Computational Thinking in Mathematical Modeling Projects. A Case Study with Future Mathematics Teachers

Jhony Alexander Villa-Ochoa[1], Jaime Andrés Carmona-Mesa[1], Daniel Andrés Quiroz-Vallejo[1], Alexander Castrillon-Yepes[1], and Danyal Farsani[2](✉)

[1] Universidad de Antioquia, 005010 Medellín, Colombia
{jhony.villa,jandres.carmona,daniel.quirozv,alexander.castrillony}@udea.edu.co
[2] Universidad Finis Terrae, Santiago, Chile
dfarsani@uft.cl

Abstract. Computational thinking has been a topic of debate in research in different STEM areas. This type of thinking is considered one of the vital skill sets for societies' technological and scientific development. This document presents the results of a study that investigates the computational thinking skills embedded in a mathematical modeling project. The project was developed by three future math teachers who participated in a mathematical modeling course. Analyzing students' documents, videos, and materials made it possible to identify actions associated with decomposition, abstraction, algorithms, representation/modeling, and generalization. The components of computational thinking observed in this study show the opportunities that mathematical modeling offers to the development of computational thinking skills; however, new studies are required on the guidelines and conditions necessary for teachers to recognize the importance of the components they use and to be able to explain them to their students through modeling projects.

Keywords: Computational thinking · Mathematical modeling projects · Components · Future mathematics teachers · Communication

1 Introduction

Research on teacher education for the integration of digital technologies has been a fertile area of work. Several topics, perspectives, and research approaches characterize the knowledge for technology use (Carmona-Mesa et al. 2020a; Castrillón-Yepes et al. 2020). Recent research also reports on the need that in addition to the use of technology to teach mathematics, teachers also develop computational thinking and the ability to promote it in their students (Carmona-Mesa et al. 2021; Carmona-Mesa et al. 2020b; Zampieri and Javaroni 2020; Rafiepour and Farsani 2021a).

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In a recent study, Zampieri and Javaroni (2020) used Scratch software to promote interdisciplinary knowledge between geography and mathematics in teachers; they also promoted basic programming knowledge as a basis for computational thinking (CT). Carmona-Mesa et al. (2021) analyzed the lesson plan of a future mathematics teacher. They observed that teachers could conceive of digital technologies as a tool to contribute to the understanding and study of problems in the environment of students. The authors reported that through this experience, it is possible to identify features of CT, among them decomposition, pattern recognition, abstraction, generalization of patterns, and algorithm design.

Although there is no homogeneous understanding of CT, it is possible to recognize in the literature competencies such as understanding, defining, and reformulating problems; thinking at multiple levels of abstraction; processing in parallel, and using strategies to work with large amounts of data (Wing 2006). The development of CT is not exclusive to the area of computing; therefore, interdisciplinary work is fundamental for the development of such competencies (Zampieri and Javaroni 2020; Villa-Ochoa and Castrillón-Yepes 2020; Rafiepour and Farsani 2021b). In that sense, the recognition of the opportunities offered by the different disciplines to promote the development of this type of thinking remains a necessity both for K-12 (Quiroz-Vallejo et al. 2021) and university education (Villa-Ochoa and Castrillón-Yepes 2020). Therefore, this study was carried out to identify CT components present in developing a mathematical modeling project.

2 Theoretical Background

In this section, we will describe the understanding of CT and mathematical modeling projects.

2.1 Computational Thinking

In research there is no single understanding of CT or its pedagogical and didactic foundations. According to Tikva and Tambouris (2021), CT definitions can be classified into two broad categories, (i) generic definitions that focus on CT as a thought process and (ii) definition models that describe what CT entails. The second includes the literature that seeks to develop models and describe the components that make up the CT for the authors. In a recent review, Villa-Ochoa and Castrillón-Yepes (2020) found that research on CT at the university level can be understood as an object of study or as a tool. In the first case, the CT is understood as solving a problem, a set of skills or competencies, and as theoretical and analytical resources. In the second case, the authors recognized CT as a methodological tool or as a resource or context in educational research. In Wing (2006), the CT is recognized as a set of cognitive skills involved in problem-solving, systems building, and understanding human behavior. As a methodology, Roig-Vila and Moreno-Isac (2020) point towards implementing basic concepts of computer science to face everyday problems, domestic design systems, and perform routine tasks. García-Peñalvo (2016) suggests an interpretation as applying a high level of abstraction and an algorithmic approach to solve any problem.

