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*Article*

# Evidence-Based Optimization of Classroom Teaching Units Using 3D Printers for Designing Models—From the 2D Picture to the 3D Flower Model

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**Abstract:** The implementation of digital tools into science education is a major demand of various stakeholders, such as teachers, schools and ministries of education. However, teaching innovations and the introduction of new competences need to be carefully tested and optimized for successful and sustainable application and learning success. Our aim was to develop and establish an easily adaptable teaching unit comprising the aspects of 3D printing from computer-aided modeling to slicing, printing and post-processing, which is linked to curricular learning content. The original teaching concept developed with a small group of students has been adapted to the conditions in large groups and full-size 9th grade school classes. With an increased sample size, it was now possible to investigate and analyze the teaching approach with respect to student's motivation, learning success as well as the quality and acceptance of the teaching–learning arrangement for designing and 3D printing flower models. The goal of the study was to further optimize the existing teaching tool based on the evaluation of the student experience. While the exploration of this teaching approach ties into the current discourse of innovative biology teaching, the efficacy is evidenced by results that indicate a positive impact on student's motivation and a high learning success regarding computer-aided modeling and 3D printing. As a result, the teaching-revised concept reported in this article is based on the students' evaluation and can be provided as well-tested teaching material for schools.

**Keywords:** design-based research; 3D printing; floral models; computer-aided modeling



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## 1. Introduction

The fact that digital and modern technologies are becoming more and more important in the classroom was not only demonstrated by the COVID-19 pandemic. Digitization has been advancing rapidly for decades, and digital skills are becoming increasingly relevant [1], including in the vocational sector [2–5]. In Germany, a lack of digitization in schools has been recognized and countermeasures have been taken, for example, as part of the "Digitalpakt Schule" (Digital Pact for Schools).

Technologies that have long been established in the private and professional sectors are often only used in school settings years later and initially by a few skilled and dedicated teachers [6]. These technologies include computer-aided modeling and 3D printing. Despite their high potential for teaching [7], these technologies are only gradually finding their way into schools [8].

Implementation research provides the reasons for this: Research has shown that innovations in education are only sustainable if they promise a high level of learning success and generate acceptance and motivation among students [9]. In addition, teachers need to consider themselves competent enough to implement these teaching innovations [10,11].

A well-known problem of teaching–learning research in the implementation of educational innovations is the theory–practice problem [12]. It describes the difficulty of transferring educational theory knowledge into instructional practice concepts. This also applies for computer-aided modeling and 3D printing as an innovation in (biology) teaching. The presented project overcomes this problem by developing, testing and providing data-based teaching materials.

Since 2017, the project "Blühende Fantasie—3D-Druck von Blütenmodellen" (Flowering Fantasy—3D printing of flower models) of the Institute of Botany at Leibniz Universität Hannover continuously promotes the introduction of 3D printing and computer-aided modeling into the school classroom. To achieve this goal, scientifically tested teaching materials that are accepted and perceived as motivating by the students are needed. For this purpose, a teaching concept for modeling and 3D printing flower models (Figure 1) with students was developed and piloted in schools [13]. This was followed by a phase of scientific investigation in 9th grade school classes and optimization based on the accompanying surveys. The project thus ties in not only with the data-based discourse on innovative teaching approaches but also with current political efforts and ultimately with the requirements of the labor market.

(**a**) (**b**)

**Figure 1.** Student model of (**a**) *Arabidopsis thaliana*; (**b**) *Erodium cicutarium*. Source: Marcel Bonorden.

In contrast to publications from the pilot phase, the research interest is now on the survey of students' experiences on motivation, learning success as well as quality and acceptance. Based on these data, the teaching concept is revised. The following research questions were relevant for this:

1. How does the use of 3D printing in biology classes affect the motivation and self-assessment of learning success?
2. What kind of structural adjustments were successful for optimization of the teaching concept based on student evaluation data to improve the learning outcomes?

## 2. State of the Art

Since the first patenting of the stereolithography process in 1984 [14], there have been numerous innovations based on it in the field of additive manufacturing. Although there have always been early adopters of these technologies in education [15,16], these were initially limited to university education in the fields of architecture and engineering [17,18]. With the expiration of many 3D printing patents in the recent years, the technologies became affordable for home users. The expiration of patents for the fused-deposition modeling process in 2009 led to a growing open source community and increasingly established this technology in the general population [19], advancing to the most used 3D printing process in the private sector. This also enabled the use of 3D printing in schools, where the technology is mainly used to teach students about 3D printing in technical subjects, as a supporting technology during teaching, and to produce artifacts that aid learning [15]. Three-dimensional (3D) printing requires the objects to be created in advance using computer-aided modeling.

Educational research indicates a positive impact of 3D printed models on student engagement [20] and content performance [21,22]. In addition, existing projects link computer-aided modeling and 3D printing in the classroom to teach learning content [23]. Research continues to suggest that the use of these two technologies can lead to higher learning outcomes than traditional teaching methods [24]. Other studies suggest the promotion of creativity [25,26] as well as skills in (product) design [14,27,28].

Although the research results are promising and several school and research projects on 3D printing in education exist, the implementation in the classroom is still in its infancy. Thus, there remains a particular need for teaching materials that enable teachers to integrate the technology into the classroom [14]. For this, curricula have already been developed in the field of technology education in schools or engineering courses in universities [29,30]. However, there is a lack of teaching materials in general and especially in other subject areas, for example in biology.

## 3. Theoretical Framework

### *3.1. Didactic Conception*

- Model competence and learning from models

  Models are essential for science education [31]. Modeling and model competence thus represent a part of basic science education and are important for understanding science [32]. In science education, learning with models and modeling are assumed to enhance cognitive, metacognitive, social, and epistemological skills and thus can increase learning success [33–35]. Therefore, working with models is one of the basic methods in biology to better understand complex phenomena and encourage deep thinking, at least in the German school system [36]. The development of the teaching concept is based on the assumption that students engage much more intensively with the learning content during independent modeling than with conventional models. This is because students need to first think through model design as a foundation before actually designing the model [31]. Here, a reduction in the original to the essential features takes place, for which an intensive technical examination of the object to be modeled is necessary [31]. Of extraordinary importance is a model criticism, in which the reductions and extensions are discussed in comparison to the original, thus deepening model understanding and model competence [37].

- Motivation

  The teaching concept is based on the fundamental pedagogical insights of the self-determination theory of motivation [38]. This states that autonomous, self-determined work can increase the extrinsic as well as intrinsic motivation of students.

- Problem orientation

  The problem-oriented learning approach combines instructional with constructivist aspects [39]. In constructivism, it is assumed that knowledge cannot be directly passed from one person to another, but it has to be acquired independently and actively in a context of action [40]. In problem-based learning, the learning process is understood as an active and self-directed process, which, however, can be stimulated and supported by the teacher who takes on a moderating and advising function [41].

### *3.2. Research Approaches*

The investigation and optimization of the teaching concept for computer-aided modeling and 3D printing in the classroom is based on various research approaches, which are briefly described here.

- Design-Based Research (DBR)

  Characteristic for research with DBR is the iterative approach, in which design, implementation, analysis and re-design alternate iteratively [42]. A wide variety of methods can be combined, for example, quantitative methods such as closed-ended questionnaires and qualitative methods such as interviews. The goal of DBR in teaching–learning research is to design practical learning environments for schools and to incorporate the findings into the review and further development of existing learning theories [43]. Thus, the DBR approach links application-oriented, theory-based, and epistemology-oriented research [44,45].

- Field research

  In field research, researchers integrate themselves into the research field in order to avoid influencing it when collecting data [46]. In the case of this project, the researcher has taken on the role of a teacher, teaching the subject matter to the students.

- Experimental research

  Experimental research investigates how, in a controlled setting, a change in the learning environment affects learning [47].

