire their teaching qualification at university, and there are over 450 training courses available to advance their professional position (Eurydice, 2023). Our study, therefore, involves teachers of STEM subjects at the upper primary level.

The later division of students between primary and secondary suggests that the Montenegrin system aims to strengthen foundations for students until the ninth grade, and it focuses less on the period after that, while in Austria, diversification occurs earlier, and a variety of upper secondary school choices are available. Furthermore, Austrian policies explicitly target the promotion of technology, while in Montenegro, this is done more implicitly through recommendations for STEAM subjects.

Method

In Montenegro, workshops were conducted with 10 schools and around 200 teachers new to 3DMP, aged between 24 and 63, and with a wide range of teaching experience. Language teachers were also invited to ensure clear communication between the workshop team and participants. We monitored responses to workshops and developed them further for the next school by taking notes and gathering feedback before and after workshops. The workshop structure was improved by better linking it to Bloom's taxonomy (Krathwohl, 2002), and introducing more personalisation per school by inspiring them with personalised content. We took artwork from each school, turned it into a personalised 3DMP example and gave examples of why 3DMP could be helpful in education, such as how 3DMP works to help teachers understand software and machines. We introduced the 3DMP process and challenged teachers to develop and produce self-created models. To motivate teachers, we asked them to design items they would 'find useful for the classroom' and to send us developed ideas as a competition. After one year, we interviewed teachers still using 3DMP to get opinions (Anđić et al., 2022b). As described in Saunders and Townsend (2018), we used purposive participant selection, based on different ages and teaching experience, to achieve heterogeneity and cover important aspects that may be related to STEAM education by using 3DMP, following suggestions of Åkerlind (2012) and Green (2005).

We then developed a non-compulsory university course in Austria with similar goals and general structure. Over 100 Austrian student teachers, aged 22 to 46, all before or at the beginning of their professional careers, took part in this course. They were studying two subjects: mathematics and another STEAM subject. Due to STEM teacher shortage, some participating teachers already worked in schools part-time during their studies. The course covered a theoretical overview and examples of how 3DMP links to STEAM topics. We decided to change the part on inspiration by asking teachers to explore platforms with 3D models, as personalisation per school was impossible in this setting. We then asked participants to develop, model and 3D print their ideas 'to support their teaching', similar to the workshops, and to document their progress. Austrian participants also received questionnaires before and after the course to improve their learning experience in upcoming courses. Upon receiving questionnaires pre- and post-courses, we realised differences in opinions. We therefore decided also to interview Austrian participants at least six months after the course using the same questions we had asked the Montenegrin teachers. We also opted for as broad a spectrum as possible, and interviewed participants aged between 27 and 37 with between one and four years of teaching experience. Participants were selected from volunteers who had agreed to be interviewed after the course, based on their various ages, subjects and teaching experience.

The semi-structured interviews were conducted online, recorded, and questions were displayed on screen. We took notes during the interviews, which participants could correct spontaneously. We also produced transcripts of the recordings, which we analysed using the same codebook we had used for Montenegrin teachers. To ensure that we noticed linguistic differences, covered all relevant topics correctly and interpreted answers appropriately, we adopted a lexical similarity analysis approach. Furthermore, since using 3DMP might differ due to the different settings, we collected the project documentation of Montenegrin and Austrian teachers to find similarities and differences, looking for STEAM and transdisciplinarity. Project documentation included an overview statement, justification of why 3DMP is a good choice for this project idea and descriptions of the challenges that teachers encountered and the solutions they developed.

Analysis approaches of pedagogical and technological opinions

The collected documentation and interviews of both groups were searched for pedagogical and technological opinions. We developed a coding scheme from Montenegrin interviews in which we grouped coding elements into overarching themes, and we used the same scheme for Austrian teacher interview data. Differences became apparent when we began grouping interview data into an additional dimension: perceived obstacles and opportunities. For example, the overarching theme of technology, which includes complexity or compatibility, among other aspects, was always perceived negatively by Montenegrin teachers, such as mentioning the lack of 'compatibility of older computer devices with printers and modelling software'. In contrast, Austrian teachers had a more mixed perception of technology, stating, in addition to concerns about complexity, that: 'Technology plays an important role in our daily lives, and is therefore important and prepares children in school.' This prompted us to look for links to differences in their school systems by mapping the OECD analysis attributes to our collected overarching themes, and looking for relevant aspects in the interview data and project descriptions. The overarching themes of the coding scheme are shown in Table 1, where we align them with the OECD analysis attributes.

