Enhancing Computational Thinking with 3D printing: Imagining, designing, and printing 3D objects to solve real-world problems

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ABSTRACT

Printing 3D objects is exciting and engaging for young learners. However, how can this emerging technology benefit the development of skills, such as Computational Thinking (CT) and Design Thinking (DT), through a meaningful process of imagining, designing and tinkering with objects that could be used in real-world problems? Our knowledge is still limited, due to the complexity of designing 3D printable models from scratch with the existing digital tools. This paper discusses a web-based tool that enables learners to create and dynamically manipulate the behavior and properties of 3D printable models with high-level programming. This design aims to foster computational thinking, creativity, and design thinking skills as it focuses on the design process of the model, its behavior and its usage after printing. It also presents the results of a pilot study in which secondary school students engaged in a Design Thinking project for designing and printing sustainable everyday objects using this design. The study revealed new kinds of educational potential of 3D printing including the understanding of complex mathematical and CT ideas that were too complicated before, and the connection of CT practices with real-world problems through the implementation of a Design Thinking project with digital media.

CCS CONCEPTS

• **Social and professional topics** → Professional topics; Computing education; Computational thinking; Professional topics; Computing education; K-12 education; Professional topics; Computing education; Computing literacy.

KEYWORDS

Computational Thinking, 3D printing, Logo-based programming, Design Thinking, Emerging Technologies

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1 INTRODUCTION

The rapid technological advancements in 3D printing technology have transformed it from an industry-oriented technology to an emerging educational technology [24]. Acquiring and hosting a 3D printer is nowadays affordable for many schools and families. Even though 3D printing is an engaging and exciting technology for children, there are still very limited studies on the added value it can bring to the learning process. Recent studies have yielded promising results, showcasing its potential as a transformative tool for acquiring new knowledge, mainly in STEM education, and for skill development [5, 8, 16, 10, 17, 23]. However, there is still a need for more empirical evidence and a deeper understanding of how 3D printing can bring added value to learning different subjects and to skills development in K-12 students [8]. Especially, regarding the process of designing and programming the 3D printable object, the activities for younger children are usually limited to following given instructions [8, 16], printing ready-made objects [17], or using 3D pens to create the object [23]. As a result, there is a gap in pedagogical approaches and tools for children that equally enhance the computational and engineering aspects of 3D printing (i.e. coding and printing). The open question, therefore, is what children can learn from the process of imagining, programming, manipulating, and printing a 3D model to solve a real-world problem. In this paper, we discuss an online tool, called MaLT2-ext, that allows students to create complex 3D models with high-level procedural programming, dynamically manipulate their behavior, and 3D print them to be used by others in realistic situations. In order to connect 3D design and printing in MaLT2-ext with real-world problems we employed the Design Thinking (DT) methodology [21, 29] and extended it with digital technologies. In our approach, students used MaLT2-ext and other digital tools to design and develop a solution to a socio-scientific real-world issue following the stages of DT. To study the pedagogical potential of this approach, we organized a pilot study with secondary school students who designed and printed a maquette for a vertical garden in the context of a Design Thinking project. The study aimed to answer the following research questions:

A) Whether and how the described approach to 3D printing design enhances students' Computational Thinking?

B) What DT skills do students develop using the above technologies in a digital-based DT project?

