U.PORTO

MESTRADO
MULTIMÉDIA - ESPECIALIZAÇÃO EM EDUCAÇÃO

AN EDUCATION 4.0 PEDAGOGICAL APPROACH FOR INTRODUCING SMART MANUFACTURING TO 5TH GRADE STUDENTS

Leonor Cónego

M
2021

FACULDADES PARTICIPANTES:

FACULDADE DE ENGENHARIA
FACULDADE DE BELAS ARTES
FACULDADE DE CIÊNCIAS
FACULDADE DE ECONOMIA
FACULDADE DE LETRAS

U.PORTO

An Education 4.0 Pedagogical Approach for Introducing Smart Manufacturing to 5th Grade Students

Leonor Cónego

Masters in Multimedia at University of Porto

Supervisor: Prof. Dr. Gil Gonçalves (Professor Auxiliar)

Co-supervisors: Prof. Dr. António Baía Reis (Professor Auxiliar Convidado)

Prof. Rui Pinto (Assistente convidado)

30 de junho de 2021

An Education 4.0 Pedagogical Approach for Introducing Smart Manufacturing to 5th Grade Students

Leonor Cónego

Masters in Multimedia at University of Porto

Aprovado em provas públicas pelo Júri:

Presidente: Prof. Dr.ª Carla Morais (Professor Auxiliar)

Vogal Externo: Prof Dr. Manuel Silva (Professor Coordenador)

Orientador: Prof Dr. Gil Gonçalves (Professor Auxiliar)

Abstract

This research is developed within the scope of the European project "ShapiNG" (Shaping the next Generation of Manufacturing Professionals), whose main goal is to attract young students for activities in the field of manufacturing. Providing students with learning experiences that help them to understand the skills they need to succeed in the workplace is a difficult proposition in today's quickly changing world pervaded by technology. The purpose of this study is to identify key technologies and approaches that combined may constitute a suitable pedagogical architecture to create awareness and motivation among young students as to inspire them to pursue a career in Engineering.

Drawing on David Ausubel's theory of learning, a case study was conducted to evaluate the effectiveness of the conceived architecture. The research methodology population consisted of 60 students from the 5th grade attending the "STEAM" class at "escolaglobal". The covered topics were 3D modeling and 3D printing. After a thorough literature review and an in-depth fieldwork involving participant observation, questionnaires and interviews were done in order to collect data regarding the (a) knowledge obtained on the covered topics, (b) benefits of working collaboratively and individually, (c) effectiveness of the instructional material, and (d) motivation to pursue a career in Engineering.

Ultimately, through our research we were able to obtain the following main results: there are no significant differences on the acquired knowledge between individual and collaborative work for the proposed activities; benefits of collaborative work are related to the possibility of negotiating concepts and enhancing leadership and organizational skills, whilst benefits of individual work are related to the possibility of self-overcoming and being creative; motivation influenced the perceived quality of instructional material with motivated students rating better the instructional material than the unmotivated ones; male students are more motivated to pursue a career in Engineering than female. Ultimately, the main results of this study provide a conceptual and practical gateway to bring in effective approaches to future research and activities focused on motivating young students to pursue a career in Engineering.

Resumo

Esta investigação é desenvolvida no âmbito do projeto Europeu "ShapiNG" (Shaping the next Generation of Manufacturing Professionals), cujo objetivo principal é atrair estudantes para atividades no campo da indústria. Proporcionar aos estudantes experiências de aprendizagem que os ajudem a compreender as competências necessárias para ser bem sucedido no local de trabalho é uma proposta desafiante no mundo de hoje em rápida mudança e dominado pela tecnologia. O objetivo deste estudo é identificar as tecnologias e abordagens-chave que, combinadas, podem constituir uma arquitetura pedagógica adequada para criar consciência e motivação entre os jovens estudantes, a fim de os inspirar a escolher uma carreira em Engenharia.

Com base na teoria de aprendizagem de David Ausubel, foi realizado um estudo de caso para avaliar a eficácia da arquitetura concebida. A população da metodologia de pesquisa consistiu em 60 alunos do 5º ano de escolaridade que frequentavam a aula de "STEAM" na "escolaglobal". Os tópicos abordados foram modelação e impressão 3D. Após uma revisão minuciosa da literatura e um profundo trabalho de campo envolvendo observação participante, questionários e entrevistas foram feitas com o objetivo de recolher dados relativos a (a) conhecimentos obtidos sobre os tópicos abordados, (b) benefícios de trabalhar colaborativamente e individualmente, (c) eficácia do material instrucional, e (d) motivação para seguir uma carreira em Engenharia.

