JPPIPA 10(8) (2024)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Advantages and Disadvantages of Using 3D Printing by Science Teachers

Syinta Khefrianti[1*], Asep Kadarohman[1], Wiji[2] ,Wandy Praginda[3]

[1] Science Education Program, Universitas Pendidikan Indonesia, Bandung, Indonesia.
[2] Chemistry Education Program, Universitas Pendidikan Indonesia, Bandung, Indonesia.
[3] Balai Besar Guru Penggerak Jawa Barat, Bandung, Indonesia.

Received: December 11, 2023
Revised: April 13, 2024
Accepted: August 25, 2024
Published: August 31, 2024

Corresponding Author:
Syinta Khefrianti
syintakhefrianti@upi.edu

DOI: 10.29303/jppipa.v10i8.6518

Abstract: 3D printing transforms abstract contexts into more concrete ones and effectively enhances creativity. The purpose of this study is to explore the benefits and challenges teachers face in using 3D printing. The research method used in this study involved a narrative review of various literatures related to the use of 3D printing by science teachers. The results of this study show that there are benefits in using 3D printing as well as barriers experienced by science teachers. The benefits obtained by teachers are not only limited to themselves but also colleagues due to collaboration and of course for students. Teachers' pedagogical skills in designing lessons and using technology also experienced positive changes. Meanwhile, the obstacles in using 3D printing are also felt by teachers such as limited teacher skills, availability of tools and the use of tools that are relatively time-consuming.

Keywords: Fabrication laboratory; Learning teacher; 3D printer; 3D printing

Introduction

Technology laboratories have employed digital fabrication in recent years to emphasize hands-on learning processes in technology and engineering education (Lin et al., 2023). Fabrication laboratory is a design process that involves the use of computers and all digital machines connected to computers as a whole, from the data management stage to the production stage (Indrawan & Purwanto, 2021). One of the increasingly affordable and popular digital fabrication technologies today is 3D printing, where digital technology transitions from a fully online environment to the 'physical' world. Maker spaces in digital fabrication allow people to share access to technology, learn to use it, and build social capital (Rayna & Striukova, 2021; Kit Ng et al., 2022). 3D printing is a rapid prototyping technology based on digital models. It utilizes adhesive materials such as metal powder or plastic and creates objects through layer-by-layer printing, which is a form of additive manufacturing (Chen & Cheng, 2021).

3D printing technology has gained significant attention in education as part of the maker movement and is gradually being widely adopted in education; (Chen et al., 2023; Novak, 2022). 3D modeling is a core technique fundamental to 3D printing that became popular in the 2010 (Huang et al., 2019). Various areas in the field of education utilize 3D printing, including pharmacy, mathematics, biology, chemistry, sports, fashion, engineering, and even early childhood and special education (Ucgul & Altıok, 2023). One 3D printing tool, the 3D printer, is advantageous as it is affordable, compact, and easy to deploy, making it increasingly popular in educational environments.

3D printing technology has played an important role in the development of maker spaces, which also has the potential to enable the integration of art (A) with science, technology, engineering and math (STEM) fields. This opens up new opportunities for implementing STEAM (Buruiana et al., 2019). There are many examples of 3D printed replicas used by scientists to visualize their research. 3D printed organisms, organs

How to Cite:
Khefrianti, S., Kadarohman, A., Wiji, & Praginda, W. (2024). Advantages and Disadvantages of Using 3D Printing by Science Teachers. *Jurnal Penelitian Pendidikan IPA*, *10*(8), 559–565. https://doi.org/10.29303/jppipa.v10i8.6518

and chemical structures (both large and small) can be used to educate and engage non-specialists and facilitate deeper understanding and insight from the scientists studying them (Hartings & Ahmed, 2019).

When it comes to the use of 3D printing in education, it is not only the tools that must be prepared but also the teacher as the learning designer. Unfortunately, digital technologies that are very close to the learning activities carried out by teachers related to 3D printing are less used than digital presentations (Thyssen et al., 2023). Yet, in recent years, digital fabrication, and especially design and 3D printing related activities, have taken root in school education as curriculum-based and maker-oriented learning activities (Leinonen & Virnes, 2020). This article aims to explore the benefits and challenges teachers face in using 3D printing in learning.

