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Evaluation of the Pedagogical Impact of the Educational Usage of 3D Printing in Czech Lower Secondary and Grammar Schools

Kamil Malinka* Masaryk University, CZECH REPUBLIC

Libuše Vodová Masaryk University, CZECH REPUBLIC

Martina Jančová Masaryk University, CZECH REPUBLIC

Lenka Sobková Masaryk University, CZECH REPUBLIC

Vladimír Schindler Masaryk University, CZECH REPUBLIC

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Abstract: In this article, we discuss the impacts of using 3D printing in education. Our primary goal is to evaluate the pedagogical impact of lessons utilizing 3D printing. We asked one hundred ninety students in four reference schools about the acceptability of existing 3D materials for teaching. Although the results show high attractiveness for the target group, it turned out that the available lessons primarily focus on the acquisition of technical skills and do not use the potential of education in other areas. We, therefore, proposed a concept for creating multidisciplinary teaching lessons that connect the technical part with other educational areas. We show the application of our concept in a newly developed lesson in biology, where we again evaluate its acceptance among the students. The results show that although the multidisciplinary lessons are more complex, they are still acceptable to the students, and, most importantly, they add significant educational value. Finally, we discuss the possibilities of incorporating 3D printing into the teaching curriculum. We also use a selected use case to illustrate the real-world problems we have encountered.

Keywords: *3D print, education, pedagogical impact, teaching aids.*

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Introduction

With the development of 3D printing technology in recent years, the price of printers has dropped significantly, and thus the availability of this technology has increased. It opens up new possibilities in various fields, from industry, medicine, and architecture to everyday home use. However, we see in 3D technology a huge pedagogical potential that currently needs to be utilized more and, in the Czech Republic, is only slowly finding its way into education. Despite the long-standing need to document how 3D printing technology is used in education worldwide, there is no comprehensive and accessible literature search on the topic - little is known about the educational effects and implications of 3DP for learning (Ford & Minshall, 2019; Novak et al., 2021). However, using digital fabrication technologies to support learning is far from new.

Reengineering and architecture are the first disciplines that recognize the benefits of incorporating these technologies into teaching (facilitating learning, developing skills, and increasing student engagement) (Berry et al., 2010; Stier & Brown, 2000). Engaging with these technologies inspires creativity, improves students' attitudes toward science, technology, engineering, and mathematics (STEM) subjects, and increases teacher interest and engagement (Horowitz & Schultz, 2014).

Most other studies support these observations with their results on how 3D printing technology supports the teaching of STEM subjects in schools, e.g., the positive correlation between student learning and the engagement of 3D in teaching atomic structures in chemistry classes (Chery et al., 2015), the creation of a police whistle in teaching audio frequencies in physics (Makino et al., 2018), computational thinking through linking Minecraft and 3D printing (Roscoe et al., 2014), or design thinking through a 3D printed city planning game, Kidville (Mahil, 2016). Other studies show issues with technology literacy and student attitudes toward new technologies, cost, and integration into curriculum and teaching standards (Bull et al., 2015; Kostakis et al., 2015; Nemorin, 2017). 3D printing also brings some challenges, especially

* **Corresponding author:**
Kamil Malinka, Masaryk University, Czech Republic. ✉ malinka@ics.muni.cz

with longer projects, frustration, physical fatigue, and mental exhaustion, which require a huge amount of personal enthusiasm, organization, and support from a single motivated and interested teacher alongside sporadic episodes of student attention and effort from the lead teacher (Nemorin & Selwyn, 2017).

However, there are relatively few studies looking at the use of 3D printing technology purely in primary schools (Abu Khurma et al., 2023; Ford & Minshall, 2019). That is why we decided to cover little-explored areas of primary and secondary schools and practical aspects of 3D printing usage in teaching.

This article was created as part of a project that responds to the current availability of high-quality 3D printing, the demand for methodological support for using 3D printing in education, and didactically correct teaching aids (models) for individual school subjects. Our primary goal is to create teaching materials utilizing 3D printing in education and to evaluate their pedagogical impact. When creating new lessons and methodologies adopting 3D printing, we encountered a lack of information regarding the impact on teaching, appropriate ways of creating lessons, and the fluctuating quality of existing materials. We, therefore, decided to cover these areas too. Specifically, we focus on the quality of existing lessons, the appropriate approach for creating new multidisciplinary lessons that better utilize the potential of technology, and integrating this approach into the curriculum.

The main contributions of this article might be summarized as follows:

- We evaluated the quality and focus of existing materials for 3D printing that are publicly available.
- We have experimentally verified a high level of student acceptance of this technology - even when using complicated multidisciplinary lessons.
- We showed a statistically significant positive effect of 3D models on the mastery of the curriculum content in a selected biology course.
- We have formulated recommendations for creating new multidisciplinary lessons and appropriate ways to integrate them into the curriculum.

Literature Review

This section summarizes the current state of 3D printing adoption in schools. The first part is focused on the technical problems related to the deployment of 3D printing at schools and summarizes available teaching documents. It aims to show what other factors influence actual deployment, put our research in the context of a natural environment that should use the results, and summarize the available materials for subsequent comparison of their quality and focus. The following section then summarizes state-of-the-art results regarding the teaching effect of 3D printing. We planned to add publications addressing curriculum issues, but the research still does not cover this area. Here, therefore, we see another contribution to our work.

The purchase of commercial teaching models is usually expensive. However, their use has many advantages. The spatial visualization of structures that are challenging to observe on natural objects with the naked eye or the representation of hard-to-reach products of nature is undoubtedly desirable and beneficial. Moreover, students' participation in producing models, which 3D printing makes accessible, and working with them directly in the classroom will develop their other skills.

There is a wide range of different types of printers and materials used. For use in education, it is necessary to guarantee the equipment's health and safety and select devices that allow sufficiently high-quality printing and meet any other parameters. Furthermore, knowledge of production technology is necessary to create a realistic model, e.g., the printing of more complex structures requires specific adjustments in 3D models. Similarly, it is necessary to have sufficient insight into the methods and forms of teaching, course content, and practical teaching experience so that the proposed methodology, tools, and procedures are didactically correct and reflect the current needs of schools.

According to the available studies (Malinka & Schindler, 2021), schools face three main challenges in implementing 3D printing into the curriculum:

- Managing and controlling access to the printer,
- Operating costs and advocating for return on investment,
- Integrating 3D printing projects into the curriculum (lack of teaching materials, lack of technical knowledge, lack of easy access to the printer).

If schools overcome the initial difficulties and purchase a printer, they continue to face problems with the lack of quality learning content. Several projects are trying to create content (Be3D Academy, n.d.-b; CREATE Education, n.d.; MakerBot, 2022; PrintLab, n.d.; Thingiverse, n.d.). Usually, they are linked to 3D printer manufacturers trying to boost sales. As a result, the size of freely available databases of 3D models is constantly expanding, but only a tiny proportion of them have significant pedagogical potential.

Also, their focus is mainly on the technical aspects (only for teaching the basics of 3D modelling and printing) and higher classes. The websites serve more as a signpost for pre-selected models, so there is a lack of support for teachers and students. The quality of the materials is generally adequate. Still, the companies usually do not have the space or pedagogical experience to adapt the materials to reflect the curricula and their specificities in the individual countries (e.g., the Framework Educational Programmes in the Czech Republic, FEP).

Another significant problem is the additional time burden for teachers: they must find a suitable model, check that the print is of sufficient quality, match their ideas, prepare teaching materials, and consider how to integrate it into lessons. Although teachers are using available ready-made teaching materials, e.g., through portals of commercial 3D printer vendors such as Be3D Academy (n.d.-b), they still encounter these general problems:

- Low correspondence of existing materials with the frame educational program (existing materials are more of an "extra"),
- Lack of a broader set of teaching materials,
- Teachers' lack of knowledge often leads to a decision not to purchase equipment,
- The problem of defining the overall benefits of integrating 3D printing into teaching.

We decided to focus on the last issues. Several publications or websites creating 3D models that would be well suited for use in school classes. However, very few authors have addressed their implementation in the classroom and the subsequent evaluation of whether teaching with 3D models has been more effective.

Next, in this section, we cover relevant research on using 3D printing and focus on evaluating its impact on teaching. Given that the main expansion of 3D printing is currently taking place in universities, we try to emphasize those works that focus on primary and secondary schools. We also focus on a range of biology lessons.

