TEACHING REFLECTIVE USE OF TECHNOLOGY: A PILOTED WORKBOOK BASED ON EVACUATIONS

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ABSTRACT

Applying computing technology during problem solving and the reflection of the appropriateness of this application are crucial skills for modern life. This is especially true while working on interdisciplinary STEM problems. However, up to now, few ready-to-use materials are available to foster such competencies. This paper starts bridging this gap by presenting a workbook for students in higher secondary education (around age 15). The workbook focuses on a complex STEM problem, primarily rooted in mathematics, computing, and technology education: Estimating the time it takes to evacuate a building. In the workbook, students work through five exercises focused on the problem of trying to make a sports hall safer. For three potential changes to the building, they should evaluate whether it increases the safety of the sports hall and whether the measure can reasonably be evaluated with a given simulation. During their work, students become aware of arguments useful for such an critical evaluation. For example, a change can only be evaluated if its magnitude is greater than variation in the (randomized) fleeing algorithm of the software. After development of the workbook, we used a design-based research approach to improve its quality. To do so, we asked eight educators for feedback and piloted it with 20 students from two mathematics classes of different capabilities. The results show that students had fun while working on the exercises and both the students and their tutors evaluated the workbook to be educationally relevant. Several issues, most importantly regarding the wording of several exercises, were identified and improved. Multiple exercises were further sub-divided to better suit learners of the age targeted.

KEYWORDS

Digital Simulations, Building Evacuations, Critical Reflection, Problem-Solving

1. INTRODUCTION

Applying computing technology during problem solving and the reflection of the appropriateness of this application are crucial skills for modern life (Jang 2016). This is especially true while learning to work on complex and authentic STEM problems: real-life problems used as learning experience for multiple skills that are only little simplified for education (c.f. Section 2). In such problems, application of technology (the T in STEM) is important: “Usually, to get a solution, computer programmes (Excel or more sophisticated ones) must be applied” (Kaiser *et al.* 2013). However, while several approaches for teaching with authentic and complex problems are published (c.f., Kaiser *et al.* 2013), none of the approaches in this list explicitly focus on the use and reflection of such “sophisticated” computing technologies. This is unfortunate as teaching the (reflective) use of technology is a key goal of education (c.f. Section 2). Moreover, designing suitable scenarios for such a use-case also is not easy: “[d]esigning authentic learning scenarios is therefore one of the key challenges in education interventions that aim for STEM literacy” (Ciolan & Ciolan 2014).

Thus, the central goal of this paper is to present a workbook that starts bridging the gap. It uses evacuations as a STEM context to introduce the students to key concepts of computing and STEM problem solving:

- Applying technology based on a computing concept (a grid automaton) to the solving process of a complex and authentic STEM problem.
- Reflecting the appropriateness of a software solution based on this concept in (steps in) the problem solving process.

The workbook itself is designed for an educational setting in which students work on a single leading question for an extended period of time. Examples of such settings include mathematical modeling weeks (c.f., Kaiser & Schwarz 2010) or teaching-learning labs at university (c.f., Klock & Siller 2021). It is designed to last around 6 hours of working time and consists of five key exercises with many sub-exercises. It is based on the following problem: “The director of a school wants to increase the safety of the schools' sports hall. To do so, several different options with certain, individual price tags are available. Decide which one should be implemented given a certain (limited) budget”. In the workbook, students are asked to simulate changes in the duration of an evacuation after certain changes to the sports hall (e.g., removing or relocating lockers, or adding further doors). Additionally, they are asked whether the simulation environment provided to them is suitable to evaluate the impact of the change.

To assess and improve the quality of the workbook, we employed a design-based research approach: First, we asked eight mathematics educators to comment on any aspect of the workbook they consider needs improvement and used that feedback to improve the workbook. Second, we then revised the workbook based on their feedback. Third, we asked students of two mathematics classes (totaling 20 students around age 15) of different capabilities to come to our university and work through the workbook. During this work, they should fill out a questionnaire regarding their disposition towards the exercises and their learning process, i.e., things they found hard or useful. Additionally, these students were supervised by tutors which also commented on any problems of the students or within the exercises. Fourth, after each of the class finished working through the workbook, the feedback gained was used to improve the exercises. Additionally, the results of the questionnaire showed that students had fun while working on the exercises and both the students and their tutors evaluated the workbook to be educationally relevant.

