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OPTIMIZATION OF THE 3D PRINTING AND TEST OF MATERIALS FOR TEACHING AND LEARNING FOR STUDENTS WITH VISUAL IMPAIRMENT[i]

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Abstract:
The article presents the studies and steps followed to optimize the 3D printing of an inclusive material, the "Adapted Multiplication Domino". This material is a game that follows the same rules as a traditional domino, but with numerical representation at the ends of each piece with mathematical operations (multiplication and division), so that students can calculate, play, and fix math contents, which can be played by students with and without Visual Impairment. During the printing of the first prototype of this material, the printed pieces contained stringings (traces of filament in empty spaces of the piece), which made it difficult for blind students to read the braille operations. A literature review about problems in 3D printing was realized, using databases and platforms such as SciELO, Google Scholar, and Capes Periodical Portal, to be able to identify and solve the problem that was occurring. With that done, the complete game was printed and tested, to collect feedback, and based on that, making the necessary changes and obtaining a satisfactory and adequate result.

Keywords: 3D printing, visual impairment, didactic material

1. Introduction

3D printing is getting more and more popular in the current market environment. The fast growth of this technology over the last decades resulted in tools capable of producing three-dimensional items with richness in details, and permitting the development of pieces with different shapes, colors and materials. Such features qualify 3D printing as applicable to assist students with visual impairment in their learning process, from the development of materials with tactical representation.

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Thus, the 3D printing showed itself as a useful tool for the education of students with visual impairment inside the classroom, since the availability of adapted and diversified materials is not enough to meet the demand, and the conditions are still precarious (Mamcasz-Viginhesk, Lúcia, et al., 2019). This precarious situation comes from the absence of structuring in the scenario of inclusive education, and the lack of adapted materials results in problems and even a possible non-comprehension of certain subjects by students with visual disabilities. In accordance with Jafri (2015, p.1):

> "*Unfortunately, in many cases, much of this information may not be amenable to the sense of touch either because it is presented in two-dimensional form (for example, as images or distant scenery) or because the entities are on a large scale (e.g., buildings) or physically inaccessible precluding tactual exploration. Though a sighted observer may provide verbal descriptions of these details but these are usually not sufficient for blind individuals to construct complete and accurate mental representations of physical entities[...]".*

With the highlighted facts, there is a need for the development and application of materials that could assist the teaching of students with visual impairment in an inclusive perspective. The material "Adapted Multiplication Domino" was idealized by Thiago Roberto dos Santos (CNPq 08-2020 scholarship holder, author of this paper), which is a game that follows the same rules as a traditional domino, but with numerical representations on the extremities of each piece of mathematical operations (multiplication and division), so the students can calculate, play and fix mathematical contents simultaneously. The game puts itself from the inclusive perspective by introducing mathematical operations in indo-arabic numerals and in braille, so it can be used by students with or without visual impairment simultaneously. The domino, initially, was designed and printed in 3D printers by FDM (Fused Deposition Modeling) to be tested subsequently. However, during the printing process, some problems were identified, such as the occurrence of filament scraps between the braille spheres, which made the use of the domino by the blind students impossible. Thus, this research fits as the continuity of the project begun by Santos (2020).

According to Santana (2015), even with the great popularity of 3D printers in the current market, little is known about the limitations of their performance. With this highlighted aspect, in addition to the problems of the developed material's printing process, it was decided, in this research, to conduct a bibliographic review about the problems in the 3D by FDM printing process, fix them and optimize the printing of "Multiplication Domino", making it applicable. After the corrections and optimizations, a material's validation was conducted to verify its capability of application as a truly inclusive material.

2. Material and Methods

The methodology used in the execution of this research can be divided into three main steps. The first one, denominated "Bibliographic review" was performed after noticing some problems in the braille's printing in the pieces of the first prototype of the domino, making the effective application of the developed material impossible. For the development of this review, the only instrumental needed was the use of a computer with internet access to make possible the research of articles about potential problems in 3D printing by FDM. The database used was Google Scholar. The keywords used were "Impressão 3D", "Problemas" and "Parâmetros da impressão 3D", combined with the Boolean operator "AND", in Portuguese. And respectively, in English: "3D printing", "Problems" and "3D printing parameters". The bibliographic review carried out answers the following punctual question: Which are the possible problems that can be found by researchers in the 3D printing by FDM?