Maněnová and Chadimová (2015) investigated the effect on the teaching process of using gamification elements of specific 3D models of historical objects. Historical objects originating from the Czech Republic were used in the subject Man and his world. The pupils were more active in the lessons than the teacher.

NEWTON Fab Lab Initiative study by Togou et al. (2019) shows statistically significant improvements in students' interest in science classes, engagement, confidence when solving STEM-related problems, and a statistically significant drop in students' boredom. NEWTON FAb Lab initiative is an educational platform that aims at promoting the concept of curriculum-based fabrication laboratories (Fab Labs). A research study was carried out in a primary school in Ireland on a male sample of 29 6th-grade students (10-12 years old). The results showed that the NEWTON Fab Lab Initiative could encourage students to learn STEM-related subjects even if they have a negative or impartial attitude toward learning them. Using these technologies while learning made students enjoy the lessons more while feeling more engaged, less bored, and less anxious, which is essential in stimulating students' motivation to engage actively in the learning process.

The study by Moore and Tyler-Wood (2019) explored the efficacy of The National Science Foundation's (NSF) grant project on gifted students from rural middle schools and how the project affects gifted students' knowledge and affinity toward STEM. Two campuses were selected to participate in the NSF research grant based on access and demographic similarities. One campus received the treatment, and the other acted as a contrast group for comparisons. The treatment campus completed a unit of curriculum based on the solenoid using a 3-D printer to learn knowledge and skills across the STEM fields. The solenoid curriculum in this study does help shift the learning from the teacher to the students. The total number of students involved was 304; however, complete data were collected from 198 students, and 23 of them were identified as gifted and talented. The results showed that gifted students' affinity toward science and engineering increased and displayed more positive feelings toward these topics than before the intervention began. The non-gifted students gained a conceptual understanding of how objects are rendered in a three-dimensional space due to completing the solenoid curriculum; their posttest scores increased.

Ford and Minshall (2019) described categories of uses for 3D printing, which include teaching students about 3D printing, teaching educators about 3D printing, assistive technology in teaching, or making aids to assist teaching. Regarding the use of 3D printing in schools, they report that there has been an improvement in the understanding of science and mathematics. Including 3D printing in the school curriculum has received positive feedback as it can provide opportunities to practice different learning styles.

Fung et al. (2019) wrote a study to motivate primary school students to improve their learning of Chinese characters using 3D models. The data collection was done by using pretest and posttest. The study shows that through 3D models, learning Chinese characters is more interactive and intriguing.

Data from 47 peer-reviewed articles concerning 3D printing in chemistry teaching are summarized in an article by Pernaa and Wiedmer (2020). Most of the studies dealt with the 3D printing of research tools, and few studies examined the impact of 3D printing on teaching or students' perceptions of it. The articles that addressed perceptions or impact on learning summarized that using three-dimensional models promotes understanding of the subject matter. Another study reported that 90% of pharmacy students found that three-dimensional models improved their engagement and learning outcomes.

In evaluating the impact on learning, the work of Novak et al. (2021) is significant. It provides a systematic review of 78 studies addressing learning with 3D print at several levels of education. From these studies, five major trends were formulated regarding the field of 3D printing in learning, which includes preparing the next generation of engineers, supporting learning with low-cost 3D printed tools, and fostering creativity and innovation. They conclude the article by stating that there is likely to be a lot of interest using of 3D printing in learning. In addition to general conclusions supporting our results, this work mentions that four studies produced significant shifts in pre- and post-tests in K-12 STEM education, similar to ours.

J. Chen and Cheng (2021) report on the impact of 3D printing on elementary and middle school students learning. In creating three-dimensional models, students can improve their practical skills and qualifications. Observing objects before modelling them helps to improve students' observation and concentration. When modelling, pupils' creativity, and spatial imagination are improved.

The perception and deployment of 3D printing in the Nigerian education sector for science and technology programs are discussed in Inoma et al. (2020). They cite improving students' visual-spatial skills as a benefit of introducing 3D printing into education. Another benefit may be increased student interest in learning and, thus, improved academic performance. They summarize that 3D printing promotes group learning. Regarding the area of biology, most existing studies about using 3D-printed teaching aids in biology are concentrated on human anatomy or molecular biology. However, there is a lack of studies concerned with the impact of 3D printing on students of life sciences (Hansen et al., 2020).

Existing studies are primarily concerned with the impact of using 3D models in teaching and are focused on upper grades, possibly universities, and teacher education. Our work extends the findings to applications in non-STEM subjects. In addition, we also focus in greater detail on the practical aspects of the overall workflow of deploying 3D printing in the classroom, i.e., including teacher and student requirements, implementation time, and curriculum constraints.

Methodology

Research Design

During our work in the area of 3D printing usage in education, we encountered a lack of information that would have focused more on evaluating the benefits of incorporating 3D printing into teaching. We decided to explore this area more. The context of the experiment and further discussion of the results reflect that the whole research took place in the Czech Republic.

In this article, we focus on the problem of defining the overall benefits of incorporating 3D printing into teaching. We are interested in the quality of available lessons, their student acceptability, and how to maximize the benefit of new lessons.

In particular, we decided to define and answer the following research questions:

- RQ1: What is the focus and quality of the currently existing lessons?
- RQ2: How is incorporating 3D printing into the classroom being accepted by students?
- RQ3: Are students able to handle more complex assignments in multidisciplinary lessons?
- RQ4: What is the pedagogical impact of implementing 3D printing in the classroom? Can we assess the added value?

To answer our RQs we performed two experiments on students from primary and secondary schools. The first experiment aimed to test students' acceptance of 3D printing and find the main problems students face. Here, we primarily focused on RQ1, RQ2, and RQ3. The second experiment's main goal was to test the pedagogical impact of 3D models on learning (RQ4). As a research design to answer the research questions, we used two quantitative research approaches: A questionnaire survey (experiment 1) and a test (experiment 2).

Selection of Schools and Participants

In our research, we wanted to involve different types of schools, e.g., lower secondary and grammar schools, schools that did not have any experience with 3D printing, and schools experienced with 3D printing. We were limited in the number of 3D printers we could lend to schools. That is why we had four reference schools: two lower secondary schools and two grammar schools. Three schools are from Brno, and one is from Třebíč. One school had no experience with 3D printing before (ZŠ Kamínky, Brno), and the other three schools had experience at different levels. Teachers of the involved course chose participants of the research (pupils of selected schools) due to test lessons on 3D printing. For a more detailed description, see Table 1.

Sample and Data Collection – Experiment 1

The first experiment aimed to test students' acceptance of 3D printing and find the main problems students face. We primarily focused on RQ1, RQ2, and RQ3. Testing of the lessons took place in computer science classes. In the first phase, the students tested existing lessons in the Be3D Academy. They downloaded the available materials, workflows, and supporting models and solved the task according to the described procedure. The work output was a model printed on the school's 3D printer. Then, students completed an online questionnaire that consisted of 12 items. Three of them were related to the identification of school, class, and age of participants (pupils), and other nines asked about the realization of the selected lesson (the ability to complete the lesson, school-like grading of the lesson, enjoying of 3D printing, usefulness and interesting of lesson and identifications of problems with completing of the lesson). Then, we repeated the whole process for the new lessons we created.

In this experiment, we used a quantitative research approach. We conducted a questionnaire survey in nine classes of four reference schools (Table 1) and obtained 190 responses. The experiment was conducted over six months. Thirty-one lessons were tested. The lessons that received the most responses were: Introduction to 3D Printing, Loaded Dice, and Flooding Fallout. In the second phase of the experiment, only the new comprehensive lessons developed by our team were tested, namely Cartogram, Under the Microscope, Orthographic Projection, and Stereometry (see Be3D Academy, n.d.-a).