Por fim, através do trabalho realizado conseguimos obter os seguintes resultados principais: não há diferenças significativas no conhecimento adquirido entre o trabalho individual e colaborativo para as atividades propostas; os benefícios do trabalho colaborativo estão associados à possibilidade de negociar conceitos e aprimorar as competências de liderança e organização, enquanto os benefícios do trabalho individual estão relacionados com a possibilidade de auto-superação e de ser criativo; a motivação influenciou a qualidade percebida do material instrucional, sendo que os estudantes motivados classificaram melhor o material instrucional do que os não motivados; os estudantes do sexo masculino estão mais motivados a seguir uma carreira na Engenharia do que os do sexo feminino. Em última análise, os principais resultados deste estudo proporcionam um ponto de partida conceptual e prático para o desenvolvimento de abordagens eficazes em futuros trabalhos de investigação e para atividades que pretendam motivar jovens estudantes para seguir uma carreira na Engenharia.

Acknowledgements

In the course of this dissertation, I had continuous support of numerous people to whom I am grateful.

First and foremost, I express my deep appreciation to Prof. Gil Gonçalves, Prof. António Baía Reis, and Rui Pinto from the Faculty of Engineering of the University of Porto (FEUP) for the opportunity to be part of a research project in which I acquired professional and personal skills. As my supervisor and co supervisors, they never gave up a demanding and constructive work, integrating a process of evolution in terms of skills and guiding this master's work in an exemplary and tireless way.

I would like to express my sincere gratitude to all the involved professionals of “escolaglobal”, and particularly to Prof. Nuno Moutinho who placed trust in this project. Without this permission, this study would not have been possible.

A special thanks to Prof. Carla Morais and Luciano Moreira, from FEUP, for the time they made available to provide me with feedback and advice.

I would also like to convey my heartfelt thanks to Prof João Reis from FEUP, for the encouragement when things were tough.

An unconditional thank you to my parents for the education, support, love and for the possibility that they gave me to progress in my studies. And of course, to my sister for being more than a friend, for having accompanied me during this work without letting me give up.

And finally, I thank all my friends and all the people who contributed to the progress and realization of this work.

Index

List of Figures

List of Tables

Abbreviations and Symbols

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AR	Augmented Reality
ASA	Acrylic Styrene Acrylonitrile
BYOD	Bring Your Own Device
CAD	Computer-Aided Design
CPPS	Cyber Physical Production Systems
CPS	Cyber Physical Systems
DIY	Do It Yourself
DOLA	Differentiated Overt Learning Activities
DT	Digital Twin
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FLL	First Lego League
I4.0	Industry 4.0
ICAP	Interactive, Constructive, Active, and Passive
IIoT	Industrial Internet of Things
IoT	Internet of Things
LF	Learning Factories
LR	Literature Review
PBL	Problem Based Learning
PLA	Polylactic Acid
PrBL	Project Based Learning
RE	Reverse Engineering
RE	Reverse Engineering
SLA	Stereolithography
SLS	Selective Laser Sintering
STEAM	Science, Technology, Engineering, Arts and Mathematics
STEM	Science, Technology, Engineering and Mathematics
ZPD	Zone of Proximal Development

1. Introduction

Today, we stand at the threshold of a digital transformation in industry. A new paradigm towards Smart Manufacturing is taking place, leading us to the "4th Industrial Revolution". This revolution is characterized by the exponential use of digital technologies, such as artificial intelligence, internet technology, sensors, 3D printing and cloud computing, that are profoundly impacting the manufacturing sector. The industrial sector is looking, therefore, for people that is capable of solving ambiguous, open-ended and ill-structured problems.

With these advancements, comes a new mindset and the need to educate young students to become the manufacturing engineers of the future, aware of the main transformations, processes and concepts surrounding the so-called Smart Manufacturing paradigm. And this is where this masters' degree project takes place and relevance. A set of activities with 5th grade students were outlined and conducted, with the main goal of introducing smart manufacturing in an engaging and meaningful manner, making them consider a future career in manufacturing. In this research, we chose to adopt a pedagogical approach in which students followed an exploration guide that encourages self-structured learning. Drawing on David Ausubel's theory of learning, group and individual interaction strategies were carried out to assess which dynamic in the teaching-learning process of smart manufacturing generates more potentially meaningful learning.

In this sense, the contribution of this dissertation follows the subsequent steps:

a. On chapter 1, a contextualization is made aiming to frame the project in the European context, introduce the topic in hand as well as to identify the research objectives and define the research methodology.

b. On chapter 2, a narrative Literature Review (LR) identifies key methodologies to teach Industry 4.0 (I4.0) worldwide, skills required for I4.0 Engineering professionals, the main related evolving technologies and assessment methods;
c. On chapter 3, we identify a gap in the literature and outline a set of activities;
d. On chapter 4, the results from the activities held with students are presented;
e. Finally, chapter 5 presents the main conclusions, final remarks and future work.