After the bibliographic's review accomplishment, the second step of the project was started, consisting of the application of this study to optimize the 3D printing of the material "Adapted Multiplication Domino". For this step, the instrumental needed was a 3D printer by FDM (Ender 3), and PLA filament. With such optimization implemented, the third step of the project was conducted, and the game of dominoes was printed and sent for testing. In order to receive the test's feedback, a questionnaire was sent to the responsible by testing the dominoes, and with those answers, changes could be carried in accordance to what is needed. The questionnaire contained questions about the quality of the 3D printed pieces, the filament used, and points about inclusion to verify if the material could be effectively considered inclusive.

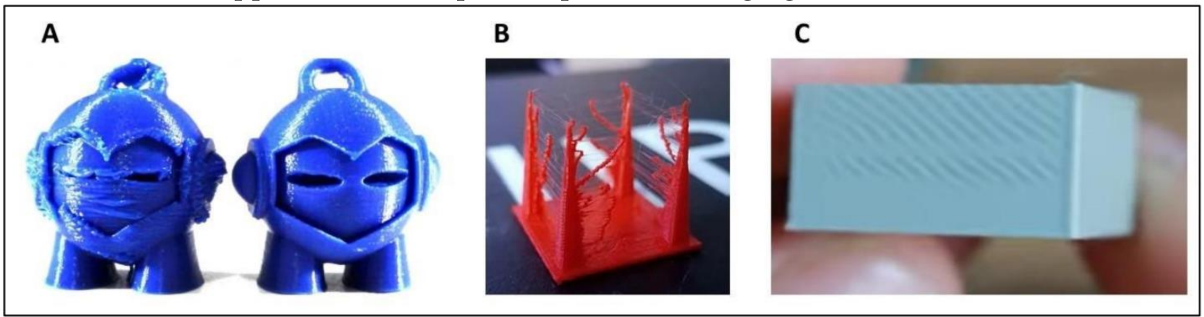
3. Results and Discussion

3.1 First Step: Bibliographic Review

As a result of the research, it was possible to identify 8 of the major problems related to the 3D printing process by FDM. The nozzle's temperature adjustment was one of the difficulties highlighted by Azevedo (2013) when he carried out the performance evaluation of the RepRas Mendel 3D printer. This is a parameter of great importance in 3D printing, which impacts mechanical and visual properties in the designed piece.

Azevedo (2013) conducted, in his research, a resistance test for traction in pieces with standardized format, varying only the parameter of extrusion temperature. A growing pattern was observed for tension until approximately 200ºC. From this point, the tension values fall, which, according to Azevedo (2013), might be a consequence of an alteration of the material's properties to this temperature. In relation to the influence of the filament's extrusion temperature over the visual piece's aspects, Laffranchi (2020) highlighted that high temperatures may generate the occurrence of "stringing" during the print. This happens because of the high heating of the nozzle, that even with filament's retraction on the piece's empty spaces during the extruder's head movement, a small amount is still extruded, generating stringings. In addition, high temperatures may generate a melted aspect in the piece, with details loss, as evidenced by Azevedo (2013). With respect to low temperatures, Laffranchi (2020) affirms that a phenomenon called sub-extrusion may occur (extruder head releases less filament than needed for the print). All the problems mentioned above can be observed in Figure 1.

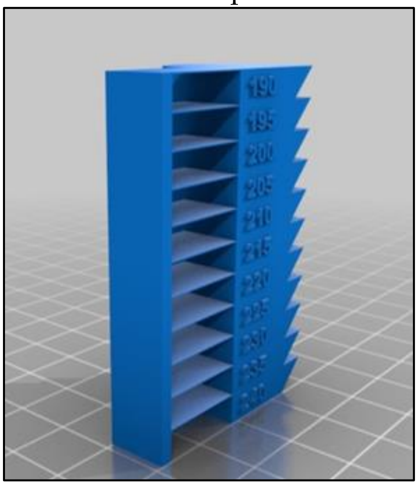
Figure 1: Problems evidenced by the lack of temperature adjustment in 3D printing. Melted appearance of the printed part (A); Stringing (B); sub-extrusion (C)



Source: Como Calibrar (2020a, 3 PrtSc, A – 1 min. 44 segs.; B – 1 min. 56 segs.; C – 3 min 8 segs.)