Method

In this narrative review, more fit-for-purpose criteria were developed to track the benefits and challenges of teachers' use of 3D printing. To conduct this narrative review, a literature search was conducted using DOAJ, ERIC, Google Scholar, Science Direct and Scopus databases. The search used the terms fablab, 3D printing, 3D printer and science teacher with publication years ranging from 2019-2023. The list of retrieved titles was further screened for the following criteria: article type (research only), subject (teachers only as participants in the research), and discipline (education only). After searching and exploring, 45 articles were reviewed that met the objectives of this study for review. The authors read abstracts and full papers and recommended criteria to develop a narrative review. The main category discussed was 3D printing and its use in education, especially by teachers. With this category, a narrative review was then conducted by establishing the scope of the topic through definitions and theories used in relation to 3D printing. Next, it presents literature on 3D printing and its use by science teachers. This article ends with a training model for science teachers in using 3D printing for learning activities.

Result and Discussion

Human needs also change as the world changes. Therefore, creating new designs in products has become mandatory to meet the ever-changing human needs. Visuality, functionality, and practicality of products have become prominent in choosing products. From this perspective, the design of existing products is becoming increasingly important. To add new functional features in the product, it aims to visualize and transfer the product into images and turn these images into a real and reasonable product (Akyol et al., 2022). Nowadays, this is very easy and at a low cost, namely with the existence of 3D printing. In recent years, education has experienced a major step forward when technologies such as 3D printing are incorporated into the classroom and into every learning process (Cruz-campos et al., 2022). 3D printing technology refers to the process of creating three-dimensional physical models that are used as learning aids to support educational content in science, technology, engineering and math (STEM) (Smith et al., 2020). The use of 3D printed models also supports visual learning and visual literacy (Howell et al., 2020).

Digital fabrication or fabrication laboratory has become more popular, especially for educational purposes, indicating the emergence of a new type of "learning by doing" (Tore et al., 2021). Studies show that professional development programs in digital fabrication assist educators in working in small groups and learning collaboratively (Voldborg & Pitkanen, 2019). One technological tool in digital fabrication is 3D printing (Mahendarto, 2020). A new educational tool called 3D printing is supposed to get students ready for a world that is increasingly technologically advanced (Pearson & Dubé, 2021). There are professional development opportunities that enable teachers to integrate "making" using 3D printing into their classrooms (Heredia et al., 2021). Applying 3D printing technology in practical curriculum offers many benefits, such as smoother and more accessible progress, as well as a shortened product development cycle and reduced development costs (Hsiao et al., 2018; Levin & Verner, 2021).

There are at least three main reasons to use 3D printing technology in learning. First, teachers should teach students to do things, not to learn. Second, learning means learning by doing, and third, learning is a process of creating and constructing knowledge, not just receiving information. Third, constructivism, active learning and environments designed to encourage students to design, create and experiment (Wibawa et al., 2021). Combination of teaching strategies and designs to help learners understand 3D-printing technologies when integrating them into curricula must be explored in practical studies (Huang & Chun, 2022).

Resources used in 3D printing can be integrated across different fields of science as part of a teaching approach based on interdisciplinarity and the application of scientific and mathematical knowledge (Cruz-campos et al., 2022). The implementation of digital tools in education is a primary demand from various stakeholders, such as teachers, schools, and education ministries (Bonorden & Papenbrock, 2022). Providing training to both teachers and school principals

significantly impacts their teaching practices, leading many teachers to plan the integration of digital fabrication into their classrooms (Sanchez et al., 2020). Teachers serve not only as facilitators but also as active practitioners, designing learning activities involving 3D printing technology (Leinonen & Virnes, 2020). Therefore, empowering educators to implement digital fabrication (DF) activities and design thinking (DT) in the curriculum and schools is crucial to enhancing student participation in learning through 3D printing (Song, 2018; Voldborg & Pitkanen, 2019).

Design-Based Learning allows teachers to design, test, and improve innovative, structured, and engaging educational methods, such as the use of software and 3D printing in STEAM education (Hsu & Ou, 2022; Lavicza et al., 2022). With the adoption of design-based pedagogy, teachers have the opportunity to visualize relevant instructional processes, such as creating integrated STEM design projects and developing methods for implementing design projects, prototypes, and testing with 3D printing (Cheng et al., 2021; Zhou et al., 2020). Teachers can also apply the 5E model of learning to engage students in the process of discovering conceptual material through 3D printing, supporting their understanding (Pizzolato et al., 2018). The advantages of 3D printing technology in the practice of design teaching make models more tangible (Wang, 2022). Differentiated metacognitive behaviors result from using various educational strategies and resources. Furthermore, employing 3D tangible objects in cognitive-apprenticeship education promotes more meta-cognition activities than standard instruction strategies do, which further contributes to successful problem-solving (Huang et al., 2019).