## 4. Materials and Methods

### 4.1. Project Description

In 2017, the project to implement computer-aided modeling and 3D printing of floral models in the classroom started as a small school-based working group. The teaching concept was successfully piloted in a theoretical BSc thesis [48] and then further developed in an MSc thesis based on first practical experiences with students [49]. The working group concept was further adapted to three different schools and afterwards again optimized [50]. Here, the focus of the study was particularly on increasing botanical expertise as well as improved practical feasibility in heterogeneous, larger learning groups. After subsequent adaptations, the concept for innovative biology teaching was transferred to regular school lessons for the first time in 2020 [13] and repeated in three iterative cycles since then. After each iteration, the investigation results as well as practical experiences from the implementation served to further develop the teaching concept. For this purpose, all project lessons are conducted by the classroom teacher and the researcher to ensure optimal coverage of the observation of both perspectives.

The objective of the project is to develop the teaching concept to such an extent and to equip it with detailed accompanying materials (worksheets, help for teachers, explanatory videos, etc.) that it can be carried out by regular teachers themselves after a short training session. In this way, the concept should help to ensure that computer-aided modeling and 3D printing are implemented in the classroom in the long term.

### 4.2. Description of the Learning Groups

In all three learning groups, the project lessons took place in the natural science profile lessons of a 9th grade class.

The first learning group was the largest class participating in the project with 31 students. The age range varied from 14 to 18 years. The implementation of the project with this group was affected by COVID-19-related homeschooling in fall and winter 2020. Alternating weekly, one-half of the class stayed home at a time and had to attend classes from there. Numerous support materials such as videos and illustrated instructions were designed to assist them. Starting in November 2020, the project had to be suspended for several months due to the COVID-19-related interruption of the classroom teaching.

In the second group, 27 students participated in the project. The age varied here from 13 to 15 years. Some of the students in this group had prior knowledge of computer-aided modeling and were particularly quick to learn the software. The second learning group was not affected by COVID-19-related class interruptions, so that the project could be carried out for the first time without disrupting the schedule. Here, the project took place from September 2021 to the end of January 2022.

The third group comprised 16 students aged 14 to 16 years. The group was comparatively small because only about half of the class chose a natural science profile. The project period was from February 2022 to the end of April 2022.

### *4.3. Realization of the Lessons*

Although many partial aspects have been modified during the three iterative cycles [13], the basic course of action of the teaching concept has remained the same (Figure 2).

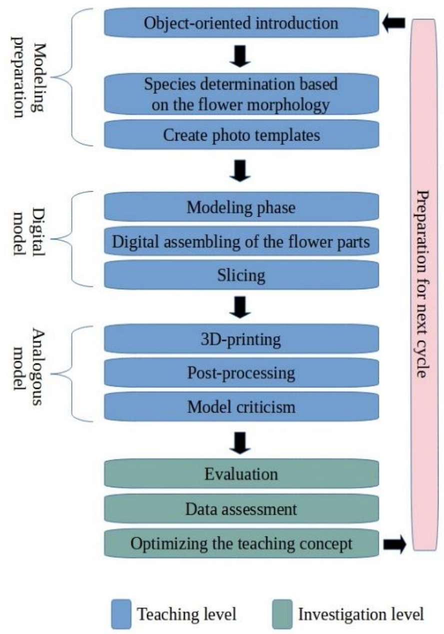


**Figure 2.** The process of the project at the teaching level can be divided according to the different modeling stages (preparation, digital and analogous model). The subsequent investigation serves as a basis for the preparation of the next iteration.

At the beginning, an object-oriented introduction takes place, in which the students get to know the 3D printer and the modeling software Blender. Afterwards, real flowers are used to determine the plant species based on an identification key. Visual material, such as photos using magnifying lenses, is produced. In the following lessons, the flower organs are modeled in groups using the photos and then assembled into a complete digital flower. Finally, the flower models are printed and are post-processed, which is followed by a unit on model criticism. In total, the concept for the project lessons includes 10 90-min lessons (Table 1, detailed version in the supplement: Table S1, evaluation results).

**Table 1.** Contents of the lessons.

| Contents of the Lessons | | |
|---|---|---|
| **Lesson** | **Activity** | **Description** |
| 1 | Introduction Blender/3D printing | Learning the basic functions in Blender |
| 2 | Introduction Blender | Learning the basic functions in Blender |
| 3 | Introduction Blender | Learning the basic functions in Blender |
| 4 | Modeling preparation | Species determination based on the flower morphology, creating of photo templates, research about the plant species, model planning |
| 5 | Modeling phase | Modeling of the flower organs |
| 6 | Modeling phase | Modeling of the flower organs |
| 7 | Modeling phase | Modeling of the flower organs |
| 8 | Model-finishing and slicing | Assembling the flower organs to form a complete flower and converting it into a printable file format |
| 9 | Post-processing | Removal of support structures, sanding and painting |
| 10 | Model criticism | Reflection of the flower models |

The software Blender is a free open source 3D graphics suite. Beyond modeling (Figure 3), it offers functions such as rigging, animation, simulation, rendering, compositing, motion tracking, video editing and game creation [51]. Because of Blender's large open source community, there are a variety of tutorials and learning content available. Therefore, the program offers students the opportunity to learn more features on their own in an interest-driven way after learning initial modeling skills.

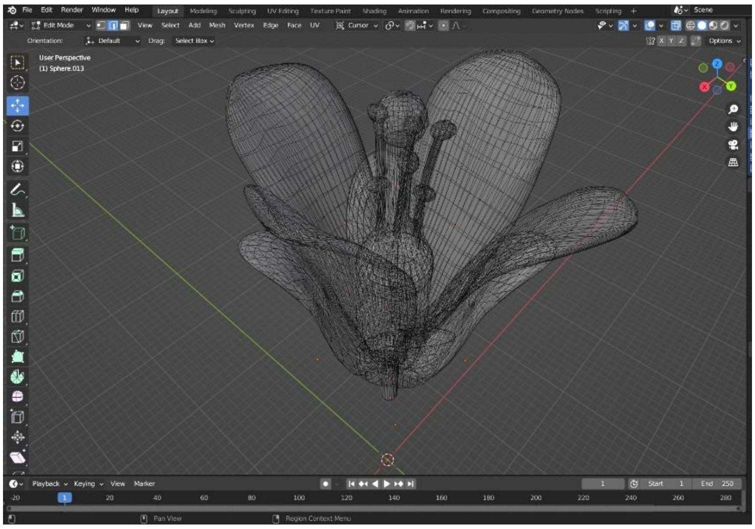

**Figure 3.** A screenshot of Blender with an *Arabidopsis thaliana* flower modeled by a student.

### 4.4. Questionnaires and Survey

Considering the iterative implementation of the project lessons in three different groups, quantitative research methods were chosen. In this way, the effect of changes to the instructional design was to be facilitated by a direct comparison of the individual items in the questionnaires. Since the instructional intervention took place in the school classroom, it was decided to use an anonymous written survey. To ensure a high response rate, the evaluation was conducted in the presence of the supervising teacher.

Several variables were relevant for the empirical testing of the instructional unit and its increasing optimization. The empirical investigation of the teaching intervention focuses on the variables learning success, motivation as well as the acceptance and quality of the teaching–learning arrangement. Due to the fact that intrinsic motivation is a significant factor in learning success [38], the Short Scale Intrinsic Motivation [52] was used to draw conclusions about this variable. To keep the scope of the evaluation practical, this time-efficient version of the Intrinsic Motivation Inventory [53] was chosen. The Short Scale Intrinsic Motivation includes a total of 12 items, with three items each assigned to four subscales (interest/enjoyment, perceived competence, perceived freedom of choice, and pressure/tension).

An additional questionnaire was used to evaluate the acceptance and quality of both the teaching–learning arrangement and the self-assessment of learning success [54]. This questionnaire was developed specifically for the evaluation of a teaching–learning arrangement for the promotion of self and social competencies and will be called evaluation in the following for simplicity. This questionnaire includes 14 questions per teaching–learning arrangement. In this research, the items of the original questionnaire were adapted to specifically query the use of computer-aided modeling and 3D printing. Since this was a single teaching–learning arrangement, the items were transferred to the different phases of the teaching intervention (introduction, modeling, 3D printing) as well as to the accompanying material. Ultimately, 10 items were queried in the "Introduction" area, 12 items in the "Modeling" area, 10 items in the "3D printing" area, and 7 items in the "Material" area.