2. BACKGROUND ON COMPLEX AND AUTHENTIC PROBLEMS

Complex and authentic problems are considered to be of high importance for STEM education: Complex and Authentic problems “shall articulate the relevance of mathematics in daily life, environment and sciences and impart competencies to apply mathematics in daily life, environment and sciences” (Kaiser *et al.* 2013). For the purposes of this paper, problems are characterized as *complex*, if they are real-world problems that are “only little simplified” (Kaiser *et al.* 2013), and if they require consistent work over a longer period of time – at least multiple hours. A more detailed discussion of properties that make problems complex is provided in (Dörner & Funke 2017). Furthermore, we characterize problems as *authentic*, if there is an “alignment of student learning experiences with the world for which they are being prepared” (McKenzie *et al.*). An overview over eight established definition of what makes problems authentic; the definition used in this paper focuses on the relevance of learning activities for later life is provided in (Anker-Hansen & Andreé 2019). With complex and authentic problems, learners can “practice the skills and knowledge that are relevant and real to workplace situations and learn it at the same time” (Har 2013).

Working on complex and authentic STEM problems frequently requires technology: “Both the design of and interpretation of experimental practices in modern science are often based on the use of computational modelling” (Gilbert 2004). This technology frequently plays two crucial but different roles: As a utility (information technology aspect) and as central approach embedded in the model (computing technology aspect). First, technology can be utilized to work better on a given problem (e.g., more efficient, collaborative, semi-automated, ...). While technology in this way, users focus on the correct *application* of the underlying technology. Second, computational concepts can be used to *create* or *comprehend* models via computational thinking, one definition of which is “the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent.” (Wing 2011). Notably, both these roles of technology are dependent on each other (see Brinda *et al.* 2008). This is especially true if the person using the program is not the same person that created it and has to treat the program as a black-box – leading to additional requirements for the comprehension of existing models and the evaluation of them (Greubel & Siller 2022). In this regard, “computational thinking complements critical thinking as a way of reasoning” (Kules 2016). Notably, corresponding activities are already included in some curriculums. For example, in the United Kingdom, students should “apply information technology, including new or unfamiliar technologies, analytically to solve problems” (Department of Education 2023).

3. THE WORKBOOK

Based on prior research, we have chosen building evacuation as context for our course. This context allows for interesting, real-world problems-solving, and meaningful inclusion of computing technology – while not being too reliant on sophisticated inner-mathematical methods or domain knowledge (Ruzika, Siller & Bracke 2017; Greubel *et al.* 2022; Andersen *et al.* 2023). To simulate building evacuations, grid automatons with agents are frequently used (Li *et al.* 2019) These consist of cells with neighbors that change state according to specified rules (the programming of the automaton). For evacuation simulations, each cells can be either *empty*, *full*, *blocked*, or *safe*. While full cells contain (exactly one) agent, empty cells do not. Blocked cells neither do nor can contain an agent. They represent walls in the building. Finally, safe cells remove each agent moving on it from the simulation. They represent the destinations in a scenario. During each *Simulation Step*, each agent can move to a neighboring cell – either in four (*neumann neighborhood*) or in eight directions (*moore neighborhood*). The *Fleeing algorithm* describes whether or how the agents move. A simple fleeing algorithm might instruct each agent to move to the cell next on the shortest path of unblocked cells to the nearest safe cell, if this cell is empty.

3.1 Educational Goals and Requirements

The workbook has the central goal of teaching students the application and reflection of technology while working on a complex and authentic STEM problem. It does so by delivering practical experience working with a comprehensive simulation on a complex and authentic problem: Estimating the duration of evacuation of a building. The workbook is available both in English and German, and can be downloaded and used for free at https://evadid.it/workbook/CELDA-Workbook-En.pdf. It consists of five exercisers, each consisting of multiple sub-exercises and explanatory text and is designed for project-like learning in higher secondary education (around student age 15) in a STEM setting focusing on computing, technology, and mathematics. It takes students around 6 full hours (not including breaks).