Table 1. Overarching coding themes derived from Montenegrin data aligned to the four aspects of OECD analysis, used also on Austrian data

Analysis attributes by OECD	Overarching coding themes
Policy choices/needs	Financial, Curricular
Knowledge choices/needs	Educational Knowledge, Learning/Education for Teachers
Pedagogical choices/needs	Learning/Teaching Quality, Representation and Visualisation
Technological choices/needs	Technical, Time, Teaching Modernisation

We chose the following analysis approach for qualitative data in cross-cultural projects based on 'Data reduction', 'Data display' and 'Conclusion drawing and verification' by Troman and Jeffrey (2007).

- Data reduction by developing and applying an overarching topic scheme to categorise topics, coding interviews, and finding topics necessary for teachers.
- Data visualisation of interviews by lexical similarity analysis comparing topic clusters to topics that we believed to be essential for teachers.
- Comparing results and drawing conclusions related to aspects of policies, knowledge, pedagogy and technology, verifying with interview data and project documentation.

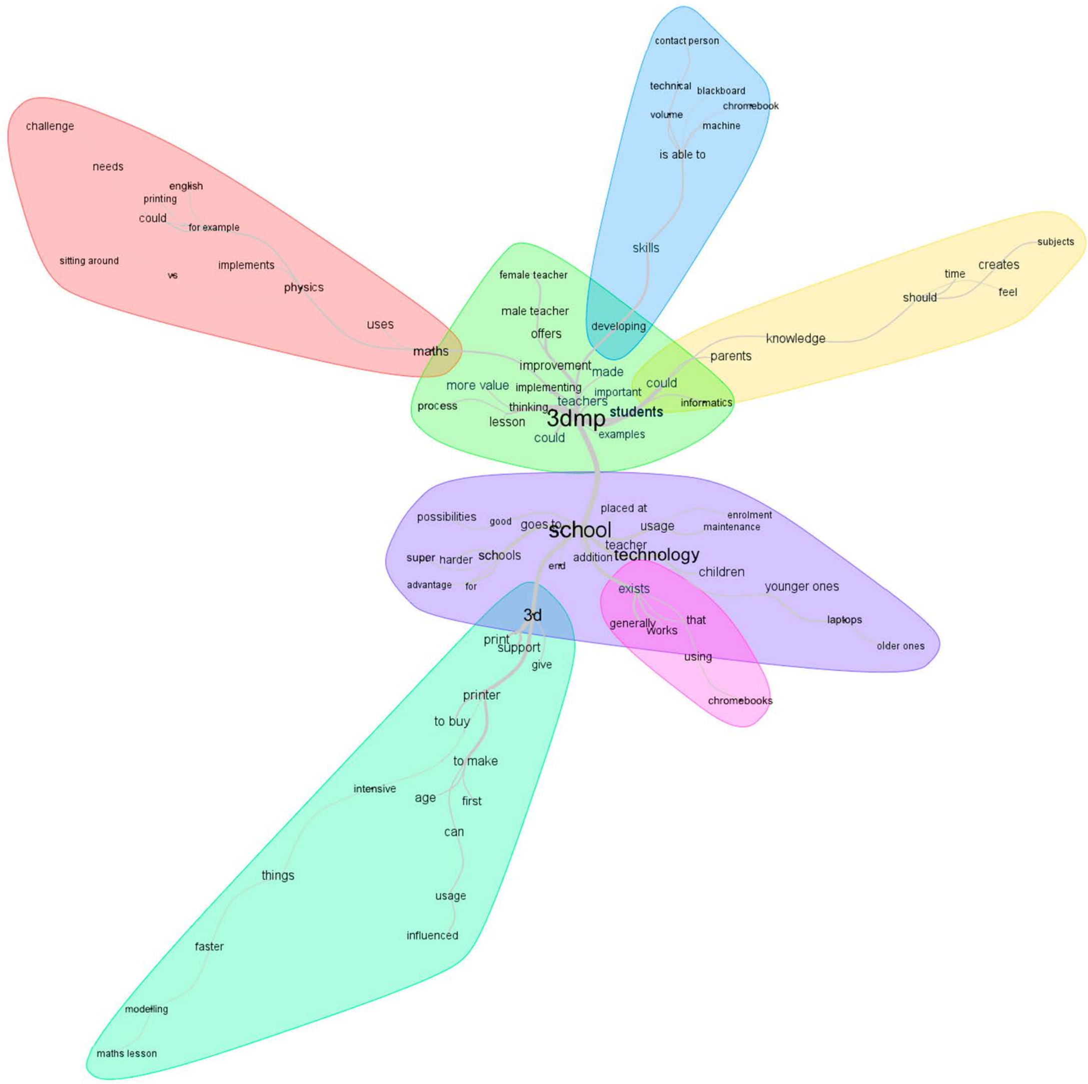
We scaled down data by selecting data parts from found overarching topics that we could connect to the aspects of OECD and sorted interview data into opportunities and obstacles. Then, to ensure that we noticed topic aspects important to teachers, we created visualisations using lexical similarity trees of concepts found in interviews. We applied a lexical similarity analysis using IRaMuTeQ – textual analysis software within the statistical program R that analyses texts and tables – to condense data from interviews to topics by generating topic clusters and connecting words often used in their context to other words (https://www.iramuteq.org/).