Teachers with expertise in 3D printing tend to have different perceptions of the methodological and didactic potential of this technology compared to those with less experience. Teachers consider 3D printing beneficial in developing students' technical skills and competencies, especially in creativity, modeling, and technology (Thyssen et al., 2023). The need for cross-disciplinary integration of technology in teaching and learning, as well as instructional design by teachers in using 3D printing (Forbes et al., 2020; Khurma et al., 2023). Additionally, teachers show a high interest in learning about technologies like modeling and 3D printing, even though they generally may not be very familiar with or have a limited understanding of working with such technology (Trust & Woodruff, 2021).

Teachers participating in professional development programs demonstrate changes in their teaching practices. They tend to adopt more flexible, inquiry-oriented, and student-centered pedagogies, empowering learners, which are crucial characteristics of learning using a 3D approach (Stevenson et al., 2019; Chytas et al., 2019). Supporting factors for the use of 3D printing include pedagogical approaches, task design, student knowledge and activities, technology, and the school environment (Bower et al., 2020). Teachers report that 3D printing can enrich the learning experience by providing a more concrete context for abstract concepts (Andic et al., 2023). Technology has become more prevalent in developing physical versions of these computer representations through the art of 3D printing in plastic (Dickenson et al., 2020).

From teacher development activities, it is evident that they adopt various methods to incorporate 3D models or modeling into classroom teaching (Y. Chen et al., 2023). Furthermore, teachers' perceptions of the usefulness and importance of integrating 3D printing affect students' motivation in science, technology, engineering, and mathematics. Teachers who view 3D printing technology as an effective learning tool to enhance teaching efficacy in science, spark interest in science, boost creativity, and increase STEM motivation for students (Arslan & Erdogan, 2021; Cheng et al., 2020; Han et al., 2021; Novak & Wisdom, 2018). Compared to engineering teachers, science teachers' confidence increases more after professional development and the implementation of lessons using 3D printing (Kelley et al., 2020). Experiments conducted with 3D printing have shown improvements in various aspects: mechanical, spatial, and associative skills, creativity, self-directed learning, imagination, and understanding abstract concepts (Cruz-campos et al., 2022).

The results of using 3D printing in the classroom by teachers reflect that students' experiences of failure have a positive impact on their learning processes. This indicates that facing poorly structured problems, as often occurs in 3D printing, can contribute to students' growth as learners (Dickson et al., 2020). Teachers acknowledge that maker spaces utilizing 3D printing provide a rich environment for literacy development, especially in terms of collaboration, knowledge exchange, giving and receiving feedback, explaining results against criteria, as well as peer and self-assessment (Falloon, 2020). Teachers' modeling knowledge significantly improves after undergoing training related to the use of 3D printings (Asempapa & Love, 2021). Teachers have a positive opinion about the use of 3D printers for educational purposes as it provides tangible materials, enhances students' desire to learn, and proves highly helpful in creating teaching materials (Ucgul & Altıok, 2023). The results of the implementation of learning by science teachers related to 3D design technology, which plays a crucial role in the development of students' knowledge and skills. Students extensively use this technology when creating projects or designing products from their projects, and

this situation motivates them in the project production process (Akyol et al., 2022).

Factors inhibiting the use of 3D printing include limitations in technological resources, teachers' abilities and confidence, and spatial constraints (Bower et al., 2020). The unavailability and difficulty of accessing digital infrastructure and virtual laboratories in many teacher education institutions also result in teachers lacking skills in using 3D printing (Alda et al., 2020). Another inhibiting factor is performance expectations, facilitating conditions, anxiety, technology literacy levels, the lack of training for teachers, and attitudes toward the use of technology, all of which significantly influence the adoption of new technology (Choi & Kim, 2018; Ford & Minshall, 2018; Holzmann et al., 2020). Limitations in teachers' and students' skills in operating relatively new digital devices must be promptly addressed by finding new methods for teacher professional development and suitable learning approaches to integrate 3D printing technology into education (Wibawa et al., 2021). Teachers involved in research on the use of 3D printing stated through responses to open-ended questions that 3D printing applications in the classroom require a substantial amount of time and can disrupt curriculum activities that need to be completed (Branko et al., 2023).