2 THEORETICAL FOUNDATIONS OF MALT2-EXT DESIGN

2.1 3D Printing as an emerging educational technology

3D printing is considered among the emerging technologies for education of the 21st century [8]. Researchers and educators are currently looking for meaningful and innovative ways of introducing 3D printing in mainstream schooling and at the same time exploring the benefits, barriers, and opportunities of this technology to teaching and learning. Recent studies provide some evidence that 3D printing can enhance students' motivation, knowledge, and skill development, but they also suggest that there is a need for further research and new designs to exploit its full educational potential. Leinonen et al. [17] discuss how 3D printing facilitates project-based learning in elementary education, allowing students to engage in practical, real-world projects that reinforce theoretical knowledge and instill practical skills. Through the direct and quick production of tangible items, 3D printing can bring concepts to life and expand our capacity for thought and imagination [18]. Additionally, studies like the one by Kuen-Yi Lin et al. [16] emphasize the development of student imagination and career interest through STEM projects using 3D printing with repetitive modelling. These initiatives not only enhance students' understanding of concepts but also promote skills such as spatial thinking, creativity, problem-solving, and technology literacy [16, 17]. The most compelling use of 3D printing in education is providing chances for instruction in real-world situations [8]. Learners can design and construct tangible artifacts and use them in practice to solve problems from their real world, in ways that were not accessible before that technology. However, as different studies point out, the current designs and task-based activities on exploiting 3D printing as educational technology may inspire students to create their ideas and innovations but do not fully unlock the added value that 3D printing activities can bring [17]. A significant gap concerns the process of imagining, constructing, and tinkering with the models to be printed, especially in K-12 education. In the small number of existing studies with primary or early secondary students [24, 25], teachers either provide children with ready-made models (e.g. [17]) or give them specific instructions on how to build them (e.g. [8, 16]), limiting their creativity and imagination of what could be printed. This happens due to the complexity for young learners to create and manipulate a complicated 3D printable object from scratch with the existing technologies, which usually require high-level mathematical and programming skills [16, 22]. On the other hand, there have been studies showing the benefits of digital 3D design and programming for learning certain concepts (math, programming, physics) and skill development (spatial skills, computational thinking skills) [7, 26], but they are missing the tangible element of physical usage, i.e. designing something for real use by a third person or to solve a real problem. This aspect could have a significant effect on children's decisions and computational thinking processes while they design and construct the 3D model, but has not yet been studied.

2.2 Logo-based programming and Dynamic Manipulation of the model behavior

Aiming to provide students with a high-level programming environment to create and manipulate the behavior of 3D models before printing them, we extended an existing web-based tool called MaTL2 (https://etl.ppp.uoa.gr/malt2) with the functionality of 3D printing. MaLT2 was originally designed and developed by the Educational Technology Lab of NKUA, as a constructionist tool that integrates traditional turtle geometry with 3D design and animation of the created models [7, 15]. It integrates three affordances for 3D model creation as shown in the two screenshots of Figure 1 1) Logo-based programming of 3D models with a language that extends Berkley Logo with commands for 3D movement, navigation, and drawing. This feature broadens the range and complexity of objects and ideas that can be expressed in the 3D space with programming. 2) Dynamic manipulation and animation of the model. A 'variation tool' with sliders, allows for the instant variation of the parameter values of any executed parametric procedure, resulting in the animation of the model on the scene. Dynamic manipulation aims to reinforce the process of abstraction by means of kinaesthetically causing the continuous transformation of a structure described formally to make better sense of how this may represent a generality, such as e.g. a property of a geometrical figure. 3) 3D navigation with a periscopic camera in the 3D scene that allows for the examination of 3D artefacts from different angles and scales. This could allow for a better understanding of the model parts, their connections, and their mapping to the respective code procedures. The design idea behind MaLT2 is to give children "principled deep structural access" to complex computational ideas [13]. This means to provide children with higher-order "building blocks" which would enable them to explore and express otherwise powerful mathematical, computational or design thinking ideas. Consider for example the "biangle" on a sphere shown in Figure 1b constructed in MaLT2. This is a figure not easily represented with traditional media and at the same time embeds mathematics hardly accessible particularly to students with other means. The original version of MaLT2 has been used in several empirical studies, showing its potential to enhance students' computational thinking and mathematical reasoning [7, 14, 15]. For the purposes of this study, we recently extended MaLT2 with the affordance of 3D printing, supporting the printing of the created models with almost all models of commercial printers. This affordance creates a connection between the digital models that students create and their representation and usage in the physical world. The aim is to enhance the development of computational and design thinking skills, but also the meaning-making processes for complex concepts, while students are imagining, designing, coding, testing and printing 3D models for real-world problems.