Ultimately, our main goal is to provide a conceptual and practical gateway for future activities focused on encouraging and raising the interest of young students, with a special emphasis on women, in pursuing a career path in the field of manufacturing engineering. Through our results, it is expected that teachers may adopt our approach, thus expectably increasing their student's motivation to become the next generation of manufacturing engineers.

1.1 Framing

This research is developed within the scope of the European project "ShapiNG" (Shaping the next Generation of Manufacturing Professionals), supported by EIT Manufacturing under the EIT Regional Innovation Scheme[1] (RIS). Besides the relevant and available funding to support our research, belonging to the EIT Manufacturing community and the visibility that comes with it was important for our project. Following on the EIT Manufacturing's agenda, where it is expectable that students interact and critically engage with challenges related to smart manufacturing from an early age, motivating them to consider a career in manufacturing, was the initial trigger to outline this research project. Thus, the activities conducted within our research were outlined to ultimately provide an accurate overview of the manufacturing industry in an engaging manner, helping and assisting universities, schools, and research and technology organizations in attracting and engaging young students in RIS countries.

1.2 Project

ShapiNG's main goal is to motivate and raise the interest of young Europeans, with a special focus on young girls, for activities in the field of manufacturing. Moreover, ShapiNG is particularly focused on developing these activities within the EIT RIS countries, namely Portugal, Spain, Greece, and Slovakia. A series of Smart Manufacturing Demonstrators are being created by the project's international partners in order to provide a hands-on approach contact with the

[1] The EIT Regional Innovation Scheme (EIT RIS) aims to advance the innovation performance of more countries and their regions across Europe, especially countries with moderate or modest innovation scores as defined by the European Innovation Scoreboard.

key topics and technologies surrounding the smart manufacturing industry and eventually generate a realistic, positive and engaging feeling about this sector. These demonstrators will help universities and other research and technology organizations in attracting young students to the manufacturing sector, and specifically within these EIT RIS countries. By "socializing" with smart manufacturing challenges and career opportunities from an early age, students will be encouraged to consider a career in manufacturing and therefore help ensure a future with available and well qualified workforce. The Smart Manufacturing Demonstrators are being used in seminars, open days and workshops to be held in different schools and ultimately promote awareness about the manufacturing sector.

1.3 Problems, Hypotheses and Research Objectives

Transformations that come along with Industry 4.0 (I4.0) involve novel technologies, raising new challenges for education. In this sense, companies will require people with competencies never needed before. I4.0 disseminates the idea of workers dealing with increasingly more complex problem solutions, systemic thinking, and creativity. Thus, it is expected that young students should start to acquire those competencies as early as possible. In this sense, our main research question is: "What defines the design of a pedagogical architecture capable of creating awareness and motivation among young students in order to pursue a career in engineering?". Aiming at answering this question, a case study based on David Ausubel theory of learning was outlined and conducted. In order to meet our main research question, the following sub-questions and corresponding hypotheses arose (see Table **1**).

Table 1. Sub-questions and respective hypotheses

	Sub-questions	Hypotheses
1.	Is 3D printing a suitable topic for introducing smart manufacturing to 5th grade students?	The attractiveness and easy to grasp concept of 3D printing make it a suitable topic for introducing smart manufacturing to 5th grade students.
2.	Are the activities proposed capable of creating potential meaningful learning on the covered topics?	Activities based on Computer-Aided Design (CAD) and problem solving can create potential meaningful learning experiences.
3.	What are the benefits of working collaboratively *versus* individually to acquire potential meaningful learning on the covered topics?	Individual performance allows students to learn meaningfully because they can learn at their own pace which stimulates critical thinking and focus. Collaborative performance fosters soft skills, such as negotiation and leadership.
4.	Which of the dynamics – individual or collaborative – has contributed to a more potentially meaningful retention of knowledge?	Collaborative activities register more meaningful learning when compared to individual.
5.	How does motivation to pursue a career in Engineering differs from male and female students?	Female motivation to pursue a career in Engineering is typically lower when compared to male.

Ultimately, and in order to address the above-mentioned questions and hypotheses, we have outlined the following research objectives:

1. Explore and validate an approach capable of constituting a proposal with scientific, pedagogical, technical and aesthetic quality, susceptible of being used by teachers and students from the 5th grade in teaching and learning activities about "Smart Manufacturing";
2. Thorough validation of the various resources and instructional materials used in the conducted activities.
3. Collect feedback from students regarding the individual and collaborative learning dynamics and experiences;
4. Understand which dynamic, individual or collaborative, is more susceptible of potentializing the acquisition of meaningful knowledge;
5. Understand how teachers can adapt the use of this pedagogical approach for their classes;

6. Develop an innovative learning process that raises the interest and motivates students to pursue a career in Engineering;
7. Promote critical thinking and innovation in todays' society, as an underlying goal of this research project to generate impact on society.