To execute the temperature calibration, a solution was found using a model (Figure 2) developed by Kiland (2017). This model consists of a tower that the user has to print changing in the G-code, changing the temperature from 5 to 5 millimeters, as shown in the piece in Figure 2. After the print is done, a visual inspection is performed to determine what is the best temperature to the used filament.

Figure 2: Model to temperature calibration



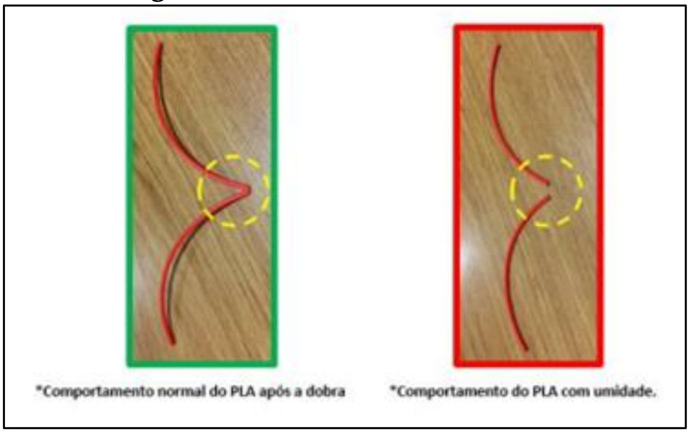
Source: Kiland (2017).

The second problem exposed in the bibliographic review is the non-adhesion between the layers, which according to Lima (2017) may occur due to the fast temperature drop of the filament and the solidification of the material. This aspect affects directly the mechanical properties in the piece, and may make the printing impossible if during the process the layers don't have enough adhesion to remain attached. A problem noticed by

Azevedo (2013) in his study, is the piece's detachment from the printing table, which may occur due to the printing table's temperature or to the small surface area of the piece with the table.

In relation to the material used, it is important to verify the moisture in the filament (third problem). According to Carvalho (2019), moist filaments may cause defects in the print, lowering the visual quality, prejudicing the layer adhesion, changing the mechanical properties, affecting the post-processing, as well as causing stringings in the piece. There is a simple test that depending on the filament and the absorbed moisture percentage, indicates if the filament contains too much moisture. The test consists in folding the filament and verifying if it remains in one piece or if it breaks, as can be seen in Figure 3.

Figure 3: Filament condition's test



Source: 3DLAB (2016).

In relation to the printing software, responsible for the discretization of the 3D model in 2D contours, that means that the processing of codes that will be recognized by the 3D printer (Guan, 2021), their use and choice to print is a very common difficulty in 3D printing. Baumann et al. (2015), conducted a study with the objective of comparing 3D printing software programs: Cura, KISSlicer, Skeinforge and Slic3r. For greater comparison accuracy, the impression parameters determined by the users were standardized, and the only variables were the codes generated by the software analyzed. From the obtained results by Baumann et al. (2015), it is concluded that the choice of this software has a direct influence on the result of the print, and has to be considered one of the parameters to be determined for printing a piece.

The sixth problem evidenced in the bibliographic review, is the already quoted phenomenon, known as stringings. As previously seen, it can be generated when the filament extrusion temperature is too high. However, if the extrusion temperature adjustment was already done, there is another parameter that could be generating the stringings, the retraction. According to Silva (2020), retraction is the parameter that provides for the printer with the information to retract the filament (reduce the pressure) of the extruder nozzle when there is any discontinuity in the piece. The 3D printing software programs display the retraction as a parameter to be specified. Therefore, does not exist an ideal value for retraction, the indicated is to perform tests varying gradually the retraction distance and the speed.