2.3 Integrating 3D design and printing in Digital Design Thinking projects

In order to achieve a meaningful integration of digital 3D model programming in MaLT2-ext with 3D printing, we employed this technology in the context of a Design Thinking project. Design Thinking (DT) is a human-centred problem-solving process that

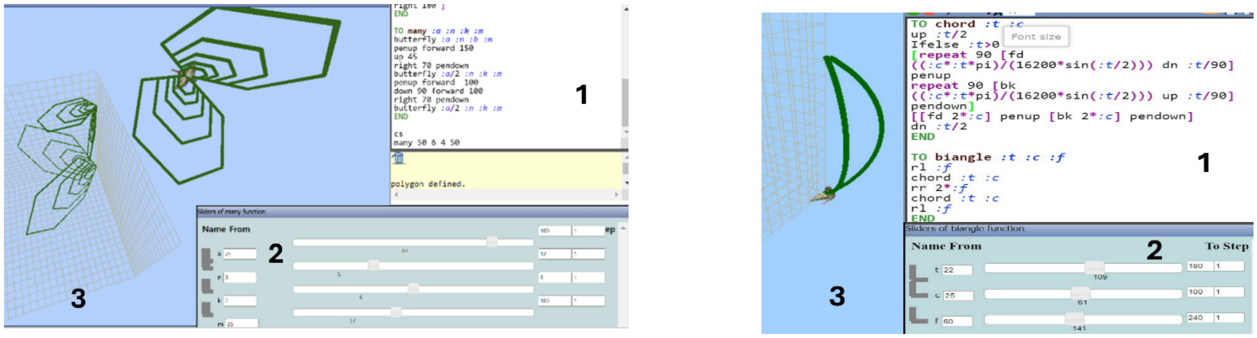

Figure 1: Two screenshots showing the 3 affordances of MaLT2-ext environment (1,2,3) a) A 3d model of moving butterflies made with polygons b) A biangle model

comes from the world of industry and has recently been transformed into an educational project-based approach [21]. It consists of distinct but interconnected and usually repeated stages including empathizing with the user, ideation and brainstorming, prototyping, testing and refinement, sustainability planning, and delivering of the final solution. Even though DT is among the necessary 21st-century skills for children, and it has shown significant learning potential, there are still important issues for its pedagogical transformation and integration into the curricula. A key problem has been the focus on tangible industrial productions, which for the education system is rather narrow, and also quite vague for teachers to monitor and evaluate [1]. Thus, the use of digital technologies in the different stages of DT, such as prototyping, ideating, and sharing, could make it a feasible, accessible, and inclusive approach for students and teachers, while at the same time preserving and expanding at scale of its dynamic, multifaceted and immersive aspects [20]. A few studies have used 3D printing technology in Design Thinking projects, with promising results [5, 9]. However, they address college or VET students with high knowledge of digital 3D modeling that use quite complex software for designing the 3D models. To the best of the authors' knowledge no empirical studies are exploring the use of 3D object design and printing in Design Thinking projects in schools. In our approach, students use digital model design in all stages of a Design Thinking project as a means to collaborate, empathize, ideate, create rapid prototypes, experiment, and iteratively create and improve computational solutions for real-world problems. Our aim through this integration is dual: From one side to study in what ways the design of something to be used by someone else in a realistic situation would affect students' computational thinking practices and perspectives. On the other side to study how the integration of digital technologies in DT projects could enhance the process of DT and students' DT skills, such as empathy, ideation, and collaboration.

3 THE EMPIRICAL STUDY

3.1 Research methodology and implementation context

Last year, we organized a pilot study with secondary school students as part of the first cycle of an ongoing design-based research [3] project, called ExtenDT2, that explores the barriers, opportunities, and enablers of emerging technologies in design thinking education [20]. With the specific study, we aimed to gain insights into the two research questions presented earlier and also to inform the redesign of activities and technology for the next two wider cycles of implementation. The study was implemented in an experimental secondary school in Greece as part of an after-school STEM club. It had a duration of 8 hours split into 5 sessions. The participants were 30 students aged 14-15 years old. Students and their parents gave written consent for participation, after being informed of the study purposes and data collection process. Two researchers and one schoolteacher were present during the implementation. The activities of the study had the form of a Design Thinking project and were co-designed by the schoolteacher and the researchers using a Design Thinking Activity Plan Template document, developed in the ExtenDT2 project [20]. In the DT project students had to design and print a 3D model representing a maquette of a construction stand for plants that could be placed in a vertical garden on a city building. The topic was freely chosen by the teacher as part of a wider environmental project they were working on the current semester. The project followed the 4 phases of the DT double diamond model "Discover", "Define", "Develop", "Deliver" [29] as follows: In the "Discover" phase students searched online for information, watched videos on vertical gardens and discussed the topic in the classroom. Each group created and published an online questionnaire on the NQuire platform to gather more information on vertical garden design from experts. In the "Define" phase, the teacher provided students with some ready-made code in the MaLT2-ext environment that created basic shapes (e.g. a cube, a rectangle). Based on the replies to the questionnaire they defined the main characteristics of their construction stand and transformed the code of the given shapes accordingly. In the "Develop" phase, the groups created 3D rapid prototypes of the garden's construction stands in MaLT2-ext, tested them with peers, and redesigned them. Each group printed one model for testing. They also shared the models and photos of both digital and physical models online asking students, teachers, or parents for their feedback. In the "Deliver" phase, they presented the digital models in the classroom and voted on which would be physically constructed.