There are different models for characterizing CT; they describe components, skills, and competencies that can be recognized through the development of specific activities. Most of them include skills such as abstraction, decomposition, algorithmic design, generalization, and evaluation. Based on a literature review, Shute et al. (2017) defined CT as "the conceptual foundation required to solve problems effectively and efficiently (i.e., algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts" (p. 151). Based on this definition, the authors developed a competency model that can be used in CT assessment. This model includes facets such as: Decomposition, Abstraction (this includes: Data collection and analysis, Pattern recognition, Modeling), Algorithms (includes: Algorithm design, Parallelism, Efficiency, Automation), Debugging, Generalization, and Iteration.

A strong trend in international research lies in the links that this type of thinking has with other areas of training, including mathematics (Carmona-Mesa et al. 2021), science, and other STEM areas (Carmona-Mesa et al., 2020b; Lee et al. 2020). The following section will describe mathematical modeling and its links with computational thinking.

2.2 Mathematical Modeling Projects

Mathematical modeling and applications is a research domain within Mathematics Education (Niss et al. 2007). Modeling is understood as a practice of articulation between two entities; one called a model that serves to act on another called modeling. The intervention of the modeling entity on the modeled entity is diverse. In math class, this practice of articulation is concretized through modeling tasks. According to Villa-Ochoa et al. (2017), different types of tasks offer a diversity of opportunities for learning mathematics, developing competencies, and how citizenship is exercised.

For Villa-Ochoa et al. (2017), modeling projects are a type of open task that promotes processes of inquiry and problem-solving. For the authors, these projects can be seen as a resource to teach content, promote the development of students' abilities, establish relationships between mathematics and other disciplines, and develop reflections and critical visions on the role of mathematics in mathematics society.

The topic, the purposes, and the ways of developing the projects are characteristics that differentiate modeling as projects (Villa-Ochoa et al. 2017). In addition, different authors recognize the connection of mathematical modeling projects with computational thinking. For example, for Shute et al. (2017), two of the main characteristics in common of mathematics and computational thinking are problem-solving and modeling. On the other hand, Ang (2021) highlights that some of the key skills of computational thinking such as gathering relevant information, studying and analyzing problems for patterns, decomposition, and developing step-by-step solutions are ideas that characterize mathematical modeling.

3 Methodology

The empirical phase of this research was carried out in a mathematical modeling course for future mathematics teachers; the course was led by two teacher trainers with research experience in modeling. The course had 12 students who had already taken the subjects of mathematics (arithmetic, calculus, algebra, etc.), pedagogical (curriculum, educational policies, educational psychology, etc.), and didactic (of algebra, arithmetic, statistics, etc.). This section presents details of the context and participants, the empirical data, and finally, the procedures for data analysis.

3.1 Context and Participants

This research was conducted during the second semester of 2018 in a 64-h course. Each session lasted four hours. The mathematical modeling course was part of a bachelor's degree program for mathematics teachers offered by the Faculty of Education at a public university in Medellin, Colombia. The program has a duration of five years, spread over ten semesters.

In the course, future teachers perform readings of scientific articles on modeling, develop tasks and analyze their scope and purposes, and participate in mini-courses with practicing teachers who implement modeling in their classes. Additionally, they develop modeling projects and class plans under the guidelines of formative evaluation (Sánchez-Cardona et al. 2021). The projects are a strategy that seeks to offer future teachers first-hand experience in modeling. Participants should meet in a group throughout the course, identify a topic of interest, and generate and validate a plan to develop the project. After developing the project, future teachers must generate a written report, a video and make an oral presentation to the whole group. See Sánchez-Cardona et al. (2021) for more details about these projects.