Table 1. Description of the Test Group

School				**Number of responses**		
Name	**Type**	**Class**	**Age**	**Count**	**Percentage**	
Mathias Lerch Gymnasium	grammar school	3. AF	15-16	18	9.5	
Mathias Lerch Gymnasium	grammar school	3. AV	13-14	31	16.3	46.8
Mathias Lerch Gymnasium	grammar school	7. AV	17-18	40	21.1	
Gymnasium Třebíč	grammar school	4. G	14-15	32	16.8	16.8
ZŠ Hudcova	lower secondary school	8. C	13-14	4	2.1	
ZŠ Hudcova	lower secondary school	9. A	14-15	10	5.3	12.6
ZŠ Hudcova	lower secondary school	9. B	14-15	10	5.3	
ZŠ Kamínky	lower secondary school	8. A	13-14	18	9.5	23.7
ZŠ Kamínky	lower secondary school	8. B	13-14	27	14.2	

Sample and Data Collection – Experiment 2

We chose models of bacteria and protozoa to test the pedagogical impact of 3D models on learning (RQ4). Due to time constraints, only the nontechnical part of the lesson was tested. The full version of the lesson will be presented in the next section. 3D teaching aids for bacteria and protozoa were tested in the 6th grade of the Kamínky Primary School in Brno. Thirty-six pupils (23 girls and 13 boys) from two classes (6.A and 6.B) participated in the testing. Pupils from both classes completed an initial knowledge test ("pretest") in early November 2021. Subsequently, the topic of bacteria and protozoa was taught. Classical frontal teaching was carried out using a PowerPoint presentation and a worksheet in one class (6.B, the "control group"). One lesson was devoted to bacteria, the other to protozoa. In the second class (6.A, "experimental group"), the experimental teaching was carried out as group work of pupils with 3D printed models of bacteria (diplococcus, streptococcus, staphylococcus, spirochete, and bacillus) and protozoa (paramecium). Also, this class devoted one lesson to bacteria and the other to protozoa. At the end of the lesson, the pupils of both classes took a posttest. The intention was to pilot the teaching aid to see if it is acceptable in this way and what impact it had on teaching effectiveness as a basis for possible modification of the final lesson. Therefore, we tested the effectiveness of working with models in the classroom compared to classical frontal teaching with presentations and worksheets.

The teaching of bacteria with 3D models was carried out as follows. The teacher first divided the pupils into five groups, each receiving cards (name of the bacterium, positive use, model of the bacterium) and a story. The pupils read the cards and matched one 3D model of the bacterium to the card. Then, each group read a story underlining everything related to the disease (symptoms, diagnosis, treatment, prevention). They then matched the last card to the 3D model, describing the pathogenic effects of the bacterium on the human body. Finally, each group presented their 3D model of the bacterium to the others and described its appearance, pathogenicity, and positive uses. Teaching protozoa with 3D models was conducted similarly in six student groups. Each group was given a model of a paramecium, an A3 sheet of paper, and supporting texts. In addition, pupils received cards with the designated role of a writer, scientist, or painter. The painter drew the paramecium construction; the scientist read the supporting texts and dictated to the writer the information to write on the poster. After creating the poster, each group briefly summarized what they had noted and described the construction of the paramecium on their assigned 3D model.

We tested the effectiveness of teaching with our designed 3D models using a "pretest" and a "posttest" (Figure 1). The tasks were designed based on learning objectives teaching biology in the Czech Republic. The tasks were intended to represent a representative sample of the biology curriculum. The pretest ascertains the level of students' input knowledge before the actual teaching on bacteria and protozoa. The pretest is identical to the posttest. The posttest determines the knowledge attained after the education on bacteria and protozoa. Students can independently answer whether they have participated in frontal teaching or teaching using 3D models. They had the same time limit of 30 minutes for both tests.

To assess the content validity, the tasks were presented to eight evaluators (biology teachers). Based on their feedback, the CVR (content validity ratio) and CVI (content validity index) values were calculated (Nikolopoulou, 2022). The evaluators rated each task on a three-point scale as (1) "not necessary", (2) "useful but not essential", or (3) "essential". The CVR was calculated for each item according to the relation: CVR=(Ne-N/2)/(N/2), where Ne is the number of evaluators who voted for the task necessity, and N is the total number of evaluators. The arithmetic mean and then the content validity index (CVI) were calculated from the CVR values of each task. Its value was expected to be above 0.75. Tasks were revised and changed as the pilot versions of the didactic tests did not achieve CVI values above 0.75. Then the tests were re-scored by the same evaluators. After this revision, the CVI value increased. The final version of the tests used in the lower secondary schools had CVI values of 0.767 (bacteria test) and 0.765 (protozoa test).

The reliability of didactic tests was calculated by using the Kuder-Richardson formula (Skutil et al., 2011). The halving method was not used because the number of tasks in the two tests was not even, and the tasks were not in increasing difficulty order. For data about reliability, see the section with results.

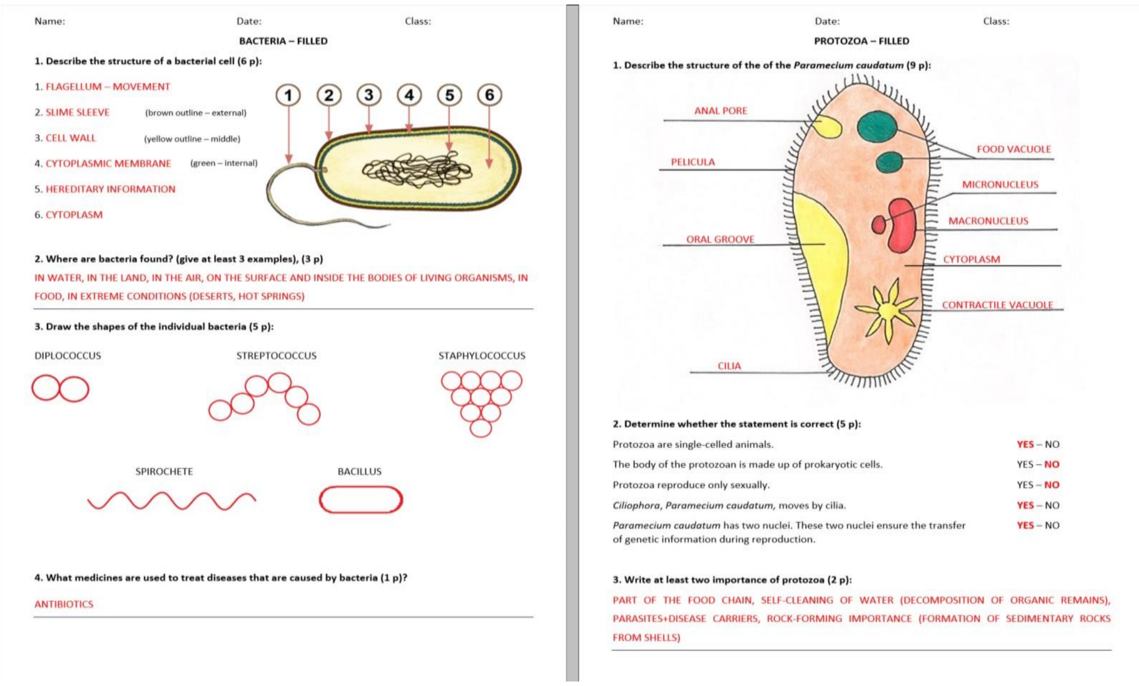

Figure 1. Sample of the Completed Test

Each correct answer in the pretests and posttests was scored. Then, the pretest and posttest scores in the experimental (6.A) and control groups (6.B) were summed. The difference in scores was tested for statistical significance. A statistically significant difference between the scores obtained in the experimental and control groups, then, may indicate a higher educational impact of teaching with 3D models over traditional frontal teaching.

Results

Experiment 1

We present the results from both phases (existing and newly created MUNI lessons) in standard graphs for better comparison. All statistical processing was performed in Statistika 14 (TIBCO Statistika Ink.); the significance level was always $\alpha = .05$. The Shapiro-Wilk test was used to test the normality of the data distribution. The t-test resp. the χ^2 test was used to determine statistically significant differences.

First, we were interested in students' ability to complete the task. 85% of the pupils could complete the original lesson task thoroughly, while 15% could partially complete the task. The numbers were similar for the MUNI lessons, with 83% completing the task thoroughly, 15% partially, and 2% failing to complete the task. There was no statistically significant difference (Table 2) between these two groups at $\alpha = .05$ (Shapiro-Wilk. W = .88 resp. .86, p= .324 resp. .27 confirmed normal data distribution; t-test = 0.546, Cohen's d = 0.48, effect size small (d < 0.50).

Table 2. Results of the Statement "Could You Complete the Task?"

Lessons	New (MUNI)	Original (Y Soft)
M	19.67	43.67
Mdn	9.00	19.00
Mod	multiple	multiple
SD	26.65	57.14
t-value	-0.65	
p-value	.55	
d	0.48	

Note. M = Mean, *Mdn* = Median, *SD* = Standard Deviation, *p*-values Marked with * are Statistically Significant, *p*-values Marked with ** are Strongly Statistically Significant (α = .01), *t*-values=Statistics of *t*-test, *d* = Cohen's measure of sample effect size for comparing two sample means.