3.2 Data collection and analysis

We collected seven types of data intending to analyze students' learning processes and interactions with the technology and between them throughout the activity. These included a researcher observation note using an observation protocol, video/audio and screen recordings from 2 focus groups (with 2 and 3 students accordingly), interviews with students of the 2 focus groups, pre and post-survey (with n=23, and n=25 responses), artifacts of learning (e.g. 3D models and their prototypes, notes, and sketches), interview with the teacher. The pre- and post-survey included questions on DT process and 21st-century skills such as creativity and collaboration and were based on two literature reviews researchers did on evaluation tools for students' a) design thinking mindset and b) 21st-century skills. We did a thematic analysis of the qualitative data of the two focus groups using the critical episode [28] as the analysis unit and following an abductive coding technique [27] (i.e. start with an initial scheme and remain open for new codes that will emerge). Critical incidents were used to identify events that were significant in the action and to explore them in depth using observational data (video, audio or written) primarily with interviews and reflections providing supporting or refuting evidence. To answer the first RQ we looked for incidents students expressed or discussed CT practices (i.e. abstraction, pattern recognition, automation, decomposition) and perspectives (e.g. questioning, developing computational solutions for real-world issues) [4, 9, 11, 12]. We aimed to identify ways of CT development that were enabled using 3D printing in the specific context. To answer the second RQ we looked for cases of engagement with DT aspects (i.e. empathy, ideation, prototyping, presenting, collaboration, testing). The thematic analysis led to five main themes concerning: difficulties/challenges, computational thinking, design thinking mindset, technology's added value (enablers), and mathematical meaning-making. For conciseness purposes, in the following section, we will describe in more depth selected codes that answer the 2 research questions discussed in this paper, using examples of relevant critical incidents. In addition, we did a descriptive statistical analysis of the pre and post-surveys to gain insights into the whole classroom that provided evidence on the second RQ.

4 FINDINGS

4.1 RQ1: Enhancement of CT through 3D design and printing in MaLT2-ext

The first RQ of this intervention concerned the enhancement of students' Computational Thinking through the use of MaLT2-ext to design, animate and print 3D models that solve a real-world problem in a Design Thinking project. Below we discuss two of the codes that emerged during the thematic analysis that concerned ways of developing CT that were enabled by the integration of 3D printing with MaLT2-ext environment.

4.1.1 Access to complex and creative ideas. One interesting finding was the codes "accessibility to complex ideas" and "creativity", that described cases where students created a digital model in MaLT2-ext, using CT practices, that was otherwise hard to imagine or create in other simulation tools (according to them or their teacher). For instance, students from focus group 1 while they had created the first model (Fig 2a) suddenly had the idea of making a vertical garden for a cylinder building. This came from while discussing a building in their neighborhood having that shape. To do so, they tried to imagine how they could "fold" a rectangle onto the surface of a cylinder, a quite complex idea mathematical-wise. Through several experiments with the code, they created the design shown in Figure 2b. During that iterative process of programming, executing, and dynamically manipulating the digital model they approached complex computational and mathematical ideas such as patterns in code repetition (CT), abstraction of procedures (CT), and linear and angular properties of a square (math). An example of such meaning-generation is shown in critical incident 1 (Table 1).