The seventh problem is the lack of calibration of the filament flow. According to Langford (2012 apud Santana, 2015), the variance of the filament diameter has a significant effect on the volumetric flow, which can result in under-extrusion problems or excess of extrusion. In addition, Laffranchi (2020) affirms that the filament adjustment is an important step for obtaining a good visual quality in the print and having more precise dimensions. In the slicing software programs, it is possible to adjust the filament flow. To perform such adjustments, Laffranchi (2020) used the lateral faces of a cube as a printing model. In the software Ultimaker Cura, the extrusion width was defined as 0.4 mm and 2 fillets for the wall. This way, the wall's thickness will result in 0.8 mm. For the initial flow value, the standard software configuration (1) was chosen. The piece was printed and with the help of a digital caliper, 4 measurements were carried out along the wall. The flow correction is based on these results, applied in equation 1:

$$S = \frac{S_0 * L}{U}$$

Being S the new flow, $S_0$the old flow, L the extrusion width and U the average width of the measured wall.

For the test performed by Laffranchi (2020), the new flow obtained by the equation was 1.40 (140%). Setting this value for the flow in the software Ultimaker Cura, and printing again, resulting in a piece with a wall thickness of 0.80 mm, as expected.

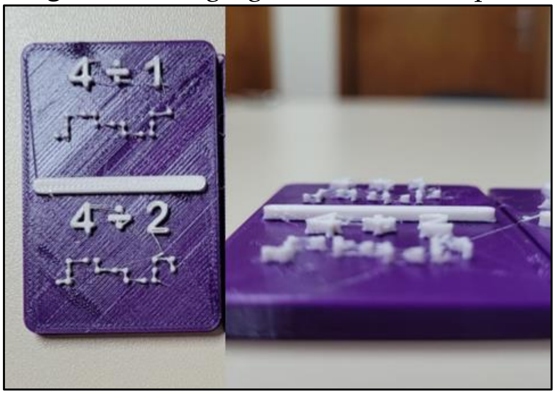
The last topic studied in the bibliographic review was the surface finish, which needs to be performed depending on the purpose of the piece, to enrich details and visual aspects. A solution found by Azevedo (2013) for pieces printed in ABS, was the use of acetone in the post-processing, which consists in heating acetone until it becomes steam, reacting uniformly with the piece's surface. However, the treatment with acetone is not efficient for other kinds of filament. Laffranchi (2020), tested a surface finish technique for pieces printed with PLA, which consists in applying thin layers of resin over the finished piece, in the same direction as the printing lines. From the tests made by Laffranchi (2020) and Azevedo (2013), it became clear that the final quality of the piece and the wealth of details are better in the piece that received the surface treatment. Thus, the post-processing of the pieces produced by 3D print FDM has a meaningful influence on the piece's result, and depending on the product's objective can even be considered as a step of the process.

The conclusion is that for the acquisition of good results in the pieces manufactured by FDM, there are countless processes to be followed before printing. The bibliographic research tried to summarize some of these important processes. With the problems explored, it was possible to identify what was happening in the domino's printing process, and consequently, follow the research's content.

3.2 Second step: Print Optimization of the Inclusive Domino

The purpose of conducting the bibliographic research about the problems in 3D printing by FDM, was to apply the knowledge acquired to optimize the material's print. The main problem occurring was the appearance of stringings between the braille's spheres, which makes the pieces illegible to visually impaired students, as can be seen in Figure 4:

Figure 4: Stringings in the braille's print

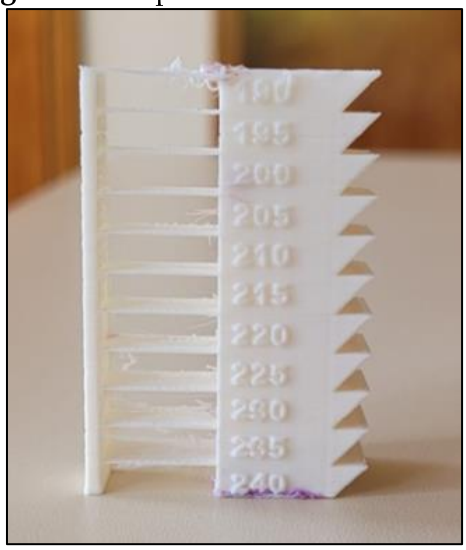


Source: Own authorship.

As seen previously in the bibliographic review, one of the reasons for the 3D print to generate stringings is the high temperature for the filament extrusion. Another possible reason is the lack of calibration of the parameter retraction in the software. The decision taken in this research was calibrating first the temperature, and if the problem was not solved, adjust the retraction.