Students were also asked to self-assess the outcome of their work. These evaluations were very positive (see Figure 2). There was a statistically significant difference (Table 3) between these two groups at α = .05 in school-like grading of the lessons (Shapiro-Wilk. W = .73 resp. .89, p = .018 resp. .335 showed not-normal data distribution; χ^2 = 30.86, df = 4, p < .001; coefficient η = .04, effect size small (η < .06). The newly created MUNI lessons were rated slightly better.

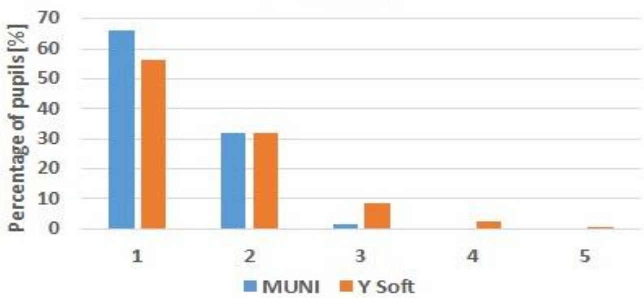

Figure 2. Evaluation of the Result of the Work With Marks as in School

Table 3. Results of the School-like Grading.

Lessons	New (MUNI)	Original (Y Soft)
M	27.12	31.82
Mdn	5.10	25.20
Mod	0.00	multiple
SD	34.86	27.33
χ^2	30.86	
p-value	p < .001**	
η	.04	

Note. *M* = Mean, *Mdn* = Median, *SD* = Standard Deviation, *p*-values Marked with * are Statistically Significant, *p*-values Marked with ** are Strongly Statistically Significant (α = .01), *t*-values = Statistics of *t*-test, η = coefficient effect size.

In the context of achievability, we were also interested in the specific problems they encountered in solving the task. The results are depicted in Figure 3. The next section of the questionnaire evaluated the lessons' interests and usefulness. The lessons were generally well received, with most students finding them entertaining and valuable (Figure 4 and Figure 5). There was no statistically significant difference (see Table 4) between these two groups at α = .05 (Shapiro-Wilk. W = .94 resp. .85, p = .671 resp. .224 confirmed normal data distribution; t-test p = .904; Cohen's d = 0.09, no effect size (d < 0.20).

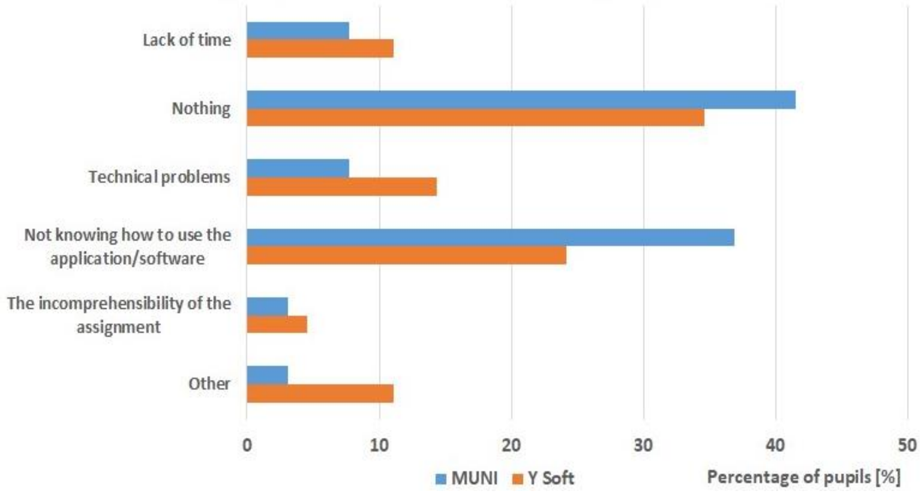

Figure 3. Evaluation of the Major Problems of Solving the Problem

Figure 4. Evaluation of the Question if Pupils Are Interested in 3D Printing

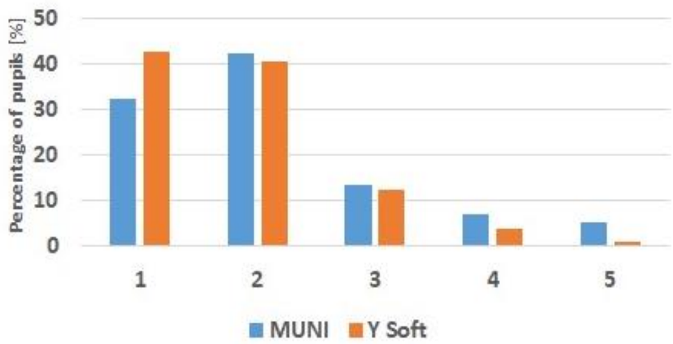

Figure 5. Evaluation of the Question Whether Find the Task Useful and Interesting

Note. 1 – yes, very much; 5 – not at all, I will never use it

Table 4. Results of the Statement "Do You Enjoy 3D Printing?"

Lessons	New (MUNI)	Original (Y Soft)
M	76.25	83.38
Mdn	69.50	81.35
Mod	multiple	multiple
SD	72.76	86.66
t-value	-0.13	
p-value	.904	
d	0.09	

Note. M = Mean, *Mdn* = Median, *SD* = Standard Deviation, *p*-values Marked with * are Statistically Significant, *p*-values Marked with ** are Strongly Statistically Significant (α = .01), *t*-values = Statistics of *t*-test, *d* = Cohen's measure of sample effect size for comparing two sample means.

There was no statistically significant difference (Table 5) between these two groups at α = .05 (Shapiro-Wilk. W = 0.80 resp. .84, *p* = .087 resp. .176 confirmed normal data distribution; *t*-test *p* = .917; Cohen's *d* = 0.07, no effect size (*d* < 0.20).

Table 5. Results of the Statement "Do You Find This Task Useful and Interesting?"

Lessons	New (MUNI)	Original (Y Soft)
M	78.02	84.10
Mdn	40.80	36.60
Mod	multiple	multiple
SD	80.82	97.29
t-value	-0.11	
p-value	.917	
d	0.07	

Note. M = Mean, *Mdn* = Median, *SD* = Standard Deviation, *p*-values Marked with * are Statistically Significant, *p*-values Marked with ** are Strongly Statistically Significant (α = .01), *t*-values = Statistics of *t*-test, *d* = Cohen's measure of sample effect size for comparing two sample means.

Experiment 2

The values of the reliability coefficient ranged from 0.43 to 0.67. The reliability coefficient of the pretest on bacteria in class 6.A was 0.67, while in class 6.B it was 0.43. The reliability coefficient of the posttest on bacteria was 0.66 for class 6.A and 0.56 for class 6.B. The reliability coefficient for the pretest on protozoa was 0.49 in class 6.A and 0.65 in class 6.B. The reliability coefficient for the posttest on bacteria was 0.44 in class 6.A and 0.61 in class 6.B.

We attribute the value of the coefficient to the lower number of tasks in the test, because both tests were designed for pupils of lower secondary school (11 or 12 years old). Considering the age of the pupils and the time allocated for our experiment, it was impossible to test the pupils with a more elaborate test. The bacteria pretest results (Figure 6) show that pupils from both classes are almost at the same level of knowledge. None of the pupils achieved a maximum of fifteen points. One-third of the points in the experimental class were scored by 45% of pupils, but in the control class, only 22%. The remaining pupils scored only 2 points or less. The low score on the bacteria pretest was expected because teachers deal with this topic marginally at lower secondary schools, and the pupils' previous experience of everyday life is limited at this age.

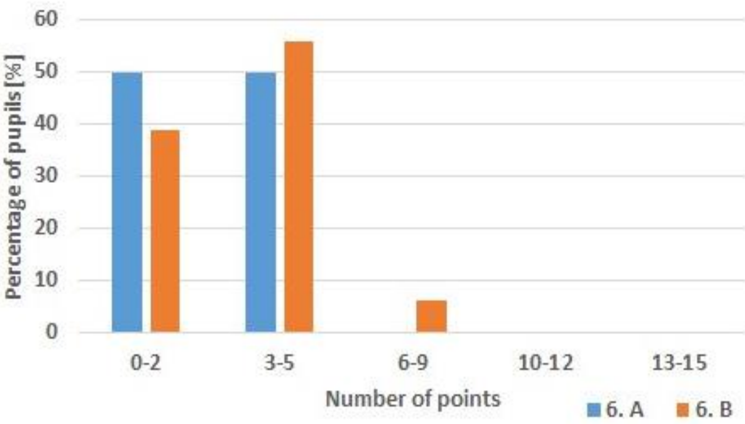

Figure 6. Results of the Pretest of Pupils 6.A and 6.B – Bacteria

None of the sixth-grade students scored total points in the protozoa pretest (Figure 7). The highest score was six. Exactly half of the pupils in 6.A and 56% of those in 6.B scored one-third of the points. The other half of the pupils scored two or fewer points in 6.A and 39% of the pupils in 6.B. Low scores were also expected for protozoa because this subject is taught only marginally or not at all at primary school.