Later, this group realized that their design looked like a curved letter "E", so they decided to print a testing letter and stick it on a mug, giving them (and us) an idea for another DT project (Figure 3). This incident was coded as creativity since students expressed a creative idea by transforming the same digital model for another physical purpose. Moreover, creativity in their designs was also evident in their responses to the post-survey relevant questions, as shown in Figure 4.

4.1.2 A "phygital" approach to CT development. A second coding category concerned a twofold implementation and development of CT practices: for the creation and manipulation of the digital model on the screen but also for the meaningful and efficient printing and usage of the physical model. We named that code "phygital CT", by combining the words physical and digital. This combination led students to a deeper engagement with CT practices that wouldn't have happened without the printing affordance. For instance, it was quite common that students initially designed their digital model in a certain way in MaLT2-ext and then realized it wouldn't be able to be printed correctly, or it wouldn't be functional as a physical model for their DT project. This led them to apply CT practices, such as pattern recognition between the 2 models and abstraction of the procedures, in order to redesign their code and improve the physical artifact. In these cases, it was the physical artifact and its purpose in the context of the DT project that led them to redesign the code and develop their CT. This was shown in lines 7 and 8 of critical incident 1 (Table 2), where the two students decided to draw and print the model horizontally, even though it was initially constructed vertically, and then turn the physical model vertically. In critical incident 2, students of focus group 2 realized that their digital creations could not be printed or constructed with physical means (Figure 5a). Thus, they decided to redesign the code that draws the digital model so that it prints a more stable physical construction (Figure 5b). This led them to apply the CT practice of pattern recognition in the code (as repeated commands), the digital 3D model (as repeated geometrical shapes), and the physical construction (as repeated blocks that are printed)

4.2 RQ2 What DT skills do students develop using the above technologies in a digital-based DT project?

The second RQ concerned the enhancement of students' Design Thinking mindset through the described approach. The analysis

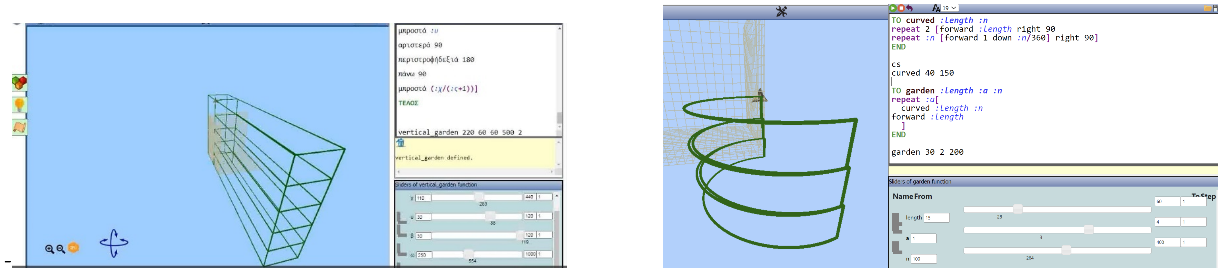

Figure 2: Designs of the vertical garden of focus group 1 a) the initial design b) the design for a cylinder building

Table 1: Critical Incident 1

Line	Alias	Transcript
1	John	Ok! But how can we make the garden for that building?
2	Max	It means we have to make it fold like that (showing with his hands)
3	John	Ok let's think. (looks at the code). Now the sparrow moves forward and turns right to create a rectangle. What about, after it turned right to create a curved line rather than a straight one?
4	Max	Like the half of the circle?
5	John	Yes! How do we make a circle? Forward a bit then turn then again
6	Max	For a full circle is repeat 360 [forward 1 right 1]. So now it should be repeat 180 [forward 1 right 1]. But as part of the rectangle. Ok lets try it.
7	John	So the two sides of the rectangle would be a half circle. Would this be printed alright though?
8	Max	If we print it horizontally, I think yes.