The findings reported in this study relate to a subgroup of three students whose modeling project focused on the use of digital technologies and mathematical modeling. The participants were fourth-year undergraduate students. Their ages ranged from 19 to 21 years. In this chapter, students are referenced using pseudonyms: Alexandra, Johana, and Daniela. The choice of this project was due to the interest that the students expressed in the development of modeling with technologies. In addition, because of their desire to voluntarily participate in the study.

3.2 The Data and Its Analysis

With the approved ethics protocol and informed consent of the students, data were collected in the form of video recordings, written productions of the participants, and researchers' field notes. In the case of this study, the following data were presented: a video of the fifth session in which the participants presented three project ideas to be developed orally. A video of the fourteenth session in which they presented the final results of the project. A written document with the report of the project results and three documents of the researchers' field notes with the reflections on the advice offered during the semester were collected.

The data was organized and saved in electronic files. We used content analysis tools that consisted of: (i) analyze and transcribe the students' dialogues in which they expressed how they developed their project, the motivations, techniques, and models built. (ii) Identify the uses of the technologies present in the realization of the project, and (iii) determine the components of computational thinking according to the definition and characteristics presented by Shute et al. (2017). The following section presents the main results of the analysis.

4 Results

In this study, the components of computational thinking present in a mathematical modeling project developed by future teachers were identified. The observation of the classes and the analysis of the documents along with videos offered evidence that the students involved decomposition, abstraction, representation and simulation, algorithms, and generalization, during the development of their project. To achieve the objective of this study, this section was organized by the five components of computational thinking (Shute et al. 2017) and, within each one, the data that support findings are described.

4.1 Decomposition

For Shute et al. (2017), decomposition consists of "Dissect a complex problem/system into manageable parts. The divided parts are not random pieces, but functional elements that collectively comprise the whole system/problem" (p. 153). In the course, the development of the projects is conceived in three phases, (i) the conception of the project idea, (ii) the design and development of the plan, and (iii) communication of the results. Although initially, the future teachers declared various ideas, they focused on the consumption of internet data on mobile devices. This decision was based on the experience of one of the participants; according to Alexandra "they called one of her classmates to offer her the increase in gigs in her data plan [mobile Internet]. This captured our attention to whether or not it is necessary to have more gigabytes available" (Video, fifth session, presentation of the idea).

In the second phase, plan design, the following parts were identified:

Define the Scope: After defining the topic, the students set out to understand the situation and define the users who could be beneficiaries and the necessary resources for the development of the plan. According to Johana "we had many ideas, but we didn't know if we could do all of them, so we focused on helping users to reflect and make decisions about their consumption [of mobile internet data]" (Video session 14, oral presentation of the draft).

Execute and Adjust the Plan: As they developed actions to develop their projects, new directions emerged. For example, Johana pointed out, "we started looking for information on consumption, and we found a study by Asomóvil Company that said that user demand was 0.4 gigs per month while companies offer plans of 1.8 gigs per month. That seemed like a huge gap, so we set out to learn more about the real demand of Colombians" (video session 14).

Construction and Testing of a Product: The students built a data consumption simulator to inform users about the actual consumption of data and inform decision-making regarding the plan they have. This simulator included the construction of models and algorithms. This will be presented later in this section.

In turn, in the communication phase, they shared their results with all the other participants in the course. They also organized a video made up of three parts: i) The main findings and reflections derived from the project, ii) a dramatization of a dialogue of potential users, their arguments, and counterarguments when making decisions about consumptions and iii) the introduction of the simulator as a response to specific user needs, they also presented some reflections on their learning and other variables to be considered in future developments.