Drawbacks of 3D printing systems include the need to operate complex computer programs, limited databases that focus on STEM fields, the significant time investment required for teachers to understand how to use these resources, and a greater emphasis on details rather than fundamental principles (Cruz-campos et al., 2022). Schools also need to be equipped with appropriate 3D printing technology (Budinski et al., 2022).

Conclusion

Teachers' use of 3D printing had a positive impact in terms of pedagogy, confidence in teaching, developing technical skills as well as having a positive impact on students. Teachers experience changes in teaching practices that are more innovative and creative for students. The use of 3D printing also increases collaboration between teachers to share in understanding and practice. Meanwhile, the barriers experienced were related to the availability of equipment, limited teacher skills and time in teaching. Schools that have adequate 3D printing equipment also cannot implement learning optimally if teachers do not understand the use and design of learning using 3D printing.

Author Contributions
This article was prepared by four people, namely S.K, A.K, W and W.P. All research members carried out each stage cooperatively until this article was completed.

Funding
This research was independently funded by researchers.

Conflicts of Interest
The authors declare no conflict of interest.

References

Akyol, C., Uygur, M., & Yanpar Yelken, T. (2022). 3D printers as an educational tool in gifted education: effective use, problems and suggestions. *Journal for the Education of Gifted Young Scientists*, *10*(2), 173–205. https://doi.org/10.17478/jegys.1105484

Alda, R., Boholano, H., & Dayagbil, F. (2020). Teacher Education Institutions in the Philippines towards Education 4.0. *International Journal of Learning, Teaching and Educational Research*, *19*(8), 137–154. https://doi.org/10.26803/ijlter.19.8.8

Andic, B., Ulbrich, E., Noah, T., Picard, D., Cvjetićanin, S., Petrović, F., & Lavicza, Z. (2023). A Phenomenography Study of STEM Teachers ' Conceptions of Using Three - Dimensional Modeling and Printing (3DMP) in Teaching. *Journal of Science Education and Technology*, *32*, 45–60. https://doi.org/10.1007/s10956-022-10005-0

Arslan, A., & Erdogan, I. (2021). Use of 3D Printers for Teacher Training and Sample Activities. *International Journal of Progressive Education*, *17*(3), 343–360. https://doi.org/10.29329/ijpe.2021.346.22

Asempapa, R. S., & Love, T. S. (2021). Teaching math modeling through 3D-printing : Examining the influence of an integrative professional development. *Reasearch Paper-Integrated STEM Education*, *121*, 85–95. https://doi.org/10.1111/ssm.12448

Bonorden, M., & Papenbrock, J. (2022). Evidence-Based Optimization of Classroom Teaching Units Using 3D Printers for Designing Models—From the 2D Picture to the 3D Flower Model. *Education Sciences*, *12*(11), 1–19. https://doi.org/10.3390/educsci12110831

Bower, M., Stevenson, M., Forbes, A., Falloon, G., & Forbes, A. (2020). Makerspaces pedagogy – supports and constraints during 3D design and 3D printing activities in primary schools. *Educational Media International*, *57*(1), 1–28. https://doi.org/10.1080/09523987.2020.1744845

Branko, A., Sorgo, A., Helm, C., Weinhandl, R., & Lang, V. (2023). Exploring Factors Affecting Elementary School Teachers' Adoption of 3D Printers In

Teaching. *TechTrends*, *67*(6), 990–1006. https://doi.org/10.1007/s11528-023-00909-y

Budinski, N., Lavicza, Z., & Houghton, T. (2022). Opportunities for 3D printing in Hybrid Education. *Open Education Studies*, *4*(1), 339–344. https://doi.org/10.1515/edu-2022-0175

Buruiana, A., Repanovici, A., Cotoros, D., Suciu, A., Buruiană, A., Repanovici, A., & Cotoros, D. (2019). Methods for for Teaching Teaching the the Use Use of of Prototyping Prototyping by for capacity optimization between used capacity and operational efficiency. *Procedia Manufacturing*, *32*, 356–359. https://doi.org/10.1016/j.promfg.2019.02.225