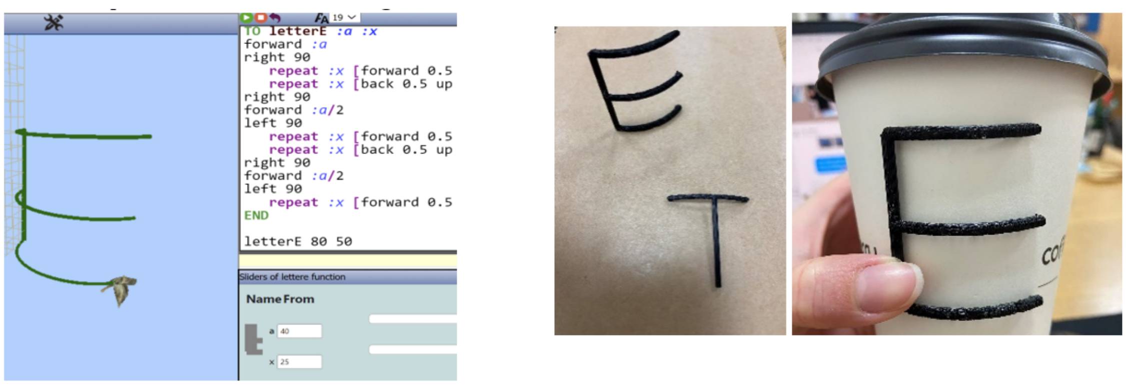

Figure 3: Group 1 creative creation of the letter E, inspired by their cylindrical garden. a) the letter E in the MaLT2-ext environment b) the letters E and T printed with the 3D printer directly from the MaLT2-ext environment

Table 2: Critical Incident 2

Line	Alias	Transcript
1	Mary	Ok but I don't think this [the 3D vertical garden] can be physically constructed ?
2	Kate	What do you mean?
3	Mary	How this will be printed? It is in the air ! This part is not supported by anything. How will it be printed correctly?
4	Kate	Haha I see what you mean. We have to program some parts that connect these
5	Mary	Or to think the shape again so that everything is supported correctly

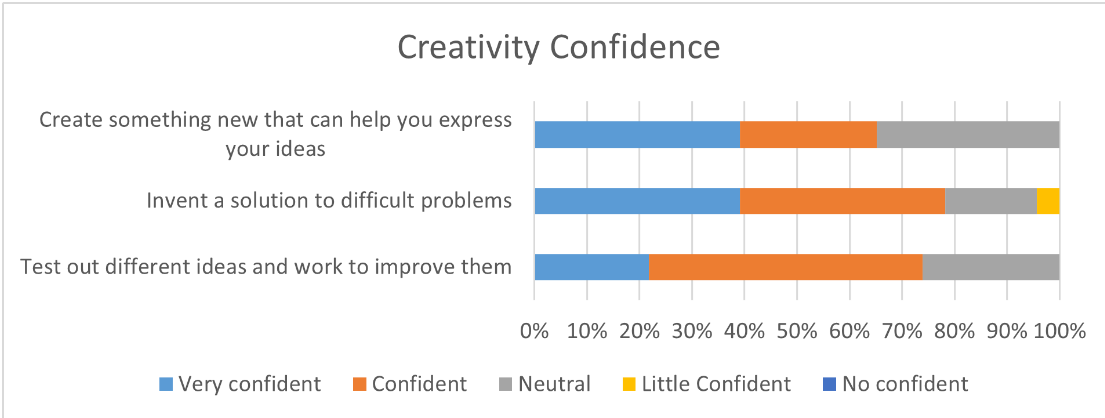

Figure 4: Post-survey results on students' confidence about their creativity

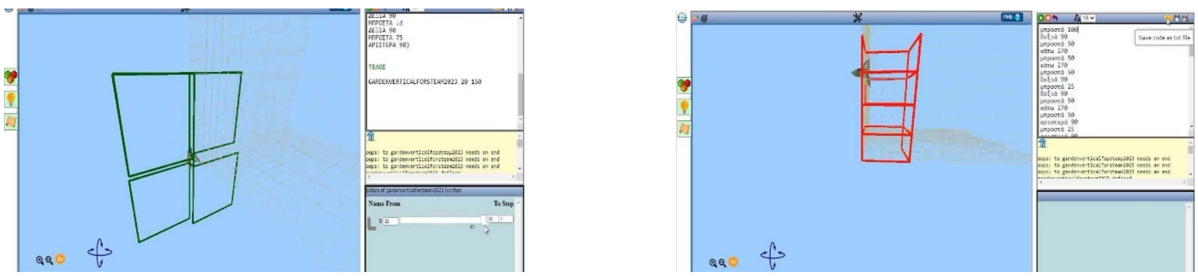

Figure 5: Group 1 designs of a vertical garden a) Initial design b) Design after considering 3D printing issues