To calibrate the temperature, a model developed by Kiland (2017) was used, it consists of a tower which the user has to print changing the G-Code, reducing the extrusion temperature in 5ºC, with the initial temperature as 240ºC and final temperature as 190ºC, from 5 to 5 millimeters, as indicated in the piece (Figure 2).

Figure 5: Temperature calibration tower



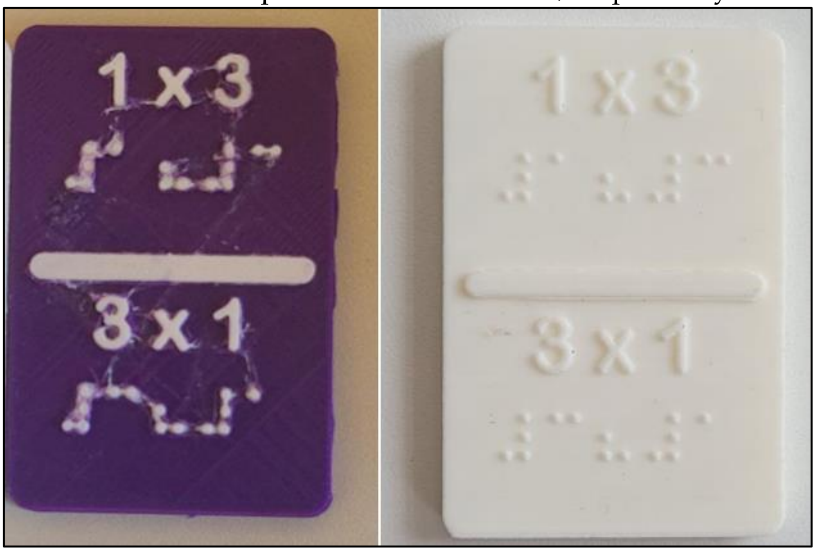
Source: Own authorship.

The printing software used was Ultimaker Cura, with the tower oriented vertically, with standard printing configurations, except for the filament extrusion temperature, which was adjusted in the code according to the tower. The result obtained through the experiment can be seen in Figure 5.

After visually inspecting the calibration tower, it was determined that the ideal extrusion temperature for the braille print is 200ºC. This choice was founded on the observation that from 200ºC (or less), the stringings are no longer evident in the calibration tower. Then, we decided that the layers where braille would be printed, this would be the chosen temperature, and it was specified in the G-code. For the other layers, the temperature used was 210ºC, from the fact that 200ºC already shows small under-extrusion traits, avoiding that the choice of this temperature affects the piece's visual aspect and the adhesion between the layers. In an attempt to don't decrease the temperature abruptly, a gradual temperature variation was written in the G-code, from 210ºC to 200ºC with a variation of 1ºC each 2 complete layers.

With this change, and also changing the piece's printing direction (the piece was being printed laid down in the printing table and was changed to be printed upright), showed a significant improvement, without the occurrence of stringings in the braille, as can be seen in Figure 6. With these defined parameters, the printing time of each domino varied between fifty and fifty-five minutes, with this difference occurring due to the variation of the mathematical operations and numbers in the domino. The printing time before the alteration of these parameters was approximately 45 minutes.

Figure 6: Comparison between the pieces before and after the parameters' alterations, respectively



Source: Own authorship.

This optimization enabled the reading of the braille by the fact that the spheres are not connected by the filament strands. In relation to the colors used for the print, it was not possible to keep the printing design with the piece's body in the color purple and the braille in the color white due to the printing direction used. It was decided to keep the piece monochromatic during the printing and, if needed, applying different colors in the mathematical operations and the division symbol in the post-processing.

With these choices defined, it was possible to print the whole game, which contains 28 pieces, totaling 27 hours of print. The print was made using white PLA filament, and the printer Ender 3, the materials were made available by the University.

3.3 Third Step: Game Testing and Necessary Modifications

The developed material was manufactured from an inclusive perspective, so it can be ideally used for people with or without visual disabilities. To analyze the accuracy of the idea, the artifact was sent for tests, in order to verify if the print was proper and if the material could be considered inclusive.