Chen, J., & Cheng, L. (2021). The influence of 3D printing on the education of primary and secondary school students The influence of 3D printing on the education of primary and secondary school students. *Journal of Physics: Conference Series*, 1–6. https://doi.org/10.1088/1742-6596/1976/1/012072

Chen, Y., Cao, L., & Zhang, Y. (2023). Teachers as makers: How K-12 teachers design 3D making lessons for classroom teaching. *Education and Information Technologies*, *28*, 6947–6975. https://doi.org/10.1007/s10639-022-11475-w

Cheng, L., Antonenko, P. D., Ritzhaupt, A. D., Dawson, K., Miller, D., Macfadden, B. J., Grant, C., Sheppard, T. D., & Ziegler, M. (2020). Computers & Education Exploring the influence of teachers ' beliefs and 3D printing integrated STEM instruction on students' STEM motivation. *Computers & Education*, *158*, 1–18. https://doi.org/10.1016/j.compedu.2020.103983

Cheng, L., Pasha, P., & Albert, A. (2021). Exploring the role of 3D printing and STEM integration levels in students ' STEM career interest. *British Journal of Education Technology*, *52*(3), 1–17. https://doi.org/10.1111/bjet.13077

Choi, H., & Kim, J. M. (2018). Implications for activating 3D printer use for education in elementary and secondary schools. *International Journal on Advanced Science, Engineering and Information Technology*, *8*(4–2), 1546–1551. https://doi.org/10.18517/ijaseit.8.4-2.5722

Chytas, C., Tsilingiris, A., & Diethelm, I. (2019). Exploring Computational Thinking Skills in 3D Printing : A Data Analysis of an Online Makerspace. *IEEE Global Engineering Education Conference (EDUCON)*, 1173–1179. https://doi.org/10.1109/EDUCON.2019.8725202

Cruz-campos, J. C. De, Rodríguez-jiménez, C., & Navas-parejo, M. R. (2022). 3D Printing in Education, Theoretical Perspective and Classroom Experiences Impresión 3D en educación, Perspectiva teórica. *CENTRA Journal of Social Sciences*, *1*(1), 67–80. https://doi.org/10.54790/rccs.16

Dickenson, C. E., Blackburn, R. A. R., & Britton, R. G. (2020). 3D Printing Workshop Activity That Aids Representation of Molecules and Student Comprehension of Shape and Chirality. *Journal of Chemical Education*, *97*(10), 3714–3719. https://doi.org/10.1021/acs.jchemed.0c00457

Dickson, B., Weber, J., Kotsopoulos, D., Boyd, T., Jiwani, S., & Roach, B. (2020). The role of productive failure in 3D printing in a middle school setting. *International Journal of Technology and Design Education*, *31*, 489–502. https://doi.org/10.1007/s10798-020-09568-z

Falloon, G. (2020). From digital literacy to digital competence: the teacher digital competency (TDC) framework. *Education Tech Research Dev*, *68*, 2449–2472. https://doi.org/10.1007/s11423-020-09767-4

Forbes, A., Falloon, G., Stevenson, M., & Hatzigianni, M. (2020). An Analysis of the Nature of Young Students' STEM Learning in 3D Technology-Enhanced Makerspaces An Analysis of the Nature of Young Students ' STEM Learning in 3D. *Early Education and Development*, *32*(1), 1–16. https://doi.org/10.1080/10409289.2020.1781325

Ford, S., & Minshall, T. (2018). Invited Review Article: Where and how 3D printing is used in teaching and education. *Additive Manufacturing*, *25*, 131–150. https://doi.org/10.1016/j.addma.2018.10.028

Han, J., Kelley, T., & Knowles, J. G. (2021). Factors Influencing Student STEM Learning : Self-Efficacy and Outcome Expectancy , 21 st Century Skills , and Career Awareness. *Journal for STEM Education Research*, *4*, 117–137. https://doi.org/10.1007/s41979-021-00053-3

Hartings, M. R., & Ahmed, Z. (2019). Chemistry from 3D printed objects. *Nature Reviews Chemistry*, *3*(5), 305–314. https://doi.org/10.1038/s41570-019-0097-z

Heredia, S. C., Tan, E., Heredia, S. C., & Tan, E. (2021). Teaching & learning in makerspaces : equipping teachers to become justice-oriented maker-educators. *The Journal of Educational Research*, *114*(2), 171–182. https://doi.org/10.1080/00220671.2020.1860871