Beforehand, students only need to be familiar with linear equations (create linear equations based on a real-world problem, solve them for a given variable, interpret it as linear function of one unknown). They can work alone or in groups of up to three. Each group needs access to a computer with a browser and a screen with a minimal resolution of 1024x768px. For working, each student should be handed out one (printed) workbook. A digital version is currently in production.

The workbook is designed to be solved without additional material: all necessary instructions, explanatory texts, links ... are included in the workbook. However, ideally, each group is additionally supervised by a tutor answering questions regarding the exercises and providing alternative explanations for unfamiliar formats (especially exercises regarding mathematical argumentation) to students. In our pilot, we tested the workbook in a video-conference setting with one tutor per group and in an analog setting with one tutor per two to three groups. In the opinion of the main author (present in both classes), both settings provided sufficient supervision to ensure a high and productive time on task.

3.2 Exercises in the Workbook

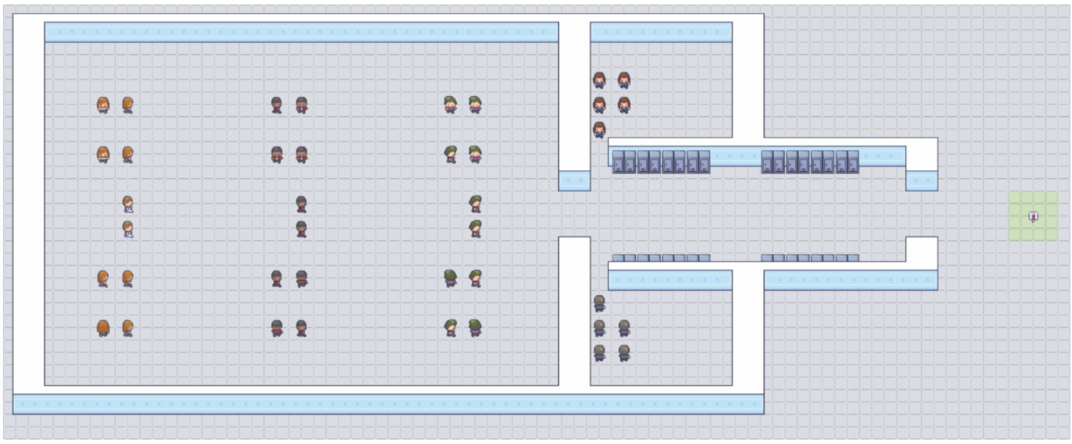
The first exercise, consisting of five sub-exercises, is used to motivate the topic. It first presents (fictional) news articles regarding evacuations, working with assumptions, and mathematical modelling. All of these models highlight the importance of a certain step in mathematical modeling cycle (Greefrath, Siller & Weitendorf 2011). For example, one article (highlighting making realistic assumptions) reads: “40 km/h are not walking speed, license revoked. (Anna Turney): Last night, a 48 year old man drove 40 km/h in a traffic-calmed street. The culprit defended this behavior by arguing that he followed the rules and did not drive faster than walking speed: After all, Usain Bolt can move with up to 45 km/h. This did not impress the judge: She argued that assuming such a walking speed is unreasonable. The jury agreed: At the end of the trial, the man lost his driving license.”. Moreover, students should think about the topics ahead. Another question reads: ”Look at this image of a building: [...] Encircle three aspects of the following list you assume have the biggest impact on the evacuation duration: 1) average walking speed, 2) speed of the slowest walker, [...] 5) width of the central hallway, [...]”.