The material was tested over a period of 2 weeks by a teacher expert in special education, with emphasis on students with visual disabilities. To receive feedback from the material's tests, a questionnaire was elaborated, with questions about the printing quality, the used filament, and issues about the inclusion. According to Vieira (2009), questionnaires sent to the respondents so that they answer it themselves are called self-administration surveys, which is the category that the questionnaire used for this research fits.

The decision to elaborate a questionnaire to gather feedback on the test conducted was guided for the ease to collect information considered necessary to the research. For that, the recommendations of Manzato and Santos (2012) and Vieira (2009) were followed. It started defining the questionnaire's objective: to collect information about the inclusive domino's applicability. From the main objective, the specific information that the questionnaire might address was considered and defined: printing quality (If the students could read properly the braille or the Indo-Arabic numerals); printing material (If the filament used - PLA - does not harm the blind students' touch); consideration about the game's insertion in the inclusion category. With the objectives defined, the respondents were chosen. For that, the test's place was defined - an institution that has an agreement with a research group from UTFPR and attends students with visual impairment - and the respondent was responsible for the test, which collected and analyzed information during 2 weeks with students and summarized them in the questionnaire's answers. With the objectives and the responders' choices defined, a covering letter was elaborated, which, according to Vieira (2009), is responsible for giving the respondent a work's first impression, as well as showing the research's importance. The questionnaire answered by the responsible for testing the material can be seen in Figure 7.

Figure 7: Questionnaire answer about the Inclusive Domino

The material "Adapted Multiplication Domino" was developed in an inclusive perspective. Considering this, the mathematical operations of multiplication and division were written in indo-arabic numerals and in braille, so it can be used by students with or without visual impairment simultaneously.

The questionnaire presented below aims to test the material, so we ask for your opinion regarding the contributions of the game in the teaching and learning process of mathematical concepts for blind students, their evaluation of the material, whether or not there were difficulties during the game, and suggestions for improvements in relation to the construction of the material.

Your contribution is important, once the indications of corrections and/or optimization in the material will contribute to its improvement and dissemination.

1) Did the blind student find it difficult to handle the domino?
(_X_) No
(___) Yes
The space provided below is reserved for suggestions and/or justifications.

Even though the major part of the blind students didn't find any difficulties while handling the material, some of them found a difficulty related to the division line, that separates the operation in the superior and inferior part of the domino. A suggestion is to facilitate the localization of the operations, concentrating the braille operations near to the division bar (center of the piece).

2) Is the material used in the domino's confection (filament- PLA) suitable for reading braille?
(__) No
(_X_) Yes

The space provided below is reserved for suggestions and/or justifications

It was noticed that the material is suitable and was carefully chosen, since the students liked it and it didn't impair the touch.

3) Can this game be defined as an artifact/mediation tool for teaching the content multiplication and division operations (tables) to all students?
(__) No
(_X_) Yes

The space provided below is reserved for suggestions and/or justifications

4) Can this game be defined as an artifact/tool that significantly contributes to the learning of the mathematical operations of multiplication and division (tables) for all students?
(__) No
(_X_) Yes

The space provided below is reserved for suggestions and/or justifications

The material helps significantly in fixing the table.

5) Can the Adapted Multiplication Domino be considered an inclusive material?
(__) No
(_X_) Yes
The space provided below is reserved for suggestions and/or justifications