4.2 Abstraction

In abstraction, three subphases can be defined (Shute et al. 2017). They are:

(a) Definition of variables, data collection, and analysis: in different phases of the project, the students determined and defined the variables; For example, in their first written report, the students indicated that they could include variables such as: i) Applications most used by Colombians, ii) Time available for the use of each of the applications, iii) Number of Gigabytes offered in the data plan, iv) Operator's signal, and v) Number of minutes included in the plan for calls.

Based on this, the students inquired at the Ministry of Technology and other companies about studies on Colombian consumption. The construction of the data included studies on which are the most used applications and the amount of data that each application consumes, the way to determine this information. As mentioned above, when reviewing the information obtained, they were delimiting its scope, therefore, its variables. It was thus that finally arguing with three variables would be enough to respond to their objectives. These three variables were: (i) most used applications, (ii) weekly consumption by application, (iii) Total consumption in the month. As will be explained later, in the availability of the data, other associated variables emerged.

(b) Pattern recognition: In this phase, we distinguish two actions, the first the use of characteristics/patterns found by other studies (example, most used applications, most influential companies, most required plans) and the identification of relationships between the variables. As mentioned in the previous phase, the characteristics/patterns derived from previous studies contributed to the understanding and adjusting of the problem. They also offered information on the determined variables and the relationships between them.

Once they determined the variable "consumption of each app per hour", the future teachers abstracted the multiplicative relationship between this value and the number of hours consumed per week. This was a crucial element in the construction of the mathematical model.

(c) Modelling: according to Shute et al. (2017) abstraction focuses on modeling the workings of a complex problem/system. This will be discussed in the next section.

4.3 Representation and Simulation

In this study, the entire development of the project was conceived as a mathematical modeling process. In other words, the conception of the problem, the construction, validation of models, and the communication of results are considered phases of a modeling process. Therefore, in this phase, we refer to the representation of the models in mathematical language and the construction of the simulator. The students constructed the linear functions that represent the consumption of each application (app) and, later, the function that would present some gigabytes consumed by the user. The following form determined this function:

$$C_t = 4(CAp_1 \times HAp_1 + CAp_2 \times HAp_2 + \ldots + CAp_n \times HAp_n) \quad (1)$$

Where:
C_t: Total internet consumption in a month.
CAp_i: Consumption of application i per week.
CAp_i: Number of hours consumed by a user in a week in the application i.

For the simulation, the students used Excel software and studied the language they required to move from the algebraic equation to programming in this software and designed the simulator image. Based on the data available per user, they built the algorithms described in the next section.

4.4 Algorithms

According to Shute et al. (2017), this phase consists of "design logical and ordered instructions for rendering a solution to a problem. The instructions can be carried out by a human or computer" (p. 153). This phase involved the students coordinating the previously built models with the data that they could access. Through internet sources and information from mobile devices, the students could determine the amount of data consumed by each application in one minute. They also observed that these values could change according to some functions of the App, for example, video calling. Therefore, to "adjust" the mathematical model to these conditions, the team separated consumption by messaging from consumption by a video call from some applications. Likewise, they carried out the consumption calculations per hour, per day, and the conversion from Megas to Gigas. In this process, the Algorithm design category (Shute et al. 2017) involved coordination; the students identified gaps and, therefore, required new developments to overcome them. Overcoming the gaps was one of the arguments students contributed to the efficiency of their algorithm, for example, in one of the consultancies. Daniela pointed out that "initially we thought about using the daily hours of consumption per application; however, we saw that from one day to the next, it was not possible to generalize, so we decided to do it by estimated weekly consumption". At another point, Alexandra noted that "we realized that when there are video calls the signal drops, so we realized that the data consumption is higher, therefore, to make our simulator more complete (adjusted to reality) we decided to include those characteristics". Finally, with all these developments, the simulator became an automatic tool in which users must fill out an estimate of weekly hours for each application. It shows the total value of gigs consumed in the month. However, the students were explicit about the limitations of their simulator since, according to them, it does not include fortuitous events or user omissions in the estimation of weekly consumption.