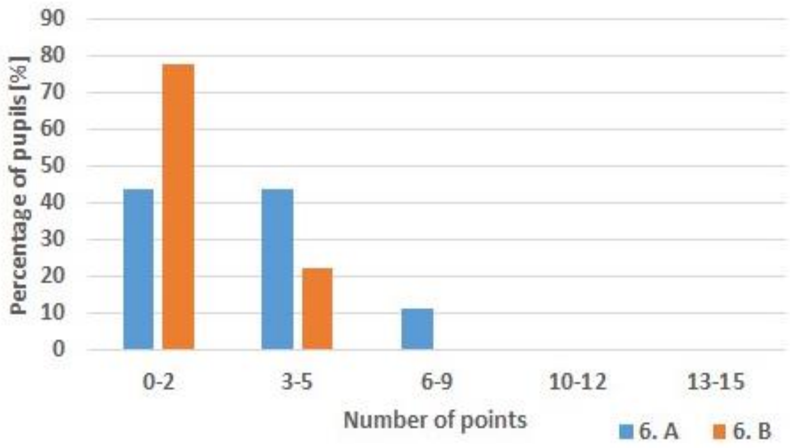

Figure 7. Results of the Pretest of Pupils 6.A and 6.B – Protozoa

In the posttest (Figure 8), it is evident that the students of 6.A obtained better results on the topic of bacteria. 78% of pupils in 6.A scored at least half the points, while only 55% of pupils in 6.B. In the final result, there was also a difference between the pupils of 6.A (experimental group) and 6.B (control group) in the lower scoring categories. While none of the pupils in 6.A ended up with six points or less, in 6.B it was 39% of pupils.

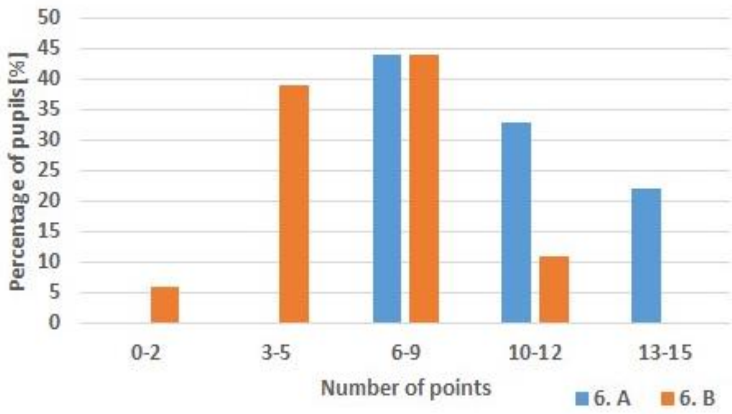

Figure 8. Posttest Results for 6.A and 6.B – Bacteria

The results of the posttest on protozoa (Figure 9) show that three pupils in class 6.A scored 14 points, whereas, in 6.B, only one pupil scored 14 points. More than 80% of the pupils in both classes scored above half the marks. None of the pupils in class 6.A had five points or less, while two pupils from 6.B scored only 3 points.

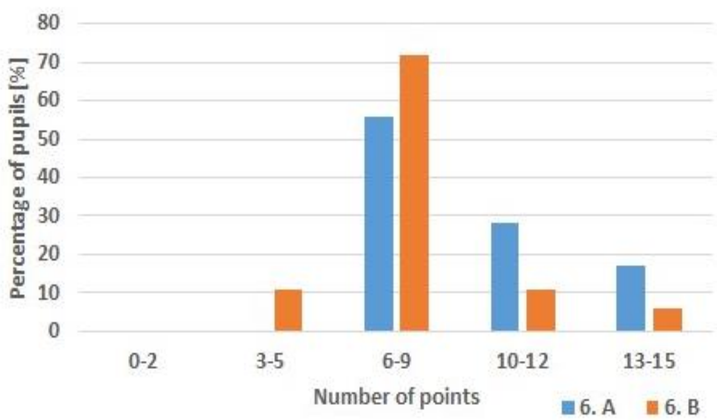

Figure 9. Posttest Results for 6.A and 6.B – Protozoa

The pupils of class 6.A performed better on the posttest; however, they also had a more significant score difference between the pretest and posttest than the pupils of class 6.B (Figure 10 and Figure 11). The graph (Figure 10) shows the difference in the students' pretest and posttest scores in class 6.A and 6.B on the topic of bacteria. None of the pupils scored less on the posttest than on the pretest, but none of the pupils had a score difference of more than 13 points. Pupils in both classes most often improved by six to nine points (44% in 6.A and 50% in 6.B). Few pupils in the experimental class 6.A achieved a higher score difference (10 to 12 points). From the graph, it can be seen that pupils in class 6.A had a more significant point increase than pupils in class 6.B. 70% of pupils in class 6.A achieved improvement by six points or more. Pupils who took part in lessons using 3D models achieved better posttest results and better progress concerning the pretest.

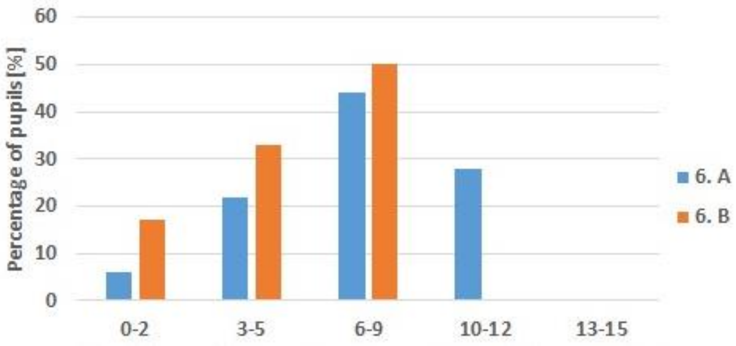

Figure 10. Difference in Scores in the Pretest and Posttest Between Pupils in 6.A and 6.B – Bacteria

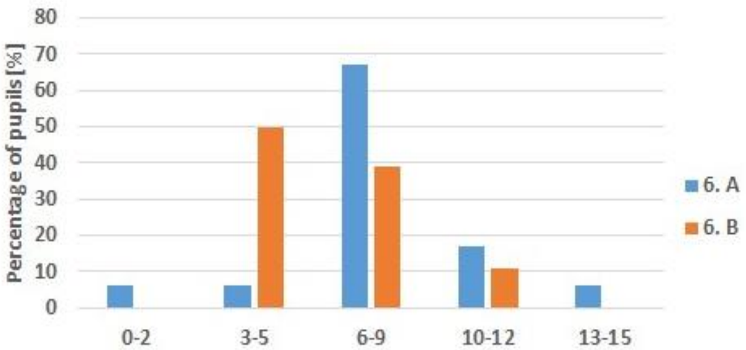

Figure 11. Difference in Scores in the Pretest and Posttest Between Pupils in 6.A and 6.B – Protozoa

The graph (Figure 11) highlights the difference in pretest and posttest scores for students in class 6.A and 6.B on the topic of protozoa. More pupils in class 6.A (17%) achieved a high score difference (10 - 12) than in class 6.B (11%). Pupils in class 6.A improved the most by 9 - 6 points (67%), while 39% of pupils in class 6.B did so. The pupils in class 6.A who participated in the learning utilizing 3D models achieved better posttest results than the pupils in Class 6.B (Figure 12), and we can observe a more significant shift in the results compared to the pretest (Figure 13).