Results of these analyses visualise the positions and structure of words in texts, which helps find indicators, intuitively visualising the text context. Here, the lexical similarity analysis helped to verify and visualise existing links between the textual corpus through similarity trees. For example, 'School' and 'technology' are two significant concepts within a topic group (purple in the centre of Figure 1). Related words build a tree, as seen in Figure 1, showing seven significant topics in Austrian teachers' data, and the positive and negative concepts we thought we had found.

This helped ensure that we did not overlook potentially important content in our overarching concepts and coding aspects, such as teachers' different views on technology according to age and teaching experience with previously introduced technologies: 'For example, a female teacher does not want to use Chromebooks, students use them perhaps for other things. The younger ones, others, use technologies – the younger, the more technology is used.' In connection with the lexical similarity tree, we could relate this sentence to the purple area in the centre. As this area revolves around technology, we were able to match both the codebook topics and the correlating sentences to the correlating OECD analysis topic.

We created a second set of classifications for the competition submissions and projects from more than 100 teachers to identify topics and their attributes. We created codes for subjects and for transdisciplinarity, leaning on ideas of Liao (2016), with at least two STEM subjects and transdisciplinarity in STEAM being, at minimum, a STEM subject connected to arts by at least design choices and creative problem solving. Creative problem solving was created to discern between mathematical problem solving and problem solving, including creative aspects beyond mathematical problem solving, as used by Madden et al. (2013).

Figure 1. Lexical similarity trees by community distributions of concepts from Austrian teachers' data, visualisation translated by the authors



Collected teachers' opinions, topics and settings for 3DMP

The reduced interview data sorted into the four aspects of the OECD analysis were collected and showed a variety of concerns and opinions of teachers. To help spot differences, we grouped them by first showing Montenegrin and then Austrian teachers' opinions.

Policy

Montenegrin teachers had many financial insecurities and concerns. They expressed worries about acquiring and maintaining 3D printers, and the costs for materials and teacher training. For example, during training, teachers often asked: 'How much does a 3D printer cost?'; 'How much does printing material cost?'; and 'Do you know any organisation that would support the application of 3DMP in teaching with donations?' Regarding the curriculum, even though teachers should be free to choose methods of delivering content, they perceived lessons not to be flexible enough for 3DMP. For example, teachers asked the question: 'How to explain the example of 3D printers in the classroom when it is not recommended for use in the curriculum?'

Austrian teachers' perceptions regarding the curriculum and finances were mixed. While they perceived their curriculum to be too overwhelming, and they saw dependencies on a school's general openness to technologies, they saw many connections to curricula of all STEAM subjects: 'I mentioned it in physics too – woah, cool.' For example, mathematical modelling is part of the curriculum that 3DMP could strengthen. Teachers also showed monetary considerations, as they stated worries regarding not knowing the costs of 3DMP, and that software licences and materials might be as costly as other proprietary software and printing ink: 'Costs – printing ink for laser- or ink printers are also pretty expensive.' They also mentioned that schools were pushed by the Ministry of Education to go towards digitisation, and, therefore, other technology-related courses were also available at their schools – 'also because of digitisation in school – the ministry forces us to an extent anyway' – and they emphasised the new subject 'Digital Literacy' being suitable for involving 3DMP.