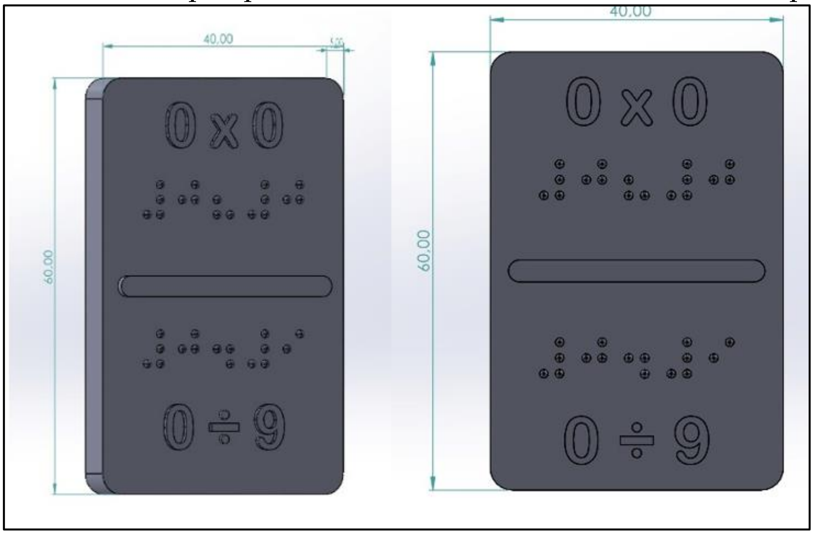
6) The domino was tested with students? How many? Were them all blind?
The material was tested during two weeks with teenagers and adult students. Being 8 students, among them 5 were blind, and 3 low vision. The blind students liked the activity because of the simplicity and the purpose of the calculations. The 3 students with low vision pointed out that the spacing of the number should be greater, and mainly there was a need to use contrast between colors (operatons and piece): White and dark, Orange and blue, red and green…

Source: Own authorship.

Analyzing the answers obtained in the questionnaire, two main problems were highlighted. The first of them, related to the blind students, was the perception of difficulty by some of those students in locating the mathematical operation in braille in the pieces because they contain operations in indo-arabic digits in high relief too. The solution found and suggested by the test's response was to invert the operations' position in the bottom part of the piece, in a way that the braille operations got closer to the division line in the center. The second problem, now related to the students with low sight, was the lack of contrast of colors between the base of the pieces and the mathematical operations. As commented in section 2.2, the choice of printing the pieces with monochromatic colors was due to the impossibility of switching filaments in the middle of the printing in the vertical mode, since each layer that contained braille's and indo-arabic digits' strings, also contained the piece's outlines and filling. In this way, the solution found was to develop a stamper to paint the operations in high relief after the printing process.

In relation to the mathematical operations' positioning, all of the material pieces were redesigned on a CAD software, changing the position of the operations in braille and the indo-arabic digits in the lower half of the pieces, as can be seen in Figure 8.

Figure 8: Frontal and perspective views of the modified domino, respectively

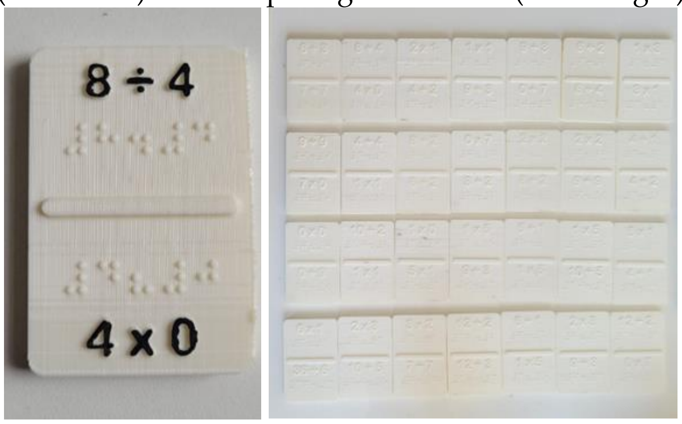


Source: Own authorship.

Based on this model, which can be downloaded by the reader on the following link: https://drive.google.com/file/d/1qmLXOQaovqSWGdF9cZLChnc1fKnDuNDO/view?usp=share_link, the dominoes game was printed again, using the same standardized parameters before the execution of the tests, except for the layer specification which occurs the temperature changes to the lower half of the domino, making that the layers where the braille was printed had the filament extrusion temperature of 200ºC.

After finishing the print, the mathematical operations (indo-arabic digits) in high relief were painted in black with the help of the stamper, to ease the painting and reduce the work time spent to improve the piece. The result obtained can be seen in Figure 9.