### 4.5. Methods of Evaluation

The data from the questionnaires were transferred to a table in the form of their Likert scale scores. Subsequently, an average value and the standard deviation were determined for each item. The average scores of the items from the questionnaire evaluating the acceptance and quality of the teaching–learning arrangement and the self-assessment of learning success were interpreted individually. The values of the Short Scale Intrinsic Motivation were first interpreted in summary according to the areas of interest/enjoyment, perceived competence, perceived freedom of choice, and pressure/stress. In the case of particularly meaningful results, individual items were additionally evaluated.

The results of the different iterations were compared using an ANOVA (InfoStat) test and then linked to the changes in the teaching concept.

## 5. Results

The results include all three iterations of the project lessons. The project lessons were carried out in succession in three different school classes and further optimized after each iteration. During the project, the students made image templates from real flowers, which were used to model the flower in the software Blender and then were 3D printed. By using two questionnaires, the students self-assessed their learning success, evaluated their motivation as well as the acceptance and quality of the teaching–learning arrangement.

A uniform four-point Likert Scale (3: "agree"; 2: "rather agree"; 1: "rather disagree"; 0: "disagree") was used for both questionnaires. A neutral item was intentionally omitted, as it has been shown that selecting this item is used to end the survey as quickly as possible without answering the question in detail [55].

### 5.1. Results from Project Run 1

The first investigation resulted in a sample size of n = 29 because two of the 31 participating students were absent on the day of the evaluation. Only the most meaningful results used for the optimization of the teaching concept are presented here. A file with all results can be found in the (supplement Table S2, evaluation results).

In the evaluation, the various items in the areas of introduction, modeling and 3D printing are assigned either to acceptance and quality of the teaching–learning arrangement or self-assessment of learning success.

The introductory lessons on the program Blender tended to be perceived as boring (1.72; s = 0.65; rather agree). It was also stated that the exercises performed during the introduction were not very motivating (1.07; s = 0.7; rather disagree). The agreement value for the aspect whether modeling in the program Blender was boring was in the middle range (1.46; s = 0.88; rather disagree).

With regard to the quality of the teaching–learning arrangement, the level of difficulty of the teaching unit was in focus. The exercises during the introduction were rated as not particularly difficult (1.21; s = 0.86; rather disagree). The students rather agreed having difficulties during modeling with respect to operating with individual tools in Blender (1.8; s = 0.82; rather agree) and creating a model from an image template (1.68; s = 0.95; rather agree).

Since the effectiveness of the teaching concept with regard to the increase in botanical knowledge has already been confirmed by initial studies [13], the focus of this project was on learning success in computer-aided modeling and 3D printing. Here, the students indicated that they had learned "something about Blender" during the introduction (2.17; s = 0.66; rather agree), "something about computer-aided modeling" during the modeling phase (2.08; s = 0.69; rather agree) and signaled that they were better able to use Blender after the lesson than before (2; s = 0.87; rather agree). For 3D printing, the students stated that they had learned "something about 3D printing" (1.83; s = 0.82; rather agree) and rather disagreed on being better able to use a 3D printer after the lesson (1.43; s = 1.08; rather disagree) (Figure 4).

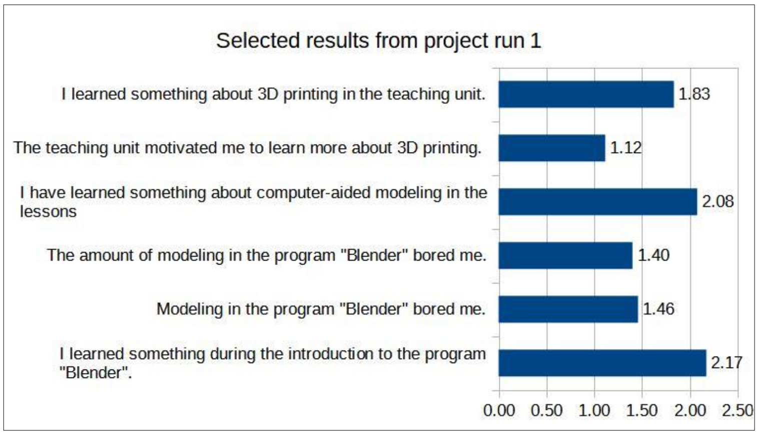


**Figure 4.** Evaluation results that were relevant for the optimization of the teaching concept after the first project run. The data of the graph correspond to the average values on the Likert scale of the class for the respective item.

The Short Scale Intrinsic Motivation aimed to draw conclusions about the students' motivation. In the area of interest/enjoyment, the questions whether the students enjoyed the activity in the lesson (1.69; s = 0.84; rather agree) and whether the activity in the lesson was interesting (1.65; s = 0.89; rather agree) are relevant.

On average, the entire group tended to be satisfied with their performance in the lessons (1.81; s = 0.69; rather agree) and rated its own modeling skills as mostly good (1.96; s = 0.6; rather agree).

Students signaled having slight concerns about completing the activity well at the beginning of the lesson (1.75; s = 0.8; rather agree). They also felt little tension during the lesson (1.09; s = 0.92; rather disagree).

### 5.2. Results from Project Run 2

For the second investigation, the sample size was n = 23 because four of the 27 participating students were absent on the day of the study. The introduction to the program Blender (1.2; s = 0.96; rather disagree) and the modeling phase with Blender were not perceived as boring (0.64; s = 0.7; rather disagree). In addition, the collaboration in groups (2.2; s = 0.96; rather agree) and the fact that the model was printed at the end (2.36; s = 0.91; rather agree) were described as motivating.

The exercises for the introduction (0.6; s = 0.76; rather disagree) and the operation of Blender with regard to the functions (0.96; s = 1.02; rather disagree) were perceived as easy.

During the evaluation, students strongly agreed that they learned "something about Blender" (2.48; s = 0.82; agree) during the introduction and about computer-aided modeling (2.44; s = 0.65; rather agree) during the modeling phase. In addition, the majority of them were better able to use the software Blender after the lesson than before (2.36; s = 1.04; rather agree). The group indicated a strong agreement with the statements about having learned "something about 3D printing" (2.52; s = 0.82; agree) and being able to handle a 3D printer better than before the lesson (2.48; s = 0.87; rather agree) (Figure 5).

In the area of interest/enjoyment, the Short Scale Intrinsic Motivation revealed high levels of agreement with the statements that the students enjoyed the activity in the teaching unit (2.35; s = 0.78; rather agree), and they perceived it as entertaining (2.29; s = 0.95; rather agree). Overall, the group was satisfied with its performance in the lesson (2.29; s = 0.95; rather agree), and believed they did well in the activity (2.08; s = 0.72; rather agree). The perceived freedom of choice was also relatively high: the statements that the activity in the lesson could be controlled by the students themselves (2; s = 0.83; rather agree) and that the approach in the lesson could be chosen by the students themselves (2.13; s = 0.95; rather agree) are largely agreed with. The students in the group felt little pressure (0.79; s = 0.93; rather disagree) and tense (0.7; s = 0.93; rather disagree).

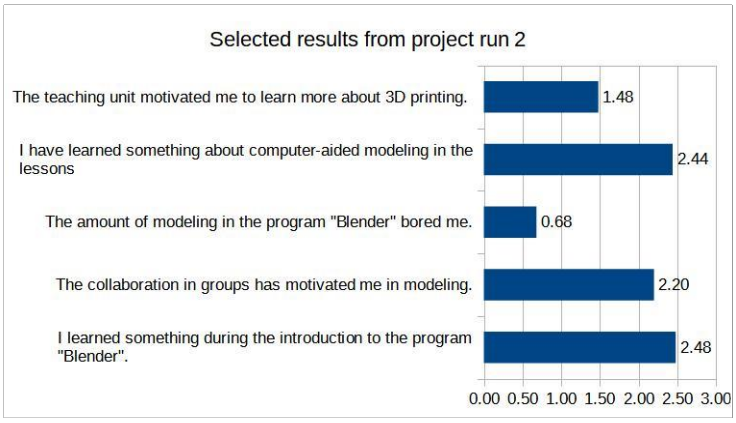


**Figure 5.** Evaluation results that were relevant for the assessment of the changes made after the previous run and the further optimization of the teaching concept after the second project run. The data of the graph correspond to the average values on the Likert scale of the class for the respective item.