Knowledge

Montenegrin teachers described knowledge challenges in making sense of 3DMP for teaching, such as the need for more technical skills to use software and hardware in the 3DMP process, and they hoped for more availability of courses in acquiring these skills. They also reported the challenge that much of the content on platforms where they could find instructions, such as YouTube, is in English, and there are no ready-to-use teaching materials in Montenegrin. One of the teachers stated: 'It would be good if we could get the materials in our native language because those available on the internet are in English. Our English is not good.' They saw great potential in 3DMP, which offers opportunities to enhance teachers' language skills and digital literacy, as well as opportunities for continuous learning while working. They reported that challenges led them to communicate more with other teachers to overcome lack of knowledge in certain areas.

Austrian teachers also felt that many teachers might need more technical knowledge. Therefore, at least one teacher, or a dedicated internal or external person, would need to know how to use 3DMP meaningfully: 'To apply it in the school, it would need a person that knows … is responsible. A process to buying, plan for exercises. Both are possible: enthusiastic teacher, if there are financial resources, could also be school training.' They also mentioned the need for immediately applicable exercises and a clear list of benefits, as Lam (2000) discovered, to know which skills could be developed by using a 3DMP activity. They suspected that 3DMP could strengthen relationships between teachers and students, as the process of 3DMP could be a journey they learn together. They stressed the need for teacher training courses to overcome anxieties about technology, that older teachers, in particular, had many reservations about technology, and that using 3DMP would improve teachers' digital literacy: 'These colleagues should overcome fear and make a first step – a usable training offer helps with the first step.' Teachers of STEAM subjects would especially welcome and be curious about 3DMP in their schools, and they could offer in-school courses.

Pedagogy

Montenegrin teachers emphasised positive aspects of both visualisation types, the virtual 3D-model creation and then the physical creation of models. They also pointed out possibilities of individualising lessons, involving students in teaching processes and creating a cross-curricular STEAM lesson, instead of just integrating one subject into another. The quality of teaching would also benefit from students' improved digital literacy. They saw opportunities for a more inclusive teaching style for relating to real problems that students would have to deal with, and for creating concrete objects.

Austrian teachers saw many possibilities to represent properties of objects through 3DMP visualisations and to create physical models relatively quickly. They talked about the haptic qualities of physical representations and the need for models for many STEAM subjects and other subjects, such as geography, political education and social studies. They also saw benefits for the quality of teaching by connecting students' personal lives, and everyday problems, with school, problem-based learning, and applying transdisciplinarity: 'Look around at home what you need, like for the smartphone, English or informatics – practical connections!' They saw great potential for creativity in arts and crafts lessons, and connections to gamification. However, they also had concerns about the quality of teaching, as they saw the introduction of laptops during the pandemic as chaotic, pointing out that machines could also lead to pure trial-and-error situations where students did not reflect on their problems.

Technology

Montenegrin teachers had many opinions about which technology knowledge needed to be learned. They saw challenges in the complexity of modelling software and printing, which could lead to overwhelming situations. They also expressed concerns about model quality and compatibility with existing software and hardware. They were particularly concerned about purchasing and maintaining printers, which is consistent with the observations by Holzmann et al. (2018). Sourcing spare parts can be a significant challenge in Montenegro. They also had concerns about time constraints, as creating models in class can take time. They pointed out that schools would have to be modernised, and that these technologies would also be used in industry, so that students could see future career paths. It would also motivate students to share their interest in the latest technologies.

Austrian teachers recognised the need for technical knowledge, due to the wide variety of software used during 3DMP, and appreciated the possibility of downloading and adapting existing objects. They saw opportunities to combine technologies such as GeoGebra, which students would already be using, with 3DMP: 'GeoGebra offers many opportunities, but you need to know it.' However, they were cautious because other technologies, such as SMART Boards, seemed to be of little value for teaching, and dependent on existing hardware and software such as computers, internet and electricity: 'SMART Boards are a bit less useful, you need more preparation time'; and, 'Power sockets. And you need control about what the students do on computers.' This would not always be available or work reliably in schools. There would also be a divide between older and younger teachers: older teachers had more concerns about using technology, while younger teachers were more open to trying new technological methods: 'The younger ones do it, the older ones do not really like to do it. More open than older ones, the younger ones are less afraid of new technologies.' Due to time constraints, teachers felt that it would be challenging to incorporate the entire 3DMP process into regular classes. However, there were ideas about how technology could be used in project weeks, additional non-mandatory courses, or during non-instructional times. They also mentioned a strong interest in 3DMP among students.