Holzmann, P., Schwarz, E. J., & Audretsch, D. B. (2020). Understanding the determinants of novel technology adoption among teachers : the case of 3D printing. *The Journal of Technology Transfer*, *45*(1), 259–275. https://doi.org/10.1007/s10961-018-9693-1

Howell, M. E., Booth, C. S., Sikich, S. M., Helikar, T., van Dijk, K., Roston, R. L., & Couch, B. A. (2020). Interactive learning modules with 3D printed models improve student understanding of protein

structure–function relationships. *Biochemistry and Molecular Biology Education*, *48*(4), 356–368. https://doi.org/10.1002/bmb.21362

Hsiao, H. S., Lin, K. Y., Chen, J. C., & Lin, C. Y. (2018). Using 3D printing technology with experiential learning strategies to improve preengineering students ' comprehension of abstract scientific concepts and hands - on ability. *Journal of Computer Assisted Learning*, *35*(2), 1–10. https://doi.org/10.1111/jcal.12319

Hsu, C.-Y., & Ou, S.-J. (2022). Innovative Practice of Sustainable Landscape Architecture Education — Parametric-Aided Design and Application. *Sustainability*, *14*(8), 1–16. https://doi.org/10.3390/su14084627

Huang, C., & Chun, J. (2022). Computers & Education Effectiveness of a three-dimensional-printing curriculum : Developing and evaluating an elementary school design-oriented model course. *Computers & Education*, *187*, 1–28. https://doi.org/10.1016/j.compedu.2022.104553

Huang, T. C., Chen, M. Y., & Lin, C. Y. (2019). Exploring the behavioral patterns transformation of learners in different 3D modeling teaching strategies. *Computers in Human Behavior*, *92*, 670–678. https://doi.org/10.1016/j.chb.2017.08.028

Indrawan, S. E., & Purwanto, L. (2021). Digital Fabrication as a Learning Media for Ligthweight. *MODUL*, *21*(2), 126–133. https://doi.org/10.14710/mdl.21.2.2021.126-133

Kelley, T. R., Knowles, J. G., Holland, J. D., & Han, J. (2020). Increasing high school teachers self-efficacy for integrated STEM instruction through a collaborative community of practice. *International Journal of STEM Education*, *7*(14), 1–13. https://doi.org/10.1186/s40594-020-00211-w

Khurma, O. A., Ali, N., & Khine, M. S. (2023). Exploring the impact of 3D printing integration on STEM attitudes in elementary schools. *Contemporary Educational Technology*, *15*(4), 1–19. https://doi.org/10.30935/cedtech/13568

Kit Ng, D. T., Tsui, M. F., & Yuen, M. (2022). Exploring the use of 3D printing in mathematics education: A scoping review. *Asian Journal for Mathematics Education*, *1*(3), 338–358. https://doi.org/10.1177/27527263221129357

Lavicza, Z., Weinhandl, R., Prodromou, T., An, B., Lieban, D., Hohenwarter, M., Fenyvesi, K., Brownell, C., & Manuel, J. (2022). Developing and Evaluating Educational Innovations for STEAM Education in Rapidly Changing Digital Technology Environments. *MDPI*, *14*(12), 1–15. https://doi.org/10.3390/su14127237

Leinonen, T., & Virnes, M. (2020). 3D Printing in the Wild : Adopting Digital Fabrication in Elementary School Education. *International Journal of Art & Design Education*, *3*, 600–615. https://doi.org/10.1111/jade.12310

Levin, L., & Verner, I. (2021). Student Practice In 3D Design and Printing for Promoting Analytical and Applied Mathematical Thinking Skills. *International Journal of Engineering Pedagogy*, *11*(3), 39–53. https://doi.org/10.3991/ijep.v11i3.19893

Lin, K. Y., Lu, S. C., Hsiao, H. H., Kao, C. P., & Williams, P. J. (2023). Developing student imagination and career interest through a STEM project using 3D printing with repetitive modeling. *Interactive Learning Environments*, *31*(5), 2884–2898. https://doi.org/10.1080/10494820.2021.1913607

Mahendarto, T. (2020). Digital Fabrication and How It Affects the Future of Indonesian Construction World. *Advances in Engineering Research*, *192*, 97–102. https://doi.org/10.2991/aer.k.200214.014