### *5.3. Results from Project Run 3*

The third study had the smallest sample size with n = 14 due to the fact that only half of the class participated in the natural science profile lessons. Two of the 16 participating students were absent on the day of the study. The introductory lessons on the program Blender were not perceived as boring (1.07; s = 0.62; rather disagree) but the introduction (1.43; s = 1.22; rather disagree) and the modeling later in the lessons (1.29; s = 1.14; rather disagree) rather did not motivate the students to learn more about Blender. The students, on the other hand, found the collaboration in groups to be particularly motivating (2.64; s = 0.5; agree).

The extent of the exercises carried out during the introduction (1.07; s = 0.62; rather disagree) as well as the extent of the later modeling phase (1.07; s = 1; rather disagree) was not perceived as too high and boring. The introductory exercises were rated as easy (0.36; s = 0.63; disagree). Similarly, the level of difficulty regarding the operation of the functions in Blender (0.43; s = 0.65; rather disagree) was perceived as low.

In the most recent survey, the group indicated strong agreement with the statement that they learned "something about Blender" (2.64; s = 0.5; agree) and about computer-aided modeling. They further stated that they were now better able to model with Blender in an out-of-school session (2.71; s = 0.73; agree). The group clearly agreed with the statements that they had learned "something about 3D printing" in the lesson (2.71; s = 0.47; agree) and that they could handle a 3D printer better than before the lesson (2.86; s = 0.36; agree) (Figure 6).

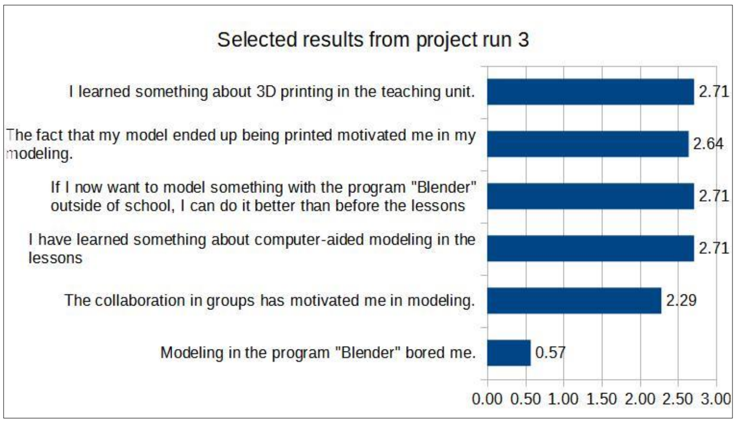


**Figure 6.** Evaluation results that were relevant for the assessment of the changes made after the previous run and the further optimization of the teaching concept after the third project run. The data of the graph correspond to the average values on the Likert scale of the class for the respective item.

In the area of interest/enjoyment, the Short Scale Intrinsic Motivation indicates that the activity in the teaching unit tended to be enjoyable (2.07; s = 1.07; rather agree) and interesting (1.93; s = 1; rather agree). The group was satisfied overall with their performance in the instructional unit (2.5; s = 0.65, agree) and stated that they had done well in the activity (2.14; s = 0.86; rather agree). The group highly agreed with the statements that they were able to direct the activity in the lessons (2.14; s = 0.95; rather agree) and they were able to choose how to perform the activity in the lesson (2.71; s = 0.47; agree).

### 5.4. Comparison of the Studies

Since conclusions for the optimization of the teaching concept are drawn from the evaluation results of the individual investigations, a direct comparison of selected items is indicated at this point. In the area of acceptance of the teaching–learning arrangement, modeling with the program Blender was rated as much more boring ($p = 0.0004$) by the first group (1.46; s = 0.88; rather disagree) than the second (0.64; s = 0.7; rather disagree) and the third group (0.57; s = 0.65; rather disagree).

During the introduction, the first group (1.21; s = 0.86; rather disagree) reported having experienced more difficulties ($p = 0.0018$) compared to the second (0.6; s = 0.76; rather disagree) and third groups (0.36; s = 0.63; rather disagree). While the results even for the first group still suggest a relatively moderate level of difficulty, they do indicate a tendency that is also reflected in the later modeling. For example, the first group (1.8; s = 0.82; rather agree) signaled greater difficulties ($p < 0.0001$) in modeling with the program Blender regarding the features than the second (0.96; s = 1.02; rather disagree) and third group (0.43; s = 0.65; disagree). Similarly, creating a three-dimensional model from a photograph tended to be more difficult ($p = 0.0411$) for the first group (1.68; s = 0.95; rather agree) than for the second (1.33; s = 1.01; rather disagree) and the third group (0.86; s = 0.86; rather disagree) (Figure 7).

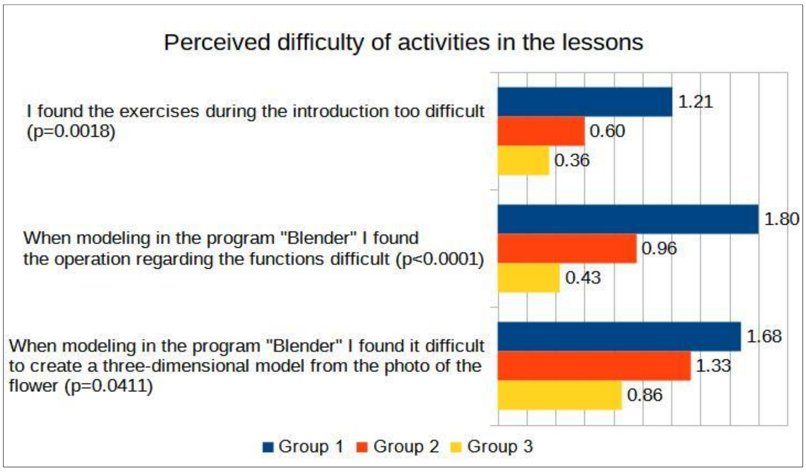


**Figure 7.** Perceived difficulty of activities in the lessons.

The items on self-assessment of learning success also show a similar tendency. For the statement of having learned "something about computer-aided modeling" during the modeling phase, students in the first group (2.08; s = 0.69; rather agree) signaled a smaller increase in knowledge than the second (2.44; s = 0.65; rather agree) and the third group (2.71; s = 0.47; agree) ($p = 0.0098$). The largest difference is in the statement of having learned "something about 3D printing". Here, the results of the second (2.52; s = 0.82; agree) and third groups (2.71; s = 0.47; agree) state a much greater ($p = 0.0011$) self-assessed increase in knowledge than in the first group (1.83; s = 0.82; rather agree) (Figure 8).

In the Short Scale Intrinsic Motivation, the agreement values of the first group in the area of interest/enjoyment are also below those of the second and third groups. However, here, the second group signaled the comparatively highest interest/enjoyment in the activity. While the first group (1.69; s = 0.84; rather agree) was least likely ($p = 0.0372$) to agree with the statement that they enjoyed the activity in the lessons, the students in the second group (2.35; s = 0.78; rather agree) rated the enjoyment in the lessons even higher than the third group (2.07; s = 1.07; rather agree). Likewise, interest in the activity in the teaching unit was rated slightly lower—but without statistical significance ($p = 0.4086$)—by the first group (1.65; s = 0.89; rather agree) than by the third (1.93; s = 1; rather agree) and the second group (2; s = 0.95; rather agree). In the area of perceived competence, the upward trend from the first to the third group can be found again. Thus, the third group (2.5; s = 0.65; agree) agreed more ($p = 0.0204$) than the second (2.29; s = 0.95; rather agree) and the first group (1.81; s = 0.69; rather agree) with the statement of being satisfied with their performance in the teaching unit. This tendency continues in the area of perceived freedom of choice. Here, the first group (1.58; s = 0.76; rather agree) signaled without statistical significance ($p = 0.0778$) being able to control the activity in the teaching unit the least compared to the second (2; s = 0.83; rather agree) and third group (2.14; s = 0.95; rather agree). A greater difference ($p = 0.0001$) between groups 1 and 3 exists in the statement that it was possible to choose how to do the activity in the teaching unit (group 1: 1.67; s = 0.78; rather agree, group 2: 2.13; s = 0.68; rather agree, group 3: 2.71; s = 0.47; agree). In the area of pressure/tension, the agreement scores of the second group (0.79; s = 0.93; rather disagree) are only slightly lower (and without statistical significance; $p = 0.1243$) than the third (1.07; s = 1.07; rather disagree) and the first group (1.32; s = 0.82; rather disagree) for the statement about having felt under pressure during the activity in the teaching unit (Figure 9).