We looked at teachers' project descriptions to see whether and how teachers would use 3DMP to create transdisciplinary STEAM experiences with problem-based approaches. Because many projects relied on mathematics (for example, geometry), we looked at whether they pointed towards transdisciplinarity by complexity or connecting to another STEAM subject, such as slopes from brachistochrone curves for physics or an animal cell for biology. Austrian teachers created transdisciplinary projects such as Spirographs connecting to art, or a model of the 'towers of Hanoi' for algorithmic thinking connecting to informatics. We also found information about settings where they plan to use 3DMP, as shown by the statement examples in Table 2.

Many descriptions by Austrian teachers contained mathematics and at least one other STEAM subject in a transdisciplinary way connecting to problem solving and design considerations. While most topics overlapped with geometry, a wide variety of other mathematical topics were also found. In the 3DMP topic data, Austrian teachers' data showed their enthusiasm for gamification or serious game opportunities by developing many games (see Figure 2), incorporating creativity and art into STEM subjects, and creating a STEAM learning experience, as well as seeing the potential for problem-based learning, as evident in Table 2. Examples of visual proofs, such as Pythagoras keychains, included labyrinths, dancing figurines resembling certain functions, tools created by geometric forms and puzzles.

While Austrian teachers created smaller objects, Montenegrin teachers submitted large objects that they had made with their students. Some Montenegrin teachers also chose a mathematical and manipulative background with geometric shapes. However, their focus also showed problem-based learning approaches, including more complex ideas, sometimes involving inclusion, such as writing aids for disabled children. They created tangible models that they could use for science lessons, such as biology. Another example was combining geography and mathematics by creating a polygon model that students could use to learn about provinces (see Figure 3). Therefore, we classified most of the Montenegrin examples as cross-curricular.

Table 2. Examples of explanations within project documentation of how Austrian teachers reasoned and planned to use 3DMP

Comments by Austrian teacher	Translation by authors
Mit meinem 3D-Projekt möchte ich ein Spiel schaffen, das sowohl für den Unterricht zwischendurch als auch für bestimmte Übungsphasen im Mathematikunterricht der Sekundarstufe 1 eingesetzt werden kann. Es soll das geometrische Vorstellungsvermögen schulen und den Schülern die Möglichkeit geben, selbst etwas anzufassen und zu fühlen.	With my 3D project, I want to create a game that can be used both for in-between lessons and certain practice phases in secondary school mathematics lessons. It is intended to train geometric imagination and allow students to touch and feel something themselves.
Für einige von uns ist es leicht, Mathematik in künstlerischen Aktivitäten oder Kunstobjekten zu erkennen. Bei 'Nicht-Mathematikern' ist dies jedoch oft nicht der Fall. Die Fragen 'Wozu brauchst du das?', 'Wozu ist das gut?' werden sowohl der Kunst als auch der Mathematik nur allzu oft gestellt. Die Herstellung eines Schmuckstücks verbindet Geometrie und Ästhetik.	For some of us, it is easy to recognise mathematics in artistic activities or art objects. For 'non-mathematicians', however, this is often not the case. The questions 'What do you need that for?', 'What is it good for?' are asked all too often of both art and mathematics. Making a piece of jewellery combines geometry and aesthetics.

Figure 2. Various Austrian 3D-printed projects, from 'dancing' functions over visual proofs to a labyrinth, Spirographs, games and unfair dice

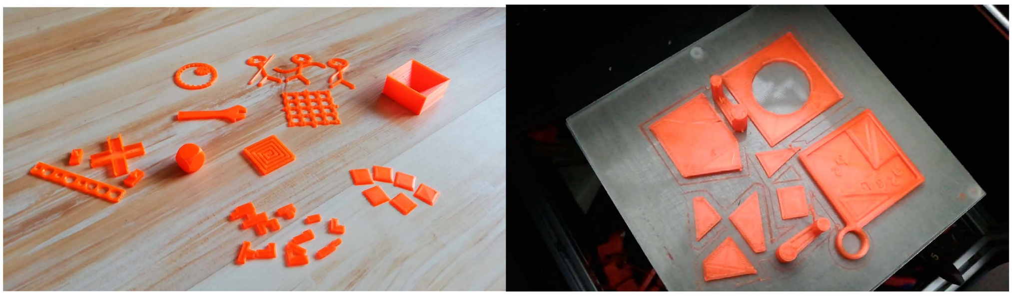


Figure 3. 3D-printed projects from Montenegrin teachers: a dodecahedron, a nerve cell, a model of the country and a writing aid