4.5 Generalization

According to Shute et al. (2017), this phase consists of "transfer CT skills to a wide range of situations/domains to solve problems effectively and efficiently" (p. 153). In the oral presentation phase before the course (session 14), the team was questioned about the limitation of the application to the set of most used applications; since some users may prefer an application not included in the list. In this regard, Daniela observed that "we did not have the conditions to take all the applications that exist, but it is possible to extend our simulator to include it" (Video session 14). Subsequently, this particular student explained to the group how to obtain the consumption data of any application installed on a cell phone and, based on this, how a box can be extended in a simulator in Excel. She also pointed out that a similar simulator could be built for home internet consumption. In their final video, the students also indicated that "… We wondered if the consumption that you think you do could vary if the increase in public Wi-Fi zones in the city is considered". With this, the students warned about using online applications that can be activated when one has access to Wi-Fi.

5 Discussion and Conclusions

Our findings prove that future teachers can use computational thinking skills when developing modeling projects with technology. The decomposition, abstraction, algorithms, and generalization were identified. Additionally, this study observed communication skills, and the use of technology in the project enabled the representation and simulation of data consumption for each application. These findings suggest that mathematical modeling projects can be a process to promote computational development, especially in modeling and simulation skills, which are an aspect that requires further research and development in Latin American curricula (Quiroz-Vallejo et al. 2021).

The experience reported in this study suggests that open problems and student participation in defining the scope and objectives of the problem is not a linear process, nor is it predetermined; Contrary to this, it consolidates as the context is understood and the available resources are recognized. Although this characteristic has been recognized in mathematical modeling projects (Villa-Ochoa et al. 2017), it is also a result that could be recognized in an understanding of computational thinking associated with complex problem-solving and linked to contexts.

The participants of this study also determined variables, relationships between them and represented them algebraically. These actions have been recognized in the literature as part of a mathematical modeling process (Blum and Leiss 2007); However, in this study, they intended to build a simulator that demanded transcending the notion of variable to the context of the software used, to communicate and make decisions regarding data consumption. Although this is a characteristic of mathematical modeling from a socio-critical perspective (Silva and Kato 2012); It can also be considered a characteristic of computational thinking since it allows to solve real problems and show a role of mathematics and computation in solving social problems.

In this project, the development of algorithms was observed in the construction of procedures to achieve the end and other actions typical of mathematical and computational thinking. Among them is the argumentation on "the logic" of the algorithm and its functionality, appropriation of a language and techniques to move from the mathematical model to the simulator in Excel, the emerging delimitation of new variables, and the developments to make them operational in the simulator. Furthermore, the students planned and developed a communication strategy. They presented their results and were also able to demonstrate communication skills that were not visible in the development of the project. For instance, students were able to extend the development of the simulator to other values of the variable "used application" or another context or problem with similar characteristics. Finally, the communication of results is a phase and skill within mathematical modeling (Blum and Leiss 2007). From the experience of these students, it could also be considered a computational thinking component, not only because it allows the results to be disclosed; but also, because through debate, the uses of the components are evaluated and made visible based on the results and in the voice of the developer.

The computational thinking components observed in this study indicate synergy between computational thinking and mathematical modeling. Our findings add to the existing literature suggesting STEM disciplines' importance in developing computational thinking (Zampieri and Javaroni 2020; Carmona-Mesa et al., 2020b) and mathematical modeling with digital technologies (Molina-Toro et al. 2019). In particular, mathematical modeling as a tool for developing computational thinking components (Ang 2021; Carvalho and Klüber 2021).

Finally, it is vital to inform the study's limitations and lines of action for future research. Although the reported experience is constituted as an input to expand the current research regarding the actions to be followed to favor that mathematics teachers can teach their disciplinary knowledge and make explicit components of the CT, the present research only describes how the actions and decisions of the teachers show some components of the CT. Therefore, it is important to expand in future studies the guidelines and conditions necessary for teachers to recognize the importance of the components they use and can make them explicit to their students through modeling projects.

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