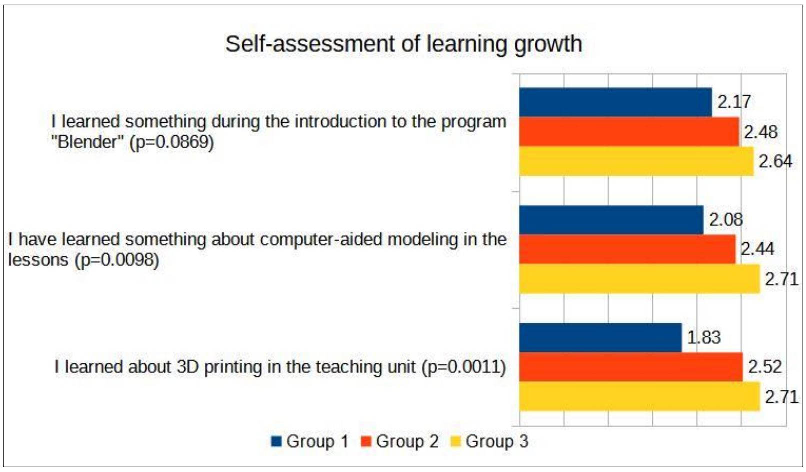


**Figure 8.** Self-assessment of learning growth.

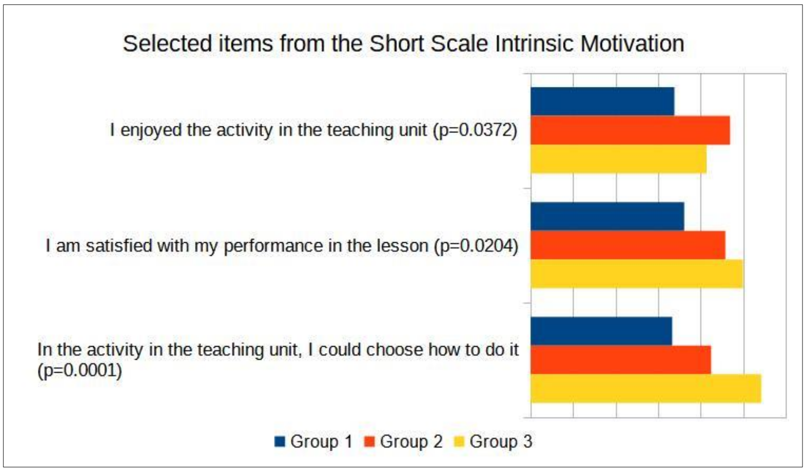


**Figure 9.** Selected items from the Short Scale Intrinsic Motivation.

## 6. Discussion

### 6.1. Discussion of the First Project Run

The optimization of the teaching concept was based on the data from the evaluation and the Short Scale Intrinsic Motivation. During the first run, the focus was initially on general feasibility, as the teaching concept had previously been tested exclusively in smaller working groups with voluntary participation. Now that the concept has been embedded in natural science profile lessons with compulsory participation, it was initially an important finding that the first group indicated that they were happy to learn about 3D printing and computer-aided modeling. This indicates a general interest of the group in this topic and forms the basic prerequisite for successful teaching.

However, this initial interest was not sustained throughout the duration of the project. The results show that there were difficulties during the introductory phase and consequently also during the later modeling. The performance during the modeling phase is thus closely linked to the introduction and mastery of the basic functions in Blender. The comparatively high level of difficulty could thus explain why the first group had relatively low agreement scores on the Short Scale Intrinsic Motivation in the interest/enjoyment domain. An optimal state of intrinsic motivation (Flow) is achieved through a "balance between perceived action capacities and perceived action opportunities" [56]. When the demands exceed the students' competencies, they feel overwhelmed. This is also consistent with the researcher's observations that problems with the basics in Blender occasionally led to frustration and distraction during free modeling. This could have led to lower results in the interest/enjoyment domain.

The self-assessment of learning success during the modeling phase is also lower than in the other groups. This supports the conclusion that after the introduction, the basic functions in Blender were not sufficiently mastered, and this led to lower learning and work progress in free modeling as well.

For these reasons, special focus was placed on the introduction in the optimization of the teaching concept. Here, more time was initially allocated to the careful elaboration of the functions (90 min more). In addition, more in-depth exercises and repetitions were designed. These were kept in the graphic style of the well-known video game Minecraft to enable a playful approach. In order to facilitate independent work and to reduce supervision effort, the formulations and explanations in the task texts were written more precisely and detailed. In addition, a backup phase, for the comparison of the intermediate status, was included.

Ultimately, a more comprehensive and thorough introduction should also lead to improving the comparatively low rated perceived freedom of choice in the Short Scale Intrinsic Motivation. Because basic functions in Blender were not adequately mastered, the group tended to be less able to develop their own approaches to modeling the floral organ, thus requiring a great deal of support.

Moreover, after the first project run, a dedicated unit on model planning was integrated into the teaching concept. Separate model planning was intended to visualize the modeling process of the entire flower from the beginning and to avoid interruptions.

Furthermore, self-assessment of learning success was low, especially in 3D printing. In order to improve knowledge of 3D printing processes and 3D printing, the teaching concept was adapted to involve the school's own 3D printer to a greater extent. This should help students learn how it operates by using the printer not only during the tutorial but also later for printing prototypes of modeled flower components.

In the first run of the project, students each modeled a flower organ, which was assembled with those of other group members to form a group model. In the evaluation, however, the students signaled that the printing of their group model at the end had not motivated them as much as had been assumed in advance. For this reason, groups 2 and 3 of the project switched from printing a particularly large group model to printing numerous small individual models (Table 2).

**Table 2.** Changes to the teaching concept between the iterations.

| Changes to the Teaching Concept between the Iterations | | |
|---|---|---|
| **After Iteration** | **Modification** | **Reason** |
| 1 | longer introduction phase (90 min more) with more in-depth exercises and repetitions | Insufficient modeling expertise throughout the project lessons |
| | More precise explanations in the exercise files | To facilitate independent work and to keep the supervision effort low |
| | backup phase for comparison of the intermediate status of the tasks | As feedback and to align the performance level |
| | Integration of a model planning unit | Students hat so interrupt their workflow during the modeling phase to plan the next work steps |
| | Greater involvement of the 3D printer | Students stated a relatively low learning-success in 3D printing |
| | Printing of small individual models instead of large group models | Students signaled that the printing of a group model did not motivate them. |
| 2 | Functions in Blender that will not be needed until later are not explained during the introduction and are instead explained as needed during the modeling phase | In order to be able to concentrate on the directly relevant functions during the introduction |
| | Increased student involvement in problem solving (students helped each other instead of the teacher intervening) | Less supervision and promotion of problem-solving skills and general competence in Blender. |
| | Printing of intermediate results | As feedback, to increase motivation and to establish an early connection between the digital and the analog model |
| 3 | Adaptation of the social form from group to partner work | As a possible adaptation to promote a group of students with high competence |

Finally, in discussing the first run, an influence of COVID-19-related teaching interruptions and alternating homeschooling on the study results must be considered. Due to the interrupted schedule, the modeling phase could only be completed after months. This likely had a negative impact on student motivation and perceived modeling competence at the time of the survey. According to observations by the teacher and the researcher, the students had slight difficulties with Blender even before homeschooling. However, this cannot be substantiated by survey data. How exactly COVID-19 affected the evaluation results overall cannot be determined from the data collected.