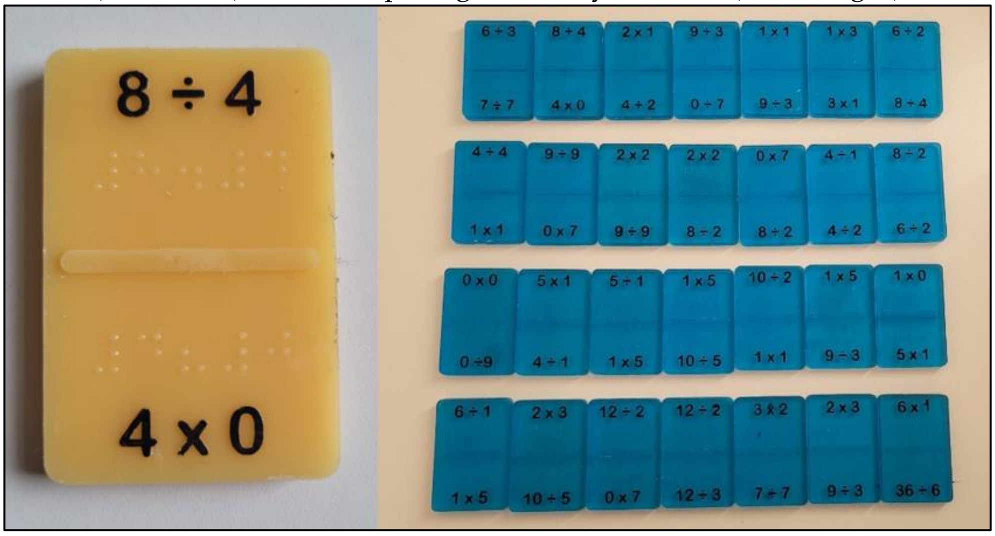
Figure 9: Result of a domino game piece in PLA
(on the left) and complete game in PLA (on the right)



Source: Own authorship.

Furthermore, during the research conducted to the elaboration of the bibliographical review about problems in the 3D print by FDM, it was noticed that a possible solution for the stringing problem, observed in the dominoes, would be the use of 3D printing with resin printers, due to operating principles. The 3D print in resin, is based on the use of photosensitive resin which is hardened, layer by layer, until forming the final piece. This print ensures great precision, because the maturation and consequent hardening of resin occur only in the spots where the ultraviolet beam is irradiated. Thus, a dominoes game was printed in the resin printer Anycubic Photon Mono S, also for testing. The game result can be seen in Figure 10.

Figure 10: Result of a domino piece in opaque resin
(on the left) and a complete game of crystal resin (on the right)



Source: Own authorship.

The quality of the parts printed in resine was very high, yet, the problem observed is that the printer used could only print two parts at a time, due to the table space, costing more time compared to the parts printed in PLA.

4. Recommendations

Considering the results obtained in this research, a test concerning the material printed in resine would be interesting, to compare the results based on what students with visual impairment evaluate. Also, the development of new materials using 3D printing to help these students in mathematics learning is highly recommended,

5. Conclusion

The use of 3D printing to the assistance in the learning process of students with visual impairment has shown necessary in the current scenario. Besides the material's elaboration, the print of it with quality of details to enable the use of the domino pieces is an essential step. In this work, it was possible to standardize the parameters to optimize the print of the material "Adapted Multiplication Domino", from the performance of studies about the problems that might occur in the 3D print by FDM.

It was noticed that the main issue that was occurring during the printing of the pieces was the occurrence of stringings between the Braille spheres, making it impossible for the visually impaired students to read and consequently, making it impossible to consider the material developed as a truly inclusive game. From the literature review, the main parameters that could generate stringings were analyzed: filament extrusion temperature and retraction. The temperature adjustment was made by printing a temperature calibration tower, developed by Kiland (2017). With this parameter adjusted and the change of printing direction of the parts, the stringing problem was solved, and it was possible to proceed with printing the complete material, using white PLA filament and the Ender 3 printer.

With the complete game printed, the material was sent for testing at an institution that serves students with visual impairments and has an agreement with a research group from UTFPR, and based on this test, feedback on the material was collected through a questionnaire sent to the person responsible for conducting the test. The necessary changes were made to the material, and thus a result applicable to schools for fixing multiplication contents using games in an inclusive manner was achieved.

Therefore, it was noticed that there is an evident need to analyze and standardize parameters for 3D printing of a material to make its use possible, in addition to the importance of conducting tests to observe what the target audience perceives (positive and negative points) regarding the material. With this, it was possible to achieve a satisfactory result from this research, contributing to the learning and inclusion of students with visual impairments.

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Conflict of Interest Statement
The authors declare no conflicts of interest.

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