The second exercise, consisting of four sub-exercises, is used to introduce to working with the digital learning environment to the students. This explicit introduction is necessary, as finding out the functionality of a digital simulation can be hard. In the exercise, they explore the functionality of the simulation environment by creating, loading, storing and executing sample scenarios. Furthermore, they should interpret the results of the simulation environment as real-world results. This is done by identifying the correspondence between the output of the simulation (the duration in simulation steps) and the real world: Every cell in the grid has a fixed length. With knowledge of that length and an assumption about a walking speed, a linear equation (or the rule of three) can be used to calculate a real-world estimate duration of the simulation.

The third exercise, consisting of eight sub-exercises, is used to reflect on the role of assumptions during modeling. The students should analyze how the simulation duration changes if different walking speeds are assumed. Additionally, they should argue whether simulation results (both for building evacuations and other domains) are useful even if they are not perfectly accurate. One task reads: “Denote at least two situations, in which simulation results are only useful if they are perfectly accurate”. Another one: “Argue, whether simulation results of a building evacuation are useful, even if they are not perfectly accurate. Use at least two different lines of argumentation.”

At this point, the workbook explicitly introduces the big problem the whole workbook is leading towards: ”A director of a school wants to reduce the time it takes to evacuate the sports hall pictured below. There are a range of different options (with different price tags) and a fixed budget. What options should be decided upon?”

Figure 1: The Sports Hall from the Exercise



In the fourth exercise, consisting of ten sub-exercises, students are worked through the process of testing hypothesis. This is done by evaluating one of the available options step-by-step: moving to sets of lockers from the hallway of the sports hall into the changing rooms. In the sub-exercises, they pose the hypothesis (“Argue, which two sets of lockers should be moved and argue why you opted for those specific two.”) and verify them afterwards (by executing multiple, similar scenarios, e.g., without the lockers). During this work, they become aware of the randomized nature of the fleeing algorithm implemented in the simulation environment. This is used to reflect on whether aspects can or can not be evaluated using such an environment: For example, to be evaluable, the effect to be analyzed has to be stronger than random variation. Thus, the students can use this simulation program to generate evidence for the hypothesis “Moving the top two sets of lockers reduces the evacuation time of a full sports hall by approx. 15%” but not for the hypothesis “Moving the left two sets of lockers reduces the evacuation time of a full sports hall by approximately 1%”.

The fifth and last exercise, consisting of five sub-exercises, returns to the big problem introduced in the prior exercise: The complete list of eight possible options (with corresponding price tags) is introduced. Possible options include the moving of objects to any new location, the widening of hallways or doors, introducing additional doors and assembly points, reducing the maximum amount of persons allowed in the sports hall, and training the persons in the sports hall to walk faster. In the sub-exercises, the students should formulate a set of concrete measures (e.g., “a one meter wide door should be added at the left of the sports hall”) they consider to be most effective and evaluate their impact. Then, they should argue whether such an evaluation based on the simulation is reasonable. Based on these results, they should use their results to make an informed suggestion solving the problem of the director. Last, they should reflect on viable options if only half the initially promised budget was available.

4. DESIGN-BASED RESEARCH AND PILOTING OF THE WORKBOOK

To assess and improve the quality of our workbook, we analyzed its quality using methods from design-based research (see Wang & Hannafin 2005). More precisely, we organized our development in phases. Note that this overall line of research is performed as design-based research. As such, the central goal was to improve the workbook and collect information necessary for the adoption by others – rather than assessing the learning outcomes with a pre-post test design.

4.1 Phases for developing the workbook

At the beginning, one of the authors created a first draft of the workbook.

Then, in the first phase, one author read the current version and commented on things to improve. These changes were implemented either by this author directly or by another author. This was iterated until no further changes were considered necessary within the author group.

In the second phase, we gave the workbook to either a mathematics or computer science educator. We asked this educator to read through the workbook and comment on every aspect they consider should or could be improved. Most importantly, they should comment on everything they consider relevant for practical implementation, e.g., exercises that are likely to be misunderstood by students. This feedback was then used by one of the authors to improve the workbook. After improvements were made, another educator was asked to provide his or her commentary. A total of eight educators were asked in this phase, two of which worked at secondary schools, six of which studies for a teaching degree for secondary schools.