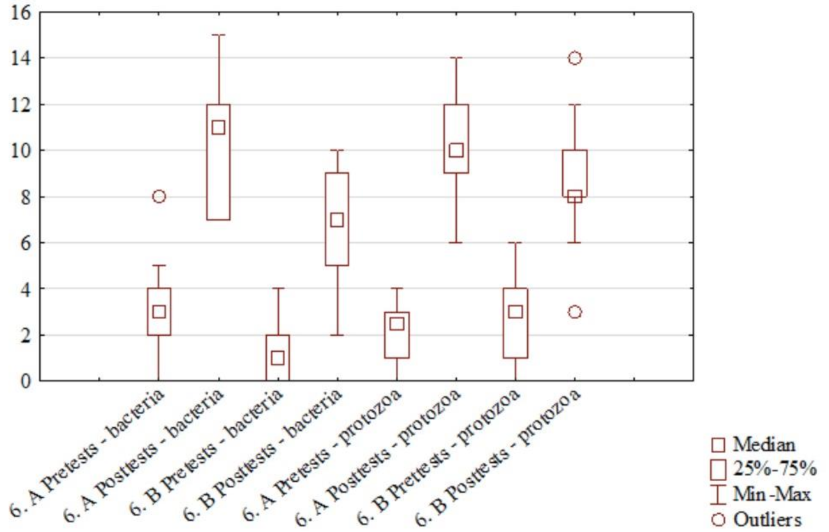

Figure 12. Results of Pretest and Posttest in Both Classes - Bacteria and Protozoa

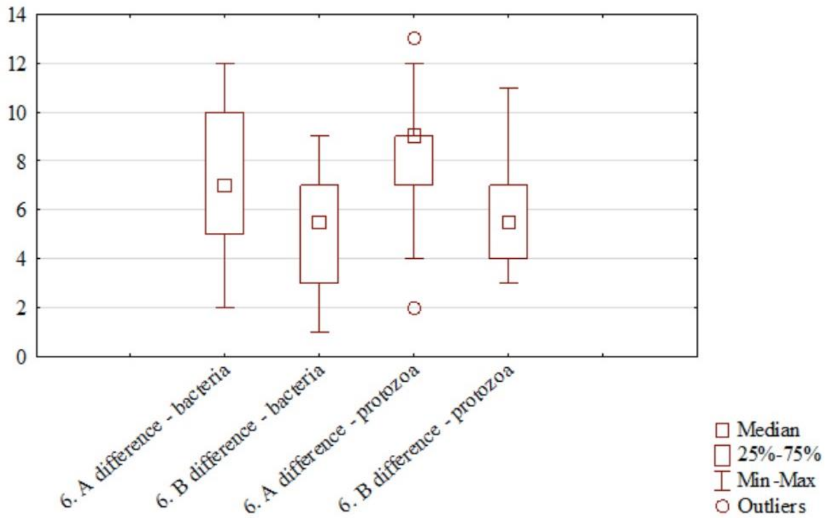

Figure 13. The Difference in Pretest and Posttest Results in Both Classes - Bacteria and Protozoa

The score values for some of the tests did not show a normal distribution of data, so the non-parametric Wilcoxon Matched Pair Test was used to test dependent samples within a class, and the χ^2 test was used to evaluate test scores between classes 6.A and 6.B. Shapiro-Wilk test showed not-normal data distribution in bacteria-pretest 6.B (p = .012) and protozoa-pretest 6.A (p = .019); therefore, we had to use non-parametric tests for all statistical evaluations with the following data sets. Other files showed normal data distribution (bacteria-pretest 6.A p = .082, bacteria-posttest 6.A p = .055, bacteria-posttest 6.B p = .151, protozoa-pretest 6.B p = .127, protozoa-posttest 6.A p = .378, protozoa-posttest 6.B p = .238).

All results of bacteria tests were found as statistically significant and with high effect size in both pretest and posttest in the experimental and control class and also between 6.A and 6.B, where pupils in 6.A have got a better score in pretest and posttest also, see Table 6. The results of protozoa-tests were found as statistically significant and with high effect size in both pretest and posttest in the experimental and control class, but no statistically significant difference and small effect size was found between the pretests in 6.A and 6.B, while in the posttests, the difference was highly significant and effect size was high (Table 7).

Table 6. Statistical Evaluation of Bacteria Tests

Topic	Stage	Bacteria	
		Posttest 6.A	**Pretest 6.B**
Bacteria	Pretest 6.A	p <.001** Z = 3.72 d = 1.24	p <.001** χ^2 = 60.25 η = .20
	Posttest 6.B	p <.001** χ^2 =136.79 d = 1.24	p < .001** Z = 3.72 η = .45

Note. p-values Marked with * are Statistically Significant, p-values Marked with ** are Strongly Statistically Significant (α = .01), Z = the Statistics of Wilcoxon Matched Pair Test, χ^2 = the Statistics of χ^2Test; d = Cohen's measure of sample effect size for comparing two sample means (> 0.80 means high); η = coefficient effect size (> .14 means high).

Table 7. Statistical Evaluation of Protozoa tests

Topic	Stage	Protozoa	
		Posttest 6.A	**Pretest 6.B**
Protozoa	Pretest 6.A	p <.001** Z = 3.72 d = 1.24	p = .523 χ^2 = 16.02 η= .05
	Posttest 6.B	p < .001** χ^2= 72.96 η = .24	p < .001** χ^2 = 75.67 η = .25

Note. p-values Marked with * are Statistically Significant, p-values Marked with ** are Strongly Statistically Significant (α = .01), Z = the Statistics of Wilcoxon Matched Pair Test, χ^2= the Statistics of χ^2Test; d = Cohen's measure of sample effect size for comparing two sample means; (> 0.80 means high); η = coefficient effect size (> .14 means high, < .06 means small).

The files with scores of difference in results of pretests and posttests in both classes showed a normal data distribution (Shapiro-Wilktest: bacteria-differences in 6.A p = .583, bacteria-differences in 6.B p = .345, protozoa differences in 6.A p = .474 and protozoa-differences in 6.B p = .075); therefore we could use parametric t-test for independent samples to evaluate statistical significance (α = .05). The differences in the shift in pupils' knowledge in experimental class 6.A and control class 6.B are statistically significant, even more so for protozoa than for bacteria (Table 8).

Table 8. Statistical Evaluation of Differences in Bacteria and Protozoa Pretests and Posttest in the Classes 6.A and 6.B

	Bacteria difference 6.A	Bacteria difference 6.B	Protozoa difference 6.A	Protozoa difference 6.B
M	7.28	5.17	8.22	5.78
Mdn	7.00	5.50	9.00	5.50
Mod	6.00	7.00	9.00	multiple
SD	3.06	2.46	2.76	2.21
t-value	2.28		2.94	
p-value	.029*		.006**	
d	0.77		0.98	

Note: p-values Marked with * are Statistically Significant (α = .05), p-values Marked with ** are Strongly Statistically Significant (α = .01), t-value = Statistics of T-test for Independent Samples; d = Cohen's measure of sample effect size for comparing two sample means (> 0.80 means high, 0.50 - 0.80 means middle effect).

Discussion

In the context of our first research question (i.e., determining the focus and quality of the lessons), our expectation that most of the current lessons are technically focused was confirmed. Thus, other subjects cannot benefit from this type of teaching. The lack of appropriate lessons is associated with the technological barrier, as lecturers from nontechnical disciplines are usually further away from technology. From a practical point of view, the quality of existing lessons is good. Students can solve problems successfully and find them both enjoyable and valuable. As an essential observation from the analysis of the existing aids, it is necessary to mention their actual content. The current lessons are more motivational in their aim to introduce students to 3D printing technology, and the objective is usually only to teach students the printing process. For this purpose, objects from everyday life, keyrings, cubes, etc., are typically used.

We also tried to find out the specific reasons students enjoy 3D printing. The answers show that students find this type of lesson attractive because it refreshes the class due to the unique content, lessons' practicality, and the student's good relationship with information technology and desire to learn new things (Figure 14).

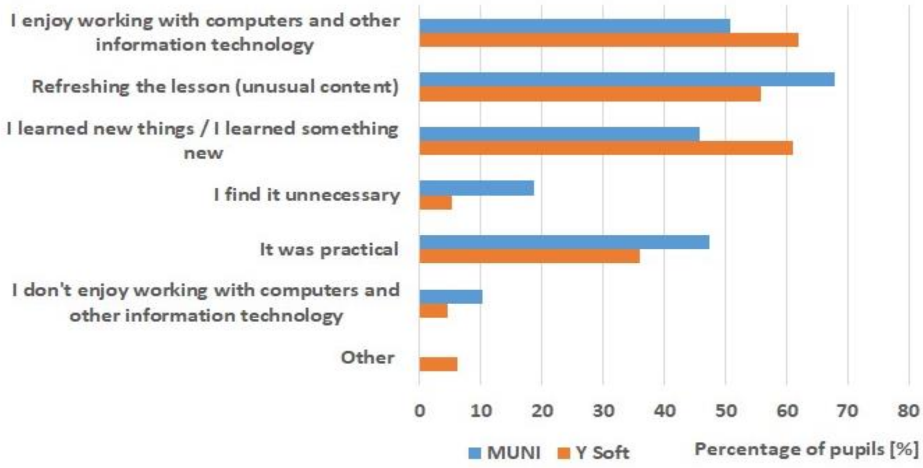

Figure 14. Evaluation of the Question What Pupils Enjoy About 3D Printing

In addition to the questionnaire survey, we analyzed existing lessons. It turned out that over 80% of the available lessons are related to technical subjects in terms of content (Figure 15). In most cases, there is a complete lack of relevance to the other subjects taught in the classes for the selected age group. Thus, this approach does not exploit the full potential that 3D printing can bring to the classroom, i.e., in addition to acquiring the skill of printing, the student also acquires selected domain knowledge. Later chapters address this issue more, discussing how to design lessons to obtain this benefit properly.