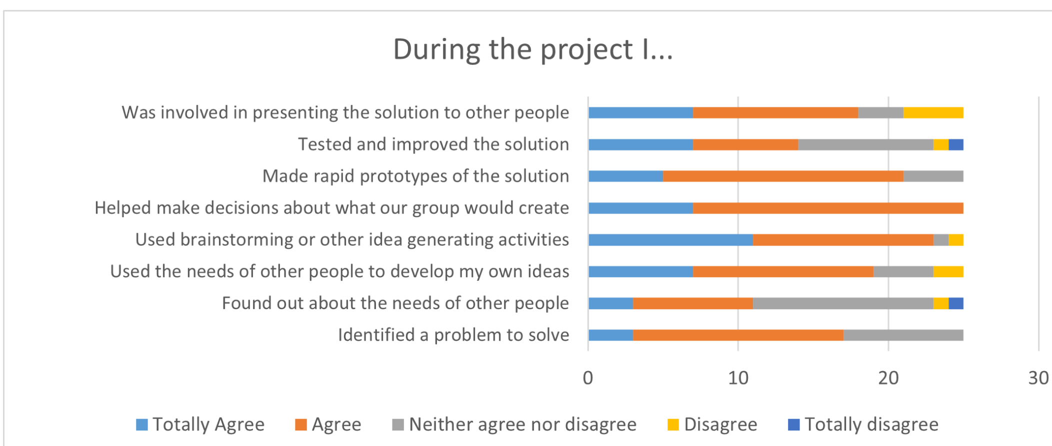

Figure 6: Post-survey students' responses about Design Thinking aspects

showed that students developed some DT aspects, including empathy, ideation, rapid prototyping collaboration, and communication of ideas. Figure 6 shows student responses on the post-survey regarding how they worked during the DT project with respect to different DT aspects (e.g. ideation, prototyping, presentation, empathy). Below we elaborate on the elements of empathy and rapid prototyping.

4.2.1 Designing with empathy. Empathizing with the target audience is a core element of the Design Thinking process and an important soft skill for children. During the analysis, we identified several critical incidents where students tried to imagine how their design would be used by the targeted users and how its use would be affected by other aspects such as the local climate or the building orientation. In many cases, students changed their initial design

Table 3: Critical Incident 3

Line	Alias	Transcript	Screenshots/Notes
1	Kate	I have an idea! I'm trying to fix the gradient (moves the sliders and animates the model). I want the whole garden to lean together.	
2	Teacher	What are you trying to do here?	
3	Kate	To change the slope	
4	Teacher	And why are you doing this?	
5	Kate	We need to give all possible solutions to the people who will use it. Let the garden be like a panel, the best for the plants and the environment, let the light go everywhere and fit every wall. That's why we have to solve this!	

to fit the needs of the "users" based on the information they had gathered from distributing an online survey in phase 2 (Discover). In critical incident 3 (Table 3) a student from focus group 2 decided to experiment with the slope of their digital model because, as she claimed in line 5, they had to give all possible solutions to the users. She also mentioned different parameters that they took into consideration for creating their model, which implies a high level of empathy for the problem they try to solve.

4.2.2 The importance of rapid prototyping. One emerging process followed by the students was what we coded as "creation of rapid prototypes" of their digital models. With the term "rapid prototypes" we refer to quick but significant modifications that a group made to their digital and/or model, resulting in a noticeably different version from the previous one. In the "Define" phase all groups created simple prototypes of their models representing only the main characteristics of the garden e.g. a single long rectangle, or many small rectangles on top of each other. The aim was to decide and create the main procedures that would draw the model on MaLT2-ext's scene. Then in the "Develop" phase, they modified the procedures' code and the parameters' values with the sliders, adding details to their model and experimenting with different prototypes according to the recorded needs. Based on feedback from their peers, they improved the models with small changes in the code, like the example presented earlier (critical episode 2). Overall, throughout the DT project, an average of 6 rapid prototypes was created by each group. The process of rapid prototyping is missing from the traditional DT projects with no technology involved since it is hard to create and modify prototypes with physical means. On the contrary, MaLT2-ext interconnected affordances enabled that process as students created quick prototypes either by making small modifications to their code or by dynamically manipulating the model's behavior with the sliders' tool, and directly seeing the result on the 3D scene.