Reflections and conclusions

Experiences and topics chosen by teachers, and the information we received from their feedback in questionnaires, indicate that both groups have various ideas for using 3DMP. Many have characteristics that could connect cross-curricular teaching in the sense of Meletiou-Mavrotheris et al. (2022). Austrian teachers seem more mathematics-oriented due to the nature of the course, and Montenegrin teachers seem more science-oriented due to their education system. Among the Montenegrins, we found more examples of inclusivity, such as writing aids or tangible models, or writing aids for blind students, where design considerations were more implicit, as seen in Figure 3. Austrian teachers seemed to focus more on real-world problems (for example, avocado-growing aids, spacers for computers by combining geometric shapes in Figure 2), games and motivating objects (for example, dancing functions, puzzles), and projects that explicitly aimed at connecting to art or design ideas (for example, jewellery, a Spirograph). In project descriptions, Austrians expressed interest in connecting art and culture by incorporating design ideas, such as 'showing the beauty of maths', as one teacher said, reflecting ideas by Liao (2016). In line with Song's (2018) ideas, Montenegrin teachers saw 3DMP as a way to network with other teachers. This could be explained by effects described by Knochel (2018), where collaboration between teachers of subjects results from hands-on experiences. Austrian teachers described collaboration and communication with teachers of other subjects, or discovering 3DMP together with students, which could also be related to the kinship mentioned by Knochel (2018) coming from hands-on experiences, a feature that the 3D-printing part of 3DMP can provide.

We therefore conclude that 3DMP is helpful for teachers from countries without STEAM curricula to create STEAM exercises for and with their students, even if they have not been trained in STEAM or transdisciplinarity. Examples show a variety of approaches that support developing critical competencies for lifelong learning. As mentioned by Leavy et al. (2023), 3DMP aiming at developing twenty-first-century skills and knowledge to use this technology helped teachers to develop complex STEAM exercises, even if they did not have STEAM experience. They implicitly developed problem-based learning exercises, and we found that many projects have an interesting transdisciplinary STEAM character in project documentations. 3DMP has stimulated creativity and critical thinking due to problem-based opportunities, connecting to what Birt and Cowling (2017) describe for mixed-reality environments. Many subjects, from science to engineering to mathematics, were covered, in conjunction with design considerations. There was also innovation from teachers developing new ways to visualise concepts with tangible objects supporting students with disabilities.

3DMP offers exciting opportunities in terms of the four Cs of the twenty-first century, in particular, collaboration and communication, in the sense that teachers cooperate to use 3DMP. Interview data suggest that they ask each other for help and that one experienced teacher per school could train other teachers (peer teaching). Cooperation between teachers and students could also be strengthened if they learn about the various technologies together. In addition, communication with software and hardware described by Bonarini (2020) could play a role, as 3D printing is a special case of robotics, and machines must communicate via software and 3D models.

The data led us to develop the following ideas regarding the aspects of the OECD analysis.

Policy

Not all students in Montenegro attend secondary school after upper elementary school (just over 50 per cent). In comparison, many Austrian students attend upper secondary school (over 80 per cent) (Federal Ministry of Education, Science and Research of Austria, 2019; Statistical Office of Montenegro, 2012). To ensure access for all students in Montenegro, it is necessary to use 3DMP from an early age, for example, in the subject Information and Communication Technologies, while in Austria, this could be part of the later subject Digital Literacy.

Policies targeting schools should consider training and professional development opportunities with easy access to technology for Montenegrin primary and upper secondary education, and for Austrian lower and upper secondary education. Pre-teaching training could be necessary as, according to interview data, younger teacher colleagues are less afraid of working with new technologies. As Austrian teachers suggested, in-school peer training could help teachers use 3DMP. However, pre-service teacher training is even more critical, especially in Montenegro, as in-service training is not compulsory.

Knowledge

Situations where only one enthusiastic teacher uses 3DMP should be avoided by providing information to all STEAM teachers in a school, as this could decrease the so-called 'truck factor' (Ferreira et al., 2019). Courses should be offered in which teachers and students learn about these technologies together, allowing them to foster relationships. Explanatory videos and interactive websites should be available to help with simple to more complex software- and hardware-related issues, where teachers could find help to avoid knowledge loss if an enthusiastic teacher leaves. One option would be to use a platform such as GeoGebra, which participants mentioned, which has many users in certain STEAM areas, and which provides shareable interactive applets.