### *6.2. Discussion of the Second Project Run*

Since relatively large changes were made to the teaching concept after the first project run, the results of the second group were particularly important for checking the effectiveness of the adjustments.

Compared to the first group, the second group agreed significantly less with the statements that the scope of the introduction phase was boring and the exercises during the introduction were difficult. The statements about the scope of the introduction are especially interesting, because in the second project run, more time was scheduled for this phase. The second group also assessed a higher learning success during the introduction as well as the modeling phase and signaled a significantly ($p < 0.0001$) lower level of difficulty while modeling.

These results could be related to the optimization of the introduction. The more detailed introduction resulted in a better mastery of the basic functions in Blender, which lowered the difficulty level for the students. The learning success in Blender also increased, since the more comprehensive basic knowledge made it possible for the students to discover unknown functions in the program independently. This is supported by the results of the Short Scale Intrinsic Motivation, which indicate a very high perceived freedom of choice. The group needed less help with modeling and used creative approaches to modeling on their own, so the teacher's control could be reduced. Solution approaches and problems were to be discussed more intensively by the students among themselves. The students also signaled a significantly higher perceived competence in the Short Scale Intrinsic Motivation, which was necessary for this more demanding form of modeling.

Another change after the first project run was the greater involvement of the 3D printer. By printing intermediate products of the modeling process, a continuous link from the digital to the analog model could be established. It was also possible to create a better understanding of the 3D printer as well as conditions to be considered in the design, such as support structures required for printing. This is supported by the high self-assessment of learning success in the area of 3D printing.

Additionally, printing small individual models (Figure 10) instead of large group models was perceived as motivating: The second group signaled strong agreement when stating that printing their own model motivated them.

**Figure 10.** A group of students with small individual models. Source: Marcel Bonorden.

All in all, the research results of the second project run indicate a very positive effect of the adjustments to the teaching concept. The results in the area of interest/enjoyment of the Short Scale Intrinsic Motivation are high and indicate that the students enjoyed the project and had a high intrinsic motivation overall.

Functions that are not relevant until the end of the modeling phase (e.g., modifiers) have been removed from the introductory phase after the second run and will be taught only when needed (Table 2).

*6.3. Discussion of the Third Project Run*

With 16 students, the third project run was smaller than the first two groups. This allowed for more intensive supervision of the students, which, in addition to the changes in the teaching concept, could be an explanatory approach for many of the study results.

The third group stated that they had almost no difficulties at all with the introduction to the program Blender. This is also consistent with the teacher's and researcher's observations that the students mastered the program's functions very quickly. The decisive factor for this could be the more thorough supervision of the smaller group during the introduction. Thus, the third group also self-assessed their learning success during this phase to be the highest.

Due to the high observed competence after the introduction, the social form was slightly adapted (Table 2). In order to optimally support the students, the group size was reduced to two students (Figure 11). Thus, instead of only one flower organ, students had to model several at the same time, which was more challenging.

Nevertheless, the group stated that they had had the least difficulty of all the groups during the modeling with regard to the basic functions and in creating a three-dimensional model from an image template. In order to cope with the workload, the students had to develop routine procedures and techniques in their modeling, which they could then transfer to the modeling of the other flower organs. Accordingly, the third group also rated their learning success highest after the modeling phase. In particular, the self-assessment of learning success in 3D printing is very high. This may also be related to the number of project participants, as there was more time overall for each student to explore the printer.

In addition, this further confirms the positive effect of incorporating the 3D printer more into the classroom. Printing intermediate results proved to be effective, as it was only here that some students realized that they still needed to adjust their model in the file. For example, printing made it possible to check whether certain structures were thick and therefore stable enough. Accordingly, the students learned to assess the extent to which the printer can realistically implement their modeling in terms of the stability of the materials and the precision when printing.

**Figure 11.** A group of two students taking pictures. Source: Marcel Bonorden.

Printing their own model was experienced as even more motivating than in the second group, which could be attributed to the change in social form. Since the students had to model several flower organs, the identification with the overall model may be higher. This change in social form was thus found to be useful for high-performing groups.

Not only the perceived competence but also the perceived freedom of choice in the Short Scale Intrinsic Motivation were rated highest by the third group. The fact that the students were free to choose not only the procedure for modeling but also the order of the modeled flower organs might explain the high perceived freedom of choice. However, the change in social form could also be the reason for the slightly higher approval ratings in the area of pressure/tension compared to the second group, but there is no statistical significance to support this.

## 7. Conclusions

Overall, the results highlight the positive effect of a continuous optimization of the teaching concept with regard to the parameters motivation, self-assessment of learning success as well as acceptance and quality of the teaching-learning arrangement. As already described, the introduction to the program was central to the further course of instruction. The results of the study as well as lesson observations have shown that a good mastery of the basic functions leads to a higher level of independence in modeling, a higher level of competence experience and to better models. Thus, the duration of the introduction estimated in the instructional design is justified.

The findings of the third group demonstrated that the students are able to transfer their knowledge and experience from modeling one flower organ to modeling other flower organs very quickly. This suggests that they are proficient enough in modeling with Blender to have the skills necessary to model other (biological) subjects. This is a valuable skill that can be used by teachers throughout the school career to have students model learning content.

The extend of the teaching concept is in fact a major challenge. Tight curricula hardly allow implementing such extensive projects in class. However, the teaching concept is designed in such a way that it is highly adaptable. On the one hand, it allows for a lot of variability, so that it can be adapted spontaneously to the individual needs and circumstances of a class and the teacher. This was once again confirmed by the changes made at short notice by the third project group. On the other hand, the teaching concept can be transferred to topics other than flower morphology or adapted to other class levels or time schedules. Therefore, shorter teaching units based on the basic course of action of the teaching concept were developed, which can be more easily integrated into the teaching schedule [57]. Although this approach uses the simpler and more intuitive program Tinkercad [58], the results and findings available in this report were essential for the elaboration.

Despite these shorter units, the teaching concept for modeling with Blender should also be an integral part of school education. It would be conceivable, for example, to implement it as part of project weeks. Afterwards, the students will have mastered the program to such an extent that the teacher will be able to use the methods of computer-aided modeling and 3D printing repeatedly and profitably in the classroom in the long term. This is because, in addition to the successful teaching of technical content and the positive effects on the intrinsic motivation of the students described above, many more aspects are relevant, such as the promotion of model competence as well as modeling skills, the handling of complex software, spatial thinking and the technical implementation of connecting elements. Research that surveyed teachers found that students who participated in 3D printing projects developed numerous skills including creativity, technology literacy, problem solving, self-directed learning, critical thinking and perseverance [59].

Due to the special research design, there are also limitations. Each project run took place in only one class. This meant that no direct comparison could be made with other classes using conventional teaching methods as a control group.

In addition, the researcher has so far taken an active role in classroom activities by providing the necessary expertise on modeling and 3D printing. This may have had an impact on the classroom dynamics.

Thus, there is also a need for further research. For example, investigating the implementation of the teaching units at further schools would be indicated. Here, the researcher could take on a decidedly passive role in the teaching process. Since the previous research interest was focused on the optimization of the teaching–learning arrangement, the effects of computer-aided modeling and 3D printing on spatial thinking and creativity, for example, could be investigated in further phases.

Nevertheless, the approach of this project is novel and unique in that projects already exist that use 3D printed models, 3D printing in the classroom, or computer-aided modeling. However, most of these projects each focus on one aspect: either working with a ready-printed model [20], printing pre-made files themselves, or modeling and printing objects with no curricular relevance [26]. Projects in which students are modeling and 3D printing curricular content are still rare. The studies on this conclude, as this study does, that computer modeling and 3D printing are perceived by students as a positive teaching method [60] and can be successfully used to teach learning content [23]. Yet, these works do not provide tested teaching materials. In contrast to that, this project can usefully combine the partial aspects of modeling and 3D printing in order to convey learning content and provides a teaching concept that can be used in schools. In this way, the theory-practice problem can be overcome, and a transfer of scientific knowledge to teaching practice can be achieved. The didactic conception of this approach is also progressive: a study on a 3D printing project states that the use of 3D printing and computer-aided modeling in the classroom, instead of learner-centered methods such as behaviorist forms of instruction, promotes a restricted learning environment and the role of the teacher as an expert [61,62]. The teaching concept from this project, on the other hand, is designed in such a way that the students acquire most of the learning content themselves and follows a problem-oriented, constructivist approach.