5 DISCUSSION AND LIMITATIONS

We presented a study that aimed to explore the opportunities and enablers of connecting 3D printing with a high-level model design digital tool and the use of this combination in a Design Thinking project. Regarding the development of students' Computational Thinking, the results reveal that the affordances of procedural programming and dynamic manipulation of the model in the MaLT2-ext environment allowed for hard-to-imagine 3D designs with embedding complex mathematical and computational concepts, like the example in the critical incident 1. This could be interpreted as a form of what Wilensky and Papert [30] called restructurations of ideas, in the sense of reformulations of knowledge disciplines through new representational and communicational forms that do not require of formal rules to explain the phenomenon fully. Such designs take 3D printing activities one step further from the traditional approach of printing conventional shapes widening the limits of creativity about what could be printed. Moreover, the multiple representations of the same model (as Logo code, as the 3D digital model and as printed object) allowed for the deeper development of CT practices, such as pattern recognition, iterative design, and debugging. So far, CT has been studied in digital or physical settings [2, 11]. We could claim that this approach combines the benefits of both since students had the opportunity to apply CT practices in both forms, as we elaborated in the "phygital" CT section. Additionally, the process of programming an artifact that will be used for a real-world problem enhanced the critical aspect of what Kafai and Proctor called Critical CT [9], in the sense that students were not only focused on the computational correctness of their digital model (i.e. the code) but also on how their solution will affect the people who will use it. So far, as shown in recent reviews [11], in most CT-related studies, students are involved in the process of developing an artifact for themselves or the teacher. Integrating a CT activity into a DT project, added the aspect of "designing something for someone else to use", which seemed to have played an important role in how students programmed their digital models.

Regarding the second RQ the results showed that the use of digital 3D model design in MaLT2-ext in combination with 3D printing enhanced students' empathy, which is an important skill for human-centred design. Even though studies have shown an increase in students' empathy in traditional DT projects with no technology involved [19], we can see that the ability to easily modify the digital model or create alternative versions allowed students to bring the needs of the user to the foreground of the design and development of the artifact. In contrast, when there is no technology involved, empathy is usually limited to the initial process of recognizing the user's needs (Discover phase) but these needs cannot be fully met and tested during the phase of development due to technical limitations (e.g. lack of resources or time for creating several prototypes). The affordances of MaLT2-ext also enhanced the process of prototyping by enabling the rapid design and testing of numerous prototype 3D models in a limited time. Iterative prototyping is a core DT process however in many school implementations cannot be efficiently performed with physical means [1].

This study had also some limitations that should be taken into account. The time was quite strict for implementing a full Design Thinking project, and this was also highlighted by the participant teachers. Students needed more time in the "Develop" stage and many groups couldn't finalize their artifacts. Moreover, most groups didn't have the time to iterate between printing and redesigning their artifact after gathering feedback for the printed model. Finally, the fact that students printed a maquette of the garden rather than a usable object, like the decorative letters in Figure 3, didn't take advantage of the full potential of 3D coding and printing in DT projects. More studies are needed, that would focus on certain CT practices and DT aspects through that process. As this study is the pilot part of an ongoing research project, in the next steps we will improve the design thinking activities, to address the above limitations and enhance the processes of sharing, feedback and iterative design of the digital and printed artifacts.

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SELECTION AND PARTICIPATION OF CHILDREN

The presented study was conducted as an intervention in an after-school STEM club of an experimental school, in the context of an EU research project with an Ethical Advisor on research ethics. The researchers had issued official approval for this intervention by their university ethics committee for educational research. A written invitation was given to students and their parents with detailed information on the research aims, activities, data collection, and analysis processes, and how they could leave the study anytime. Interested students and their parents gave their written permission for participation and data collection. Students answered the pre and post-surveys on school computers using student-unique codes generated by their teachers. During the transcriptions, all data of students' identities were removed or replaced with aliases. The data are stored in the servers of the university and can be provided only after a written request explaining the intention of use.

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