Teachers should have basic training in using computers and maintaining login options for students to use 3D software. Therefore, an assessment of the benefits and challenges of the most commonly used software should be carried out, and results should lead to a list of software with descriptions and exercises for students.

Pedagogy

According to participants' examples, 3DMP suits transdisciplinary settings and problem-oriented teaching. This offers opportunities for new learning scenarios due to the possibilities of linking to students' everyday lives by working on real challenges. To this end, teaching materials and exercises that link to defined topics in curricula of all STEAM subjects should be created and made available as inspiration, similar to what Bull et al. (2015) have begun to do. Teaching materials should be available in students' native languages, and not only in English. Due to its cross-curricular nature, 3DMP could be used in many subjects, such as those connected to digital literacy or extracurricular courses.

A significant influence on where and how 3DMP is used is the time needed for creating a 3D model and for printing in 3D. Therefore, teaching conditions when using 3DMP should be carefully chosen, for example, in project weeks, when many students can work together to shorten the time for 3D modelling. 3DMP can be taught in separate modelling and printing steps.

Technology

Participants requested well-defined processes for purchasing and maintaining the machinery and technology required for 3DMP. Such processes could be copied from existing processes for buying other machines, or they could be an extension of equipment acquisition from existing computer labs. Maintenance should be carried out by an external person looking after other machines.

Another option could be a mobile 3DMP lab providing ready-to-use equipment and support for teachers by a local organisation, which schools can request when needed. This could be helpful in Austria to kick-start using 3DMP, and it could be easy to implement, as other technologies, such as robots, can already be requested by schools, and this concept could be adapted. This could have an even more significant impact in Montenegro, as the number of schools is low, and a small number of mobile labs could be enough to give many schools access to this technology.

The analysis of pedagogical and technological teacher opinions from Montenegro and Austria about 3DMP revealed important differences in perceptions and challenges. The study provided insights into STEM teachers' conceptions regarding using 3DMP in teaching, highlighting varying opinions and sophistication levels among teachers in different subject areas. This aligns with the findings during the analysis, which indicated differences in perceptions based on the educational context and subject area. Furthermore, the theoretical framework presented by Knochel (2018) on object-oriented curriculum theory for STEAM education was relevant for understanding the pedagogical and technological aspects of 3DMP in the context of different educational systems. The framework emphasised the materiality and boundary shifts in STEAM education, which resonates with challenges and opportunities identified in teachers' perceptions from Montenegro and Austria. Additionally, the sociological analysis of Montenegrin teachers' digital capital by Cortoni and Perovic (2020) provided valuable insights into technological perceptions and challenges that teachers face in Montenegro. This reference sheds light on the digital capital of teachers, which is crucial for understanding obstacles and opportunities related to technology integration in the educational context of Montenegro.

Summary and future work

Teachers from two countries were introduced to 3DMP through workshops or a course. The educational systems of these countries were compared, and interviews collected teachers' feedback and opinions about 3DMP to look for differences and similarities. We also took examples of 3DMP projects that these teachers had developed and looked for attributes pointing towards transdisciplinarity to learn how these teachers used 3DMP. We studied these data from the perspectives of policy, knowledge, education and technology, and looked for signs of transdisciplinarity.

Considering their particular situation, we reflected on these data and developed ideas and proposals based on teachers' needs and wishes. Reflections on policy led to considerations about the importance of teacher training to get in touch with 3D printing. From the knowledge point of view, ready-to-use online teaching materials for teacher training and teaching should be made available on large platforms to help teachers acquire, create, share and use ideas connected to concepts of curricula. On an educational level, 3DMP could be divided into the 3D-modelling and the 3D-printing parts, and it might be best used in projects due to the process length from an idea to a 3D object. As for the availability of technology, we developed ideas about mobile labs with ready-to-use machines that can be requested when needed. This could also be a cost-effective way for teachers in these countries to have well-maintained machines for projects.

Our next steps, therefore, will be to look into collected data from more perspectives to find ideas about how to create meaningful teaching materials, connect 3DMP to specific parts of curricula to show benefits, and start working on the mobile laboratory idea.

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Declarations and conflicts of interest

Research ethics statement

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Consent for publication statement

The authors declare that research participants' informed consent to publication of findings – including photos, videos and any personal or identifiable information – was secured prior to publication.

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