In the third phase, we invited two mathematics classes of different capabilities to our university and let them work through the workbook together with tutors. After each class visited the university, we improved the workbook based on the feedback collected at this visit.

4.2 Method of collecting feedback with the classes

After each exercise, both students and their tutors should reflect on the quality of the exercise and possible improvements. To collect them, we asked students and tutors to fill out a questionnaire after each exercise, as well as after finishing the workbook. A 6-point Likert-scale (1=strongly disagree to 6=strongly agree) is used as format for possible answers for all closed questions used in this evaluation.

The overall goal of the questionnaires was to get insights into the following questions:

- How much do the students enjoy working on the workbook?
- How do students and tutors describe the learning process?
- How do the tutors evaluate the educational relevance?
- What aspects of the workbook should be improved?
- Are there other aspects relevant for adopters?

In the questionnaire, we used one question intended to analyze the disposition of the students towards the material and three questions in which the students reflected on their learning process:

- (DS) I had fun working on the exercise
- (W1) I learned something through the exercise
- (W2) I solved the exercise on my own
- (W3) The exercise was challenging for me

While the students filled out their questionnaire, the tutors were also asked to fill out a questionnaire with different questions. We used three questions to evaluate the attributed relevance of the material and further two question to reflect on the quality of the material:

- (R1) The exercise improves mathematical competences mandated by [the local curriculum].
- (R2) The exercise improves math. competences that the students will need in their later live.
- (R3) The exercise improves math. comp. necessary for a critical understanding of the world
- (Q1) The exercise was comprehensible by the students (regarding language content)
- (Q2) The exercise is well structured

Notably, tutors were made aware that, regarding these questions, usage of technology should be seen as sub-activity of mathematics (The wording was chosen because there is no separate technology education in Bavaria and the local mathematics curriculum encourages utilization of technology for problem-solving).

In the last questionnaire, we offered students the ability to describe what they did and did not like in the workbook overall. This was done by six open questions at the end of the workbook, as well as verbal discussions after the working period. Four of the questions asked for additional information towards the closed questions (what was especially fun, what was especially challenging, what did you need most help with, what was the most relevant thing you learning). Two further question asked for aspects that were positive or negative overall.

4.3 Classes for the Piloting

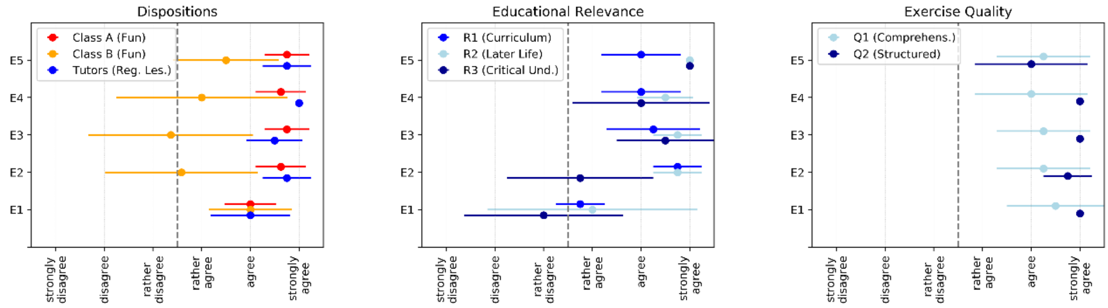
We piloted the workbook with two classes. The first class consisted of nine students from an interscholastic course in mathematics for highly capable students. Students meet multiple times a year on Fridays and/or Saturdays for additional lessons in (applied) mathematics or STEM problem solving. For these lessons, the teacher is free to teach whatever is deemed suitable for these students. This class is likely to be more motivated and capably than typical classes. The students participated in the course via a video-conference platform (Zoom) familiar to the them. They worked in groups of two and one group of three. Each group was supervised by a tutor. The four tutors were students of mathematics education for higher secondary education. They were recruited based on good impressions in the courses of the authors, or because they worked as student assistant at the chair of the authors and were known to be competent. All of them were advanced in their studies. Prior to the meeting, they were briefly introduced to the workbook, sample solutions, and the supervision process. This was done in a one-to-one meeting between one of the authors and the tutor. This lasted around 10-30 minutes. The tutors were known to the authors but not further affiliated to the creation of the workbook.