Novak, E. (2022). 3D Printing in Education. *Routledge Resources Online-Education*, 1–6. https://doi.org/10.4324/9781138609877-ree81-1

Novak, E., & Wisdom, S. (2018). Effects of 3D Printing Project-based Learning on Preservice Elementary Teachers' Science Attitudes, Science Content Knowledge, and Anxiety About Teaching Science. *Journal of Science Education and Technology*, *27*(5), 412–432. https://doi.org/10.1007/s10956-018-9733-5

Pearson, H. A., & Dubé, A. K. (2021). 3D printing as an Educational Technology: Theoretical Perspectives, Learning Outcomes, and Recommendations for Practice. *Education and Information Technologies*, *27*, 3037–3064. https://doi.org/10.1007/s10639-021-10733-7

Rayna, T., & Striukova, L. (2021). Fostering skills for the 21st century: The role of Fab labs and makerspaces. *Technological Forecasting and Social Change*, *164*, 120391. https://doi.org/10.1016/j.techfore.2020.120391

Sanchez, I., Pitkanen, K., Laru, J., & Iwata, M. (2020). International Journal of Child-Computer Interaction STEAM in Oulu : Scaffolding the development of a Community of Practice for local educators around STEAM and digital fabrication. *International Journal of Child-Computer Interaction*, *26*, 100197. https://doi.org/10.1016/j.ijcci.2020.100197

Smith, D. W., Lampley, S. A., Dolan, B., Williams, G., Schleppenbach, D., & Blair, M. (2020). Effect of 3D Manipulatives on Students with Visual Impairments Who Are Learning Chemistry Constructs: A Pilot Study. *Journal of Visual Impairment & Blindness*, *114*(5), 1–12. https://doi.org/10.1177/0145482X20953266

Song, M. J. (2018). Learning to teach 3D printing in

schools: how do teachers in Korea prepare to integrate 3D printing technology into classrooms? *Educational Media International*, *55*(3), 183–198. https://doi.org/10.1080/09523987.2018.1512448

Stevenson, M., Bower, M., Falloon, G., & Forbes, A. (2019). By design: Professional learning ecologies to develop primary school teachers' makerspaces pedagogical capabilities. *British Journal of Education Technology*, *50*(3), 1–15. https://doi.org/10.1111/bjet.12743

Thyssen, C., Meier, M., & Meier, M. (2023). 3D Printing as an element of teaching – perceptions and perspectives of teachers at German schools. *Frontiers in Education*, *8*, 1–15. https://doi.org/10.3389/feduc.2023.1233337

Tore, S. Di, Simon, G. De, & Todino, M. D. (2021). Learning by Making. 3D Printing Guidelines for Teachers. *Makers at School, Educational Robotics and Innovative Learning Environments*, 181–186. https://doi.org/10.1007/978-3-030-77040-2

Trust, T., & Woodruff, N. (2021). Educators' Interests, Prior Knowledge and Questions Regarding Augmented Reality, Virtual Reality and 3D Printing and Modeling. *TechTrends*, *`65*, 548–561. https://doi.org/10.1007/s11528-021-00594-9

Ucgul, M., & Altıok, S. (2023). The perceptions of prospective ICT teachers towards the integration of 3D printing into education and their views on the 3D modeling and printing course. *Education and Information Technologies*, *28*(8), 10151–10181. https://doi.org/10.1007/s10639-023-11593-z

Voldborg, H., & Pitkanen, K. (2019). Empowering educators by developing professional practice in digital fabrication and design thinking. *International Journal of Child-Computer Interaction*, *21*, 1–16. https://doi.org/10.1016/j.ijcci.2019.03.001

Wang, Z. (2022). 3D Printing Technology in Model Design Teaching. *International Conference on Frontier Computing*, 1829–1834. https://doi.org/10.1007/978-981-16-0115-6_213

Wibawa, B., Syakdiyah, H., Siregar, J. S., & Asrorie, D. A. (2021). Use of 3D printing for learning science and manufacturing technology. *AIP Conference Proceedings*, *2332*, 1–7. https://doi.org/10.1063/5.0045380

Zhou, D., Gomez, R., Wright, N., Rittenbruch, M., & Davis, J. (2020). A design-led conceptual framework for developing school integrated STEM programs: the Australian context. *International Journal of Technology and Design Education*, *32*, 383–411. https://doi.org/10.1007/s10798-020-09619-5