All in all, the project demonstrated that computer-aided modeling and 3D printing can be profitably used in the classroom. Through repeated implementation, the teaching concept could be scientifically optimized. With all the changes to the teaching concept, it is important to keep in mind that each class is unique and requires an individualized instructional approach. Therefore, the optimizations have been clearly highlighted so that they can be quickly reconstructed. Depending on the group, other adjustments may be necessary. In the end, teaching concepts are not rigid instructions but can be flexibly adapted by the teacher to the needs of the learning group.

To further promote the broader application in the classroom, thematically appropriate seminars for student teachers as well as teacher training courses are offered, since studies have shown that teachers often lack the necessary competence [8].

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci12110831/s1, Table S1. Detailed teaching concept; Table S2. Evaluation results.

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## References

1. Punie, Y.; Ala-Mutka, K. Future Learning Spaces: New ways of learning and new digital skills to learn. *Nord. J. Digit. Lit.* **2008**, *2*, 210–225. [CrossRef]
2. Yanuardi, R.; Widiaty, I.; Komaro, M. Vocational High School Technical Skills Facing the Industrial Era 4.0. In Proceedings of the 4th International Conference on Innovation in Engineering and Vocational Education (ICIEVE 2021), Bandung, Indonesia, 13 November 2021. [CrossRef]
3. Yang, X.Y.; Yang, C. Information Technology and Its Use in Medical Vocational Education: Present Practice and Future Prospects. In Proceedings of the 4th EAI International Conference, 6GN 2021, Huizhou, China, 30–31 October 2021. [CrossRef]
4. Ogonek, N.; Hofmann, S. Governments' Need for Digitization Skills: Understanding and Shaping Vocational Training in the Public Sector. *Int. J. Public Adm. Digit. Age* **2018**, *5*, 61–75. [CrossRef]
5. Madsen, E.S.; Bilberg, A.; Hansen, D.G. Industry 4.0 and digitalization call for vocational skills, applied industrial engineering, and less for pure academics. In Proceedings of the 5th P&OM World Conference on Production and Operations Management P&OM, Havana, Cuba, 6–10 September 2016.
6. Fahrurozi, S.K.; Budiyanto, C.W.; Roemintoyo, R. Technological pedagogical and content knowledge (TPACK) for overcoming teacher problems in vocational education and challenges in the 21st century. *J. Mech. Eng. Vocat. Educ.* **2019**, *2*, 33–40. [CrossRef]
7. Schelly, C.; Anzalone, G.; Wijnen, B.; Pearce, J.M. Open-source 3-D printing technologies for education: Bringing additive manufacturing to the classroom. *J. Vis. Lang. Comput.* **2015**, *28*, 226–237. [CrossRef]
8. Song, M.J. Learning to teach 3D printing in schools: How do teachers in Korea prepare to integrate 3D printing technology into classrooms? *Educ. Media Int.* **2018**, *55*, 183–198. [CrossRef]
9. Fassbender, U.; Papenbrock, J.; Pilz, M. Teaching entrepreneurship to life-science students through Problem Based Learning. *Int. J. Manag. Educ.* **2022**, 100685. [CrossRef]
10. Gräsel, C. Stichwort: Transfer und Transferforschung im Bildungsbereich. *Z. Erzieh.* **2010**, *13*, 7–20. [CrossRef]
11. Hofmeister, C.; Pilz, M. Using E-Learning to Deliver In-Service Teacher Training in the Vocational Education Sector: Perception and Acceptance in Poland, Italy and Germany. *Educ. Sci.* **2020**, *10*, 182. [CrossRef]

12. Stark, R. Eine integrative Forschungsstrategie zur anwendungsbezogenen Generierung relevanten wissenschaftlichen Wissens in der Lehr-Lern-Forschung. *Unterrichtswissenschaft* **2004**, *32*, 257–273. [CrossRef]
13. Bonorden, M.; Meinders, K.; Offermann, S.; Riemenschneider, A.; Papenbrock, J. Biologieunterricht praktisch und digital. Kompetenzorientierte Lehr-Lehrarrangements zur Modellierung von Blütenmodellen mit 3D-Druck. *Biol. Unserer Zeit* **2022**, *52*, 80–88. [CrossRef]
14. Su, A.; Al'Aref, S.J. History of 3D-Printing. In *3D Printing Applications in Cardiovascular Medicine*, 1st ed.; Min, J., Mosadegh, B., Dunham, S., Al'Aref, S.J., Eds.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 1–10. [CrossRef]
15. Ford, S.; Minshall, T. Invited review article: Where and how 3D printing is used in teaching and education. *Addit. Manuf.* **2018**, *25*, 131–150. [CrossRef]
16. Bøhn, J.H. Integrating rapid prototyping into the engineering curriculum—A case study. *Rapid Prototyp. J.* **1997**, *3*, 32–37. [CrossRef]
17. Celani, G. Digital Fabrication Laboratories: Pedagogy and Impacts on Architectural Education. *Nexus Netw. J.* **2012**, *14*, 469–482. [CrossRef]
18. Stamper, R.E. Utilizing rapid prototyping to enhance undergraduate engineering education. In Proceedings of the Frontiers in Education Conference, Kansas City, MO, USA, 18–21 October 2000. [CrossRef]
19. Chua, C.K.; Leong, K.F. Introduction. In *3D Printing and Additive Manufacturing. Principles and Applications*, 5th ed.; World Scientific Publishing: Singapore, 2017; pp. 1–20. [CrossRef]
20. Grant, C.A.; MacFadden, B.J.; Antonenko, P.; Perez, V.J. 3-D Fossils for K-12 Education: A case example using the giant extinct shark Carcharocles megalodon. *Paleontol. Soc. Pap.* **2016**, *22*, 197–209. [CrossRef]
21. Howell, M.E.; Booth, C.S.; Sikich, S.M.; Helikar, T.; van Dijk, K.; Roston, R.L.; Couch, B.A. Interactive learning modules with 3D printed models improve student understanding of protein structure-function relationships. *Biochem. Mol. Biol. Educ.* **2020**, *48*, 356–368. [CrossRef]
22. Howell, M.E.; Booth, C.S.; Sikich, S.M.; Helikar, T.; Roston, R.L.; Couch, B.A.; van Dijk, K. Student Understanding of DNA Structure-Function Relationships Improves from Using 3D Learning Modules with Dynamic 3D Printed Models. *Biochem. Mol. Biol. Educ.* **2019**, *47*, 303–317. [CrossRef]
23. Makino, M.; Suzuki, K.; Takamatsu, K.; Shiratori, A.; Saito, A.; Sakai, K.; Furukawa, H. 3D printing of police whistles for STEM education. *Microsyst. Technol.* **2018**, *24*, 745–748. [CrossRef]
24. Chery, D.; Mburu, S.; Ward, J.; Fontecchio, A. Integration of the Arts and Technology in GK-12 Science Courses. In Proceedings of the Frontiers in Education Conference, El Paso, TX, USA, 21–24 October 2015. [CrossRef]
25. Craddock, I.L. Makers on the move: A mobile makerspace at a comprehensive public high school. *Libr. Hi Tech* **2015**, *33*, 497–504. [CrossRef]
26. Kostakis, V.; Niaros, V.; Giotitsas, C. Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece. *Telemat. Inform.* **2015**, *32*, 118–128. [CrossRef]
27. Steed, M.; Wevers, M. 3D Printing & The Design Process: A Pilot Project Between University Student Teachers and Grade Four Students. In Proceedings of the EdMedia 2016: World Conference on Educational Media & Technology, Vancouver, BC, Canada, 28–30 June 2016.
28. Chao, J.Y.; Po, H.Y.; Chang, Y.S.; Yao, L.Y. The study of 3D printing project course for indigenous senior high school students in Taiwan. In Proceedings of the International Conference on Advanced Materials for Science and Engineering, Tainan, Taiwan, 12–13 November 2016. [CrossRef]
29. Chien, Y.H. Developing a Pre-engineering Curriculum for 3D Printing Skills for High School Technology Education. *Eurasia J. Math. Sci. Technol. Educ.* **2017**, *13*, 2941–2958. [CrossRef]
30. Ullah, A.S.; Tashi, T.; Kubo, A.; Harib, K.H. Tutorials for Integrating 3D Printing in Engineering Curricula. *Educ. Sci.* **2020**, *10*, 194. [CrossRef]
31. Upmeier zu Belzen, A. Unterrichten mit Modellen. In *Fachdidaktik Biologie*, 11th ed.; Gropengießer, H., Kattmann, U., Eds.; Aulis Verlag: Seelze, Germany, 2018; pp. 325–335.
32. Gilbert, J.K.; Boulter, C.J.; Elmer, R. Positioning Models in Science Education and in Design and Technology Education. In *Developing Models in Science Education*, 1st ed.; Gilbert, J.K., Boulter, C.J., Eds.; Springer: Dordrecht, The Netherlands, 2000; pp. 3–17. [CrossRef]
33. Louca, L.; Zacharia, Z. Modeling-based learning in science education: Cognitive, metacognitive, social, material and epistemological contributions. *Educ. Rev.* **2012**, *64*, 471–492. [CrossRef]
34. Jittivadhna, K.; Ruenwongsa, P.; Ranijpan, B. Beyond Textbook Illustrations: Hand-held Models of Ordered DNA and Protein Structures as 3D Supplements to Enhance Student Learning of Helical Biopolymers. *Biochem. Mol. Biol. Educ.* **2010**, *38*, 359–364. [CrossRef] [PubMed]
35. Srivastava, A. Building Mental Models by Dissecting Physical Models. *Biochem. Mol. Biol. Educ.* **2016**, *44*, 7–11. [CrossRef]
36. KMK Kultusministerkonferenz. *Bildungsstandards Im Fach Biologie Für Die Allgemeine Hochschulreife*; Link, Carl Verlag: Wedemark, Germany, 2020.
37. Terzer, E.; Upmeier zu Belzen, A. Naturwissenschaftliche Erkenntnisgewinnung durch Modelle—Modellverständnis als Grundlage für Modellkompetenz. *J. Didact. Biol. (ZDB) Biol. Teach. Learn.* **2007**, *16*, 33–56. [CrossRef]