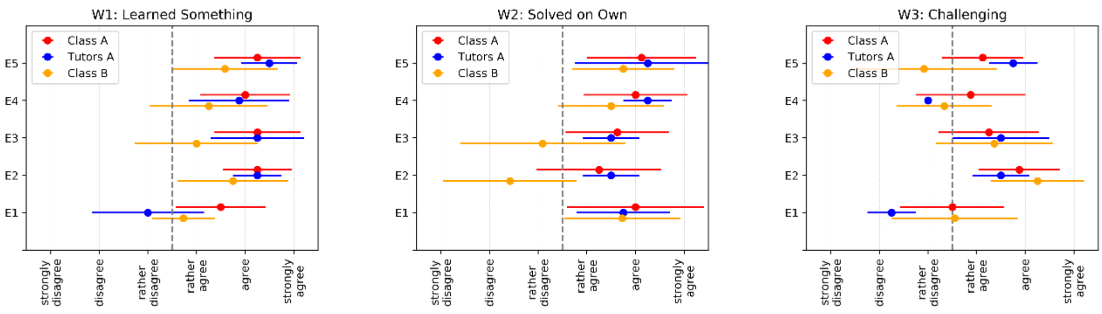
The second class consisted of twelve students (half the regular class size) from a regular higher secondary school. All students in the class took the musical school branch (having a reduced amount of mathematics lessons). Two of the students got a non-passing grade in mathematics. However, as two non-passing grades are required to fail the school year, both already knew that they passed the school year anyway. This class is likely to be a bit less motivated and capable than an average class. They worked in-person in groups of two; two students preferred to work alone. They were supervised by three tutors (two of the authors and one tutor from the prior class); one for 2-3 groups. Thus, these tutors did *not* fill out the questionnaire (again).

5. RESULTS

The overall results are visualized in below in Figure 2:

Figure 2: Visualization of the results of the closed questions.





5.1 Engagement

The first class expressed very high, the second class expressed moderate enjoyment while working on the exercises. Aspects that were highlighted as especially fun in the open questions by at least two students include: 1) Experimenting on a real-world problem, 2) using the simulation, 3) working on a mathematics problem with peers, 4) transforming the simulation result to a real-world with a formula. One student commented: “Very nice workbook and appropriate exercises. Real-life Situation (Director wants to make the school more safe)”. Another: “The simulation was very interesting and I had fun with the exercises. I found it very interesting to think about the sum of money [to be spent].” The only aspect of discontent focused on the functionality of the digital simulation environment. For example, one pupil tried to evaluate the impact of an additional door on the evacuation duration. However, the fleeing algorithms used during this execution did not lead any persons through this additional exit. The pupil complained: “Change the simulation: Persons [should] take the [additional] way leading outside [I built]” and added in the free feedback section: “The AI of the persons could be replaced by one that can learn: One can suggest a way [to take] and the simulation learns from this”.

5.2 Learning Outcome

The tutors expressed very high agreement that exercises like this should be included into regular school education. One tutor noted: “The students enjoyed this exercise [five]. This is a very motivating exercise, if time and ability (technical equipment) are available.” Another one noted at exercise four: “The reflection of results is frequently missed out in regular lessons. In every case, the verification of hypothesis is a competence that is worth fostering in regular lessons.” Another one: “Mathematics should not only teach calculations.”

Regarding the learning outcome, students and tutors had the impression that the students were learning something for all but the first exercise. For the first exercise, students thought that they learned something but tutors did not have the same impression. The reasons for this are unknown. Unfortunately, no pupil commented on what they learned. However, one tutor briefly commented on his disagreement to the first question: “It brought [things] to mind, but [the students discovered] no new findings”. The first class reported moderately stronger overall agreement than the second class. In their assessment, students listed different kind of things they learned. This included domain knowledge (“what real problems during evacuations are”, “That evacuations improve if people walks faster / in an orderly manner”, “The fact that there are many options to improve an evacuation”, ...), critical reflection (“Skepticism while differentiating realism and simulation”, “Not all things that seem good at first are the best”, ...), and approaches to problem solving (“How evacuations proceed and how one can predict them approximately with mathematics”, “Thinking about […] simulations in general”.