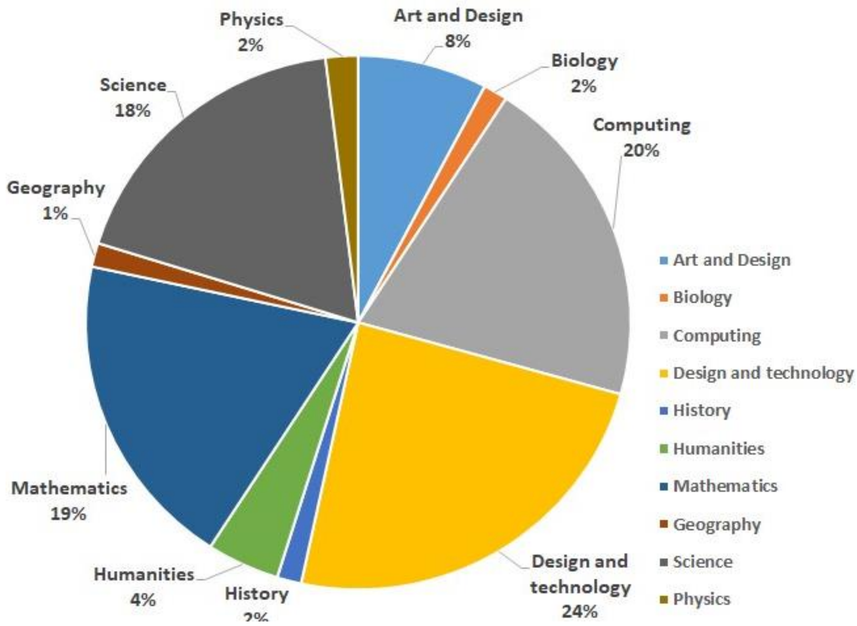

Figure 15. Assessment of the Focus of YSoft Lessons

For the second research question, we were interested in how students perceive 3D printing in the classroom. The results demonstrate a high level of student acceptance of this technology. Even without prior knowledge, students can handle more complicated tasks and find them fun but also beneficial. The most common problems were technical difficulties and unfamiliarity with modelling software. We do not consider this a problem because these are exactly the things to be learned in this lesson. In the context of justifying fun, students most often mentioned the practicality of the tasks, thus refreshing the lesson, gaining new knowledge, and having a positive attitude toward technology.

The third research question asked whether we can afford to expose students to more complex lessons with significant pedagogical benefits. Thus, part of our questionnaire investigation included evaluating the lessons we had already developed according to our multidisciplinary approach. We want to emphasize one significant finding: these more complex and challenging lessons did not negatively affect students' ability to complete them or affect their positive perceptions of them (Figure 2, Table 2, and Table 3). Compared to existing lessons, they achieved comparable results.

Thus, we can afford to increase the difficulty of the lessons for a more significant pedagogical impact without decreasing students' positive perceptions.

The first experiment showed us an explicit positive acceptance by the students. We will now address whether this technology benefits teachers and allows them to educate children in nontechnical areas more effectively. In the second experiment, our primary focus is on the pedagogical impact of lessons using this technology.

The task where students drew the shapes of individual bacteria - diplococcus, streptococcus, staphylococcus, spirochete, and bacillus showed the most significant difference in the control and experimental classes' results. The maximum number of points pupils could obtain for this task was 5. In the pretest, more than half of the pupils from classes did not receive even one point (in 6.A 72%, in 6.B 94%). The highest number of points, only two, was obtained by a single pupil in 6.A. Pupils who were taught with the help of 3D models of bacteria achieved significant differences in points compared to pupils in the control group who had only 2D aids (pictures in the presentation). 89% of the pupils in the experimental class scored 3 points or more, while only 17% of the pupils in the control class scored three points or less, and almost half of the pupils (44%) did not score a single point. In contrast, only two experimental class pupils scored two or fewer points. The results were similar in the task where pupils were asked to write names for each structure and organelle of the paramecium. Again, in the classroom where instruction was given using 3D paramecium models, pupils achieved significant differences in the scores obtained between the pretest and posttest (five or more points out of 9 were obtained by 67% of pupils, while 100% had zero points in the pretest). In the classroom without 3D models, 44% of students scored five or more points, with the most frequent scoring only two points, while in the classroom with 3D models, the most frequent scoring was 7 points. Our experimental evaluation of 3D tools confirms that models in the classroom have many advantages. They greatly help spatially visualize structures not able to observe natural objects with the naked eye or represent hard-to-reach real products of nature. Using educational models and spatial visualization of objects is undoubtedly desirable and beneficial. Assume that the teaching is carried out according to the designed lesson, and the students participate in the actual process of making the models, which 3D printing makes accessible. In that case, the improvement in spatial visualization will be even more significant, in addition to developing their other skills.

In the next section, we will discuss recommendations for lesson design to maximize the pedagogical impact. To better demonstrate the concept, we will present one selected lesson that has already been created in detail and then formulate our recommendations. Here, in addition to the technical component, we will discuss the possibilities of integrating 3D printing into the curriculum, as this is proving to be one of the major challenges. We illustrate our recommendations on a selected use case (the Czech school system), where we discuss real problems we have encountered.

Complete Lesson Under the Microscope

The lesson Under the Microscope is designed so that a typical 3D printing user can work with it, and at the same time, it can be used in teaching science or biology in lower secondary school. The essential parts of the lesson preparation are objectives, compliance with curriculum documents, lesson plan, presentation, worksheet, etc.; others are methodological supports facilitating the users to print the model (e.g., instructional videos, model overview).

The lesson is introduced with a brief annotation, followed by the specific subjects and grades in which it can be used. The correctly formulated learning objectives are essential, i.e., what the student should be able to do after completing the lesson. In addition, the time commitment of the lesson, the equipment requirements, and the knowledge (knowledge, understanding, and skills) that pupils should have before they start working on the lesson (the so-called input knowledge) are also specified. These passages present the practical aspects of the feasibility of each lesson.

Methodological support is also essential to guide them through each model's preparation and printing process. For this reason, the lessons include instructional videos, demonstrations of models with printing times, detailed printing and printer setup instructions, step-by-step instructions, worksheets for students, presentations with lesson content, and additional instructions. Everything must go through a technical inspection and testing of the delivered documents, including the control print of the model on a 3D printer and subsequent corrections. For the interactive part of the lesson, it is necessary to create renderings, graphics, and professional photography or video recording of the printed model. Also, a sample lesson should be designed. It should consist of a video recording of 3D printing and a recording of systems on the screen. The student will receive step-by-step instructions on creating a model in a 3D modeling tool.

The lesson Under the Microscope (see Be3D Academy, n.d.-a) focuses on the structure and importance of bacteria (Figure 16). The lesson begins with an introduction to bacteria and their importance. A presentation is made for this part with all the necessary information. Then, the students should observe the structure of the bacteria themselves under a microscope. For this purpose, it is recommended to obtain a slide of Streptococcus lactis. If direct observation is not possible, the bacterium can at least be observed indirectly - in a picture. This stage is critical. The students must form a correct idea about the structure of the bacteria and, at the same time, take notes based on which they will then design and model the bacterial model in 3D software. The lesson provides two options for the design of the 3D model. The simpler option is for those who are not yet familiar with printing technology or are just starting. These users can use the pre-modelled components (Figure 17), which they easily join together in the appropriate software. The pre-made components can also be used by a teacher who wants to print a 3D model of a bacterium as a teaching aid for his/her class. In the more complex version, the students model the individual components themselves and then print the whole model.