38. Deci, E.L.; Ryan, R.M. Self-Determination Theory and the Facilitation of Intrinsic Motivation, Social Development, and Well-Being. *Am. Psychol.* **2000**, *55*, 68–78. [CrossRef]
39. Linn, M.C. Summary: Establishing a science and engineering of science education. In *Toward a Scientific Practice of Science Education*, 1st ed.; Gardner, M., Greeno, J.G., Reif, F., Schoenfeld, A.H., di Sessa, A., Stage, E., Eds.; Erlbaum: Hillsdale, NJ, USA, 1990; pp. 323–341.
40. Mandl, H.; Gruber, H.; Renkl, A. Situiertes Lernen in multimedialen Lernumgebungen. In *Information Und Lernen in Multimedia und Internet*, 1st ed.; Issing, L.J., Klimsa, P., Eds.; Beltz: Weinheim, Germany, 2002; pp. 139–148.
41. Reinmann-Rothmeier, G.; Mandl, H. Unterrichten und Lernumgebungen gestalten. In *Pädagogische Psychologie*, 4th ed.; Krapp, A., Weidenmann, B., Eds.; Beltz: Weinheim, Germany, 2001; pp. 601–646. [CrossRef]
42. Reinmann, G. Innovation ohne Forschung? Ein Plädoyer für den Design-Based Research-Ansatz in der Lehr-Lernforschung. *Unterrichtswissenschaft* **2005**, *33*, 52–69. [CrossRef]
43. Klees, G.; Tillmann, A. Design-Based Research als Forschungsansatz in der Fachdidaktik Biologie. *J. Didakt. Biowiss.* **2015**, *6*, 91–110.
44. Design-Based Research Collective. Design-based research—An emerging paradigm for education inquiry. *Educ. Res.* **2003**, *32*, 5–8. [CrossRef]
45. Mandl, H.; Kopp, B. Blended Learning: Forschungsfragen und Perspektiven. *Forschungsbericht* **2006**, *182*.
46. Hense, J.; Mandl, H. Selbstevaluation—Ein Ansatz zur Qualitätsverbesserung pädagogischer Praxis und seine Umsetzung am Beispiel des Modellversuchprogramms SEMIK. *Forschungsbericht* **2003**, *162*.
47. Bortz, J.; Döring, N. *Forschungsmethoden und Evaluation*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 1995.
48. Meinders, K. 3D-Druck-Verfahren im schulischen Kontext am Beispiel der CAD-Konstruktion von Blütenmodellen. Bachelor's Thesis, Leibniz Universität Hannover, Hannover, Germany, 2017.
49. Meinders, K.; Papenbrock, J. Digitale Bildung: Botanik mal anders! *Biol. Unserer Zeit* **2019**, *49*, 312–313. [CrossRef]
50. Bonorden, M. Digitale Botanik: Konzeptionen für die Modellierung von Blüten und Umsetzung in 3D-Druck AGs in drei Schulen. Master's Thesis, Leibniz Universität Hannover, Hannover, Germany, 2020.
51. Community, B.O. The Freedom to Create. Available online: https://www.blender.org/about/ (accessed on 27 September 2022).
52. Wilde, M.; Bätz, K.; Kovaleva, A.; Urhahne, D. Testing a short scale of intrinsic motivation. *Z. Didakt. Nat.* **2009**, *15*, 31–45.
53. Deci, E.L.; Ryan, R.M. Intrinsic Motivation Inventory. Available online: https://selfdeterminationtheory.org/intrinsic-motivation-inventory/ (accessed on 10 August 2022).
54. Edeling, S.; Pilz, M. Teaching self- and social competencies in the retail sector: Findings from vocational schools in Germany, Italy and Poland. *Educ. Train.* **2016**, *58*, 1041–1059. [CrossRef]
55. Greving, B. Messen und Skalieren von Sachverhalten. In *Methodik Der Empirischen Forschung*, 3rd ed.; Albers, S., Klapper, D., Konradt, U., Walter, A., Wolf, J., Eds.; Gabler: Wiesbaden, Germany, 2009.
56. Nakamura, J.; Csikszentmihalyi, M. Flow theory and research. In *Oxford Handbook of Positive Psychology*; Snyder, C.R., Lopez, S.J., Eds.; Oxford University Press: Oxford, UK, 2009.
57. Unger, B.; Bonorden, M.; Papenbrock, J. Einsatz von 3D-Druck-Modellen und 3D-Modellierung im Biologie (NaWi)-Unterricht am Beispiel von Gelenktypen. *Nat. Digit. Toolbox Den Unterr.* **2021**, *2*, 36–39.
58. Autodesk Inc. Available online: https://www.tinkercad.com/ (accessed on 27 September 2022).
59. Trust, T.; Maloy, R.W. Why 3D Print? The 21st-Century Skills Students Develop While Engaging in 3D Printing Projects. *Comput. Sch.* **2017**, *34*, 253–266. [CrossRef]
60. Maloy, R.; Trust, T.; Kommers, S.; LaRoche, L.; Malinowski, A. 3D modeling and printing in history/social studies classrooms: Initial lessons and insights. *Contemp. Issues Technol. Teach. Educ.* **2017**, *17*, 229–249.
61. Nemorin, S.; Selwyn, N. Making the best of it? Exploring the realities of 3D printing in school. *Res. Pap. Educ.* **2016**, *32*, 578–595. [CrossRef]
62. Leinonen, T.; Virnes, M.; Iida, H.; Brinck, J. 3D Printing in the Wild: Adopting Digital Fabrication in Elementary School Education. *J. Art Des. Educ.* **2020**, *39*, 600–615. [CrossRef]