5.3 Self-sufficient working of the students

Regarding self-reliance, the first class and their tutors had the impression that the students solved the exercises rather on their own. The second class needed more support, esp. for exercises 2 and 3. The biggest aspect where help was necessary (reported by more than a quarter of all students in the free-text) was in exercise two: The creation of a formula that enables transforming the simulation duration in steps into a real-world estimate about the simulation duration. For example, some students verbalized confusion about the different role of characters in formulae: In the workbook, they were asked to use the variable x for the speed and s for the distance. However, in their physics class, x was used for the distance and s was used for seconds. One tutor noted that this was the first time the group realized that the same character for an unknown can have different meanings in different contexts and formulae. Another big aspect where help was necessary was the introduction to the simulation itself. One pupil wrote: “The simulation was hard to understand at first, but then I found it pretty good.” Notably, the students were not offered a handbook (or similar) for the environment. Instead, it was the duty of the tutor to explain the functionality of the environment, if necessary. For classroom adoption, a handbook or additional exercises that introduce all relevant functionalities in detail might be advisable. Interestingly, the mathematically more complex activities in the later exercises (verifying assumptions, creating hypothesis, experimenting with the simulation) required little help in both classes. One tutor noted for the last (most complex) exercise: “The students worked very self-reliant. My primary role was that of an observer.”

5.4 Level of Challenge

Regarding the challenge level, the students felt challenged by the exercises a bit, but not too much. Unsurprisingly, exercise two (the exercise where most help was necessary) was considered to be the most challenging one. Notably, the tutors again disagreed with the perception of the students on the first exercise. One tutor noted at multiple exercises that “the level of challenge was appropriate.” Another noteworthy aspect is the relatively low challenge reported by the second (weaker) class for the last exercise: Given that this exercise is indeed the most complex one, this might indicate that students did not grasp the full complexity of the exercise.

5.5 Educational Relevance

Regarding the educational relevance, the first exercise scored (on average) close to the middle on all three question. This is not surprising as this exercise is a preliminary exercise for the later ones. The second exercise scored high (average at least “agree”) in the questions R1 and R2 but not R3. This is likely because the relevant skills taught (handling formulas and the simulation) are primarily supplementary skills. The last three exercises all scored high on all three questions asked. Reasons for this very high score (mentioned more than twice as free text answer on any of the three exercises) included: 1) the high relevance of learning to argue logically correct and with data, 2) learning about the process of stating, verifying, and reflecting assumptions and results, and 3) demonstrating good examples for working behaviors typical for mathematicians like generalizing and finding examples and counter-examples. Lastly, regarding the quality, most of the exercises were perceived as well structured and rather comprehensible. There was no instances in which a problem with the comprehensibility of the mathematical content was noted: Instead, aspects of concern focused on the wording of exercises.

6. CONCLUSION

In this paper, we presented a workbook designed to teach students the reflective use of computing technology. We used methods from design-based research to assess and improve the quality of the workbook. Additionally, we piloted the workbook with two classes of different capabilities, totaling 20 students. Our results show that the students rather worked on their own, learned something, and were challenged an appropriate amount. The disposition towards the material was overall positive: The first class expressed fun working on the exercises, the second class was more divided and moderately positive on average. The tutors of the first class very strongly agreed to the statement that such or similar exercises should be included into regular school education. The exercises themselves were perceived as well structured and, mostly, comprehensible. Based on the feedback collected, we sub-divided multiple exercises and improved the wording (both in regard to clarity and consistency) of many exercises. We also added and indicator for the estimated work duration to each exercise in the workbook. The workbook published alongside this paper already includes these updates. Finally, we encourage educators to adopt our workbook and/or to design further new and interesting learning opportunities for the reflective use of digital technology.

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