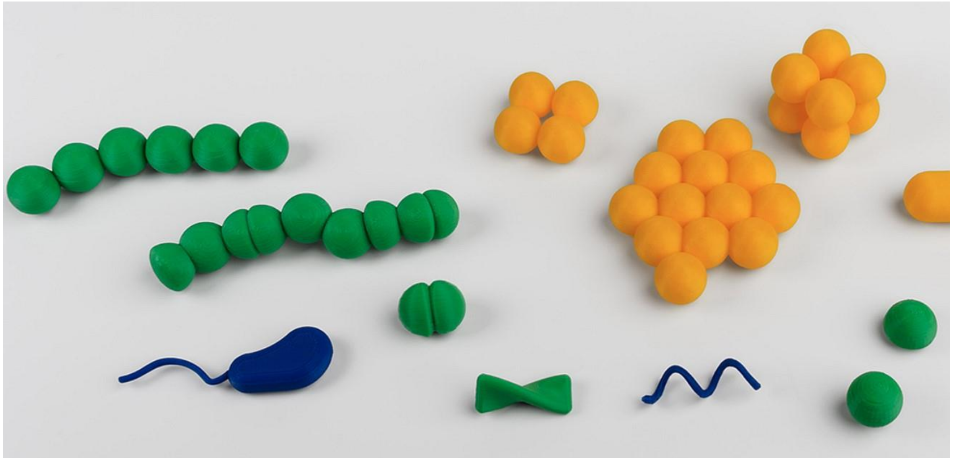

Figure 16. Lesson Under the Microscope – 3D Prints

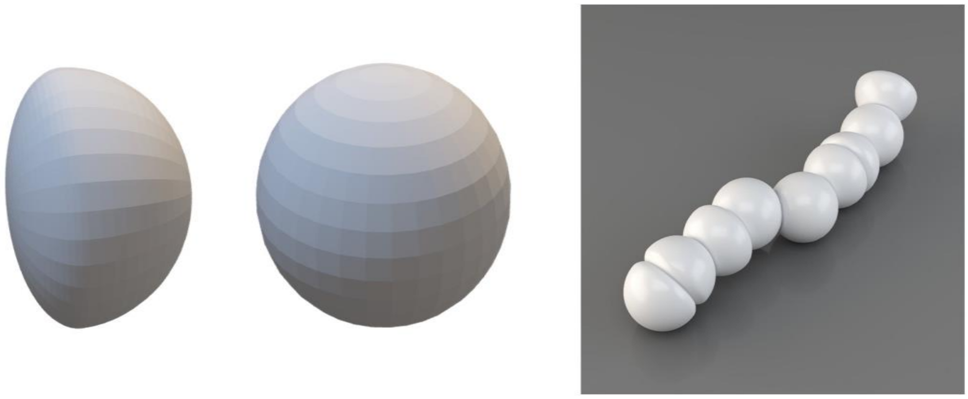

Figure 17. Lesson Under the Microscope – 3D Models

The proposed lesson's didactic benefit lies in the pupils' involvement in creating the model. They will need their notes to create the model. In doing so, they will review the technical knowledge of the structure of bacteria. Furthermore, they will develop their digital competencies and learn to work with the necessary software. Skills such as 3D modelling and printing the model can also be used in their everyday life. The manipulation of the finished model will support the formation of correct ideas about the structure of bacteria and the memorization of technical knowledge about the structure.

Recommendations for Lesson Creation and Use

Based on our experience from the lessons created so far, we have formulated several recommendations for lesson creation. Lessons should not be created on their own but concerning specific educational content. It is the interconnection of the above-presented lesson with the specific curriculum (the Framework Educational Programmes in the Czech Republic) that is unique in the context of other lessons and provides support for teachers who would like to either implement these lessons directly with pupils or just print out the models and use them as teaching aids. It is also useful to design the lessons to allow the choice of different difficulty levels, thus diversifying the educational content for basic and advanced users and lower secondary and secondary schools (grammar schools). This recommendation directly responds to the heterogeneity of the range of users and the heterogeneity of pupils in school classes. We manifested this recommendation in the form of two different lesson versions. The simpler of the two works with pre-modelled components, while the more complex version assumes that users will model the components according to the instructions. Since 3D printing technology is based on engineering sciences, it is appropriate to use this to design interdisciplinary lessons. In such lessons, the conveyance of technical content (e.g., constructing a bacterial model) is accomplished using resources from other sciences (e.g., engineering or aesthetics). If such lessons were integrated into the curriculum, students would gain disciplinary knowledge while developing their skills. It is time-consuming to create a model using 3D printing technology, from its preparation (modelling) to printing and post-processing. Many of the tutorials available on the internet need to be more accurate or contain errors. Therefore, it is essential to share partial successes with other 3D printing users and, above all, make them available to teachers interested in making educational models.

CaseStudy: The Czech Republic - Integration Into the Curriculum

The lesson described above, along with others, was designed directly to specific curriculum documents, specifically from the Czech Republic, represented by the Framework Educational Programme for Elementary Education (for primary schools) and the Framework Educational Programme for Secondary General Education (for grammar schools). In the Czech Republic, a revision of the curriculum took place last year (2021), which, on the one hand, reduced the curriculum of some subjects and, on the other hand, strengthened the curriculum of Informatics and promoted the development of digital competencies. In practice, this means fewer hours for science (Biology, Geography, Physics, and Chemistry), humanities (History, Civics), and arts (Art Education, Music Education) and more hours for Informatics. Therefore, teachers must look for ways to implement these changes in their teaching. One possibility is integrating the educational content of the different disciplines (subjects) into teaching blocks. Interdisciplinary lessons using 3D printing technology can serve as a source of inspiration for teachers. The professional content will help students develop skills (modelling, creating a model from pre-prepared components, printing on a 3D printer, and post-processing) that they can apply in their everyday lives or career choices.

Conclusion

In this article, we present the results of research that evaluated the pedagogical impact of 3D printing in the classroom. First, we evaluated the quality of existing materials that are publicly available. Most materials focus on technical subjects and aim only to teach a given technology. The relationship to other subject content taught in classes for a given age group is often completely missing. Thus, the potential to allow the student to acquire selected domain knowledge (e.g., using the potential of spatial visualization of structures) in addition to the acquired printing skills is not fully utilized. To address this problem, we suggest creating more complex multidisciplinary lessons. We then presented our concept through one biology lesson developed in such a manner.

Next, we presented the results of two experiments demonstrating high student acceptance of 3D technology and positive impacts on student performance. In the first experiment, we included newly created multidisciplinary lessons in addition to the existing basic lessons. We show that these more difficult lessons have no negative impact on adoption, and students mastered these more difficult lessons without much difficulty. In the second experiment, we looked at the pedagogical impact of the lessons. We used a selected biology lesson to show the statistically significant positive impact of 3D models on mastering the content of a lesson.

Finally, we addressed the issue of incorporating 3D printing into the curriculum. Based on the presented results, we are convinced that the interdisciplinary focus of lessons can be a way to implement new technologies in teaching specialized subjects in the long term while reflecting the transformation of the curriculum. Comprehensive multidisciplinary lessons, developed according to our concept, can also be a suitable way to deal with, e.g., the lack of teaching hours.

Recommendations

If a teacher uses 3D models in teaching, he/she should prefer scientifically correct and ideally verified in the classroom. The lessons presented are intended to facilitate the teacher's lesson preparation, but it is always necessary to consider the teacher's inventiveness, adapting the lesson to the specific learning objectives. Implementing teaching lessons is also often more time-consuming, and it is ideal to implement them in teaching blocks (at least two hours).

The models printed using 3D printing technology are also helpful in teaching at universities. University students should also be involved in their design and creation. In the future, integrative content should be incorporated into the curriculum of all schools, e.g. through integrated learning blocks or elective subjects.

Limitations

Schools focused on general education development (elementary and middle schools) participated in the research; technical schools were intentionally not included in the research because we wanted to see how 3D printing technology is integrated into education in non-STEM subjects. Also, the second experiment was conducted in only one primary school due to time and technical constraints.

Ethics Statements

The studies involving human participants were reviewed and approved by the directors of schools. The participants provided their informed consent to participate in this study.

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Authorship Contribution Statement

Malinka: Supervision, concept and design, drafting manuscript. Vodová: Concept and design, drafting manuscript. Jančová: Data analysis / interpretation, statistical analysis, technical support. Sobková: Data acquisition. Schindler: Data acquisition, technical support.

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