1.4 Research Methodology

This chapter describes the research methodology used to conduct this dissertation. There are two main reasons that motivated us to carry out this study. The first one is the need to create awareness and educate young students with the necessary skills for the future, which in its turn, has the underlying goal of decreasing the gender gap enduring in professions in the field of Engineering. The second one as to do with our interest in understanding which dynamic - individual or collaborative - most benefits the attainment of meaningful learning in this specific context in which 5th grade students are introduced to smart manufacturing.

1.4.1 Sample Characterization

The total sample was composed of 60 students from the 5th grade of "escolaglobal"[2], attending Science, Technology, Engineering, Arts and Mathematics (STEAM) classes. 34 (56.7%) of them were male and 26 (43.3%) were female. Three of them were under 10 (5%) years old and 57 (95%) were between 10 and 11 years old. This was a convenience sample given that this school was selected as pilot for our research project. Results of this pilot will be used to improve the approach before its application in additional schools. Moreover, it should be noted that most of our activities were in-person, which within today's overall constraints caused by the Covid-19 global pandemic is quite a challenge and was an accomplishment.

The basic criterion for determining the participants included (a) being a 5th grade student from "escolaglobal", and (b) being enrolled in STEAM classes. Half of the students of each class was allocated to the individual work and the other half to group work. This distribution was made randomly, using an online random list generator[3].

[2] "escolaglobal" is a private and cooperative education group formed by three schools that have a common management. This activity was developed in the school of "Terras de Santa Maria" - located in Argoncilhe – which is an alementary and secondary school.

[3] https://www.randomlists.com/

1.4.2 Data Collection Techniques

Being the author a non-expert on smart manufacturing, the thorough LR undertaken was an essential first step for our research project. It enabled the possibility of grasping facts not only fundamental concepts around 3D printing, but also broader concepts such as industrial revolutions, technology trends and its characteristics, and even understand many other important and related aspects that optimized the planning and implementation of the activities. After the LR, we sought to answer the above-mentioned research questions by outlining a Case Study, whose complexity raised the need for different research techniques, combining the use of quantitative and qualitative methodologies, i.e., a "mixed methods" approach. Collecting quantitative and qualitative data allows for a more comprehensive and holistic understanding of the research problem (Creswell, 2009; Leedy & Ormrod, 2015).

This is a case study once it involved an in depth analysis of an activity (Creswell, 2009; Leedy & Ormrod, 2015) that took place during "STEAM" classes[4]. Moreover, the information collected aimed at learning more about a "poorly understood situation" (Leedy & Ormrod, 2015, p. 272) which in this case are the benefits of collaborative and individual activities to learn 3D modeling and printing concepts. Leedy & Ormrod (2015) also stressed out that results should not be generalized. By doing so, we are making presumptions about unproven situations.

"A mixed methods case study design is a type of mixed methods study in which the quantitative and qualitative data collection, results, and integration are used to provide in-depth evidence for a case(s) or develop cases for comparative analysis" (Creswell & Clark, 2018, p. 176).

In this sense, the design adopted was the "convergent parallel design" (see Figure **1**), with the collection and analysis of qualitative and quantitative data occurring simultaneously. Nevertheless, both approaches were prioritized equally and analysis was done independently. Finally, results converged in the interpretation phase (Creswell & Clark, 2010).

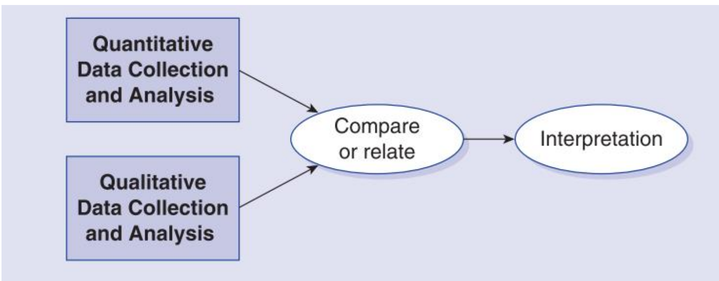


Figure 1. The convergent parallel design. Extracted from Creswell & Clark, 2010

[4] At "escolaglobal", "STEAM" classes take place weekly and have 1 hour each, its mission is to endow students from pre-school to the 9th grade with critical thinking, creativity, communication and collaboration by means of design thinking, storytelling and game learning. Students acquire skills, for example, on logic programming and computational thinking.

On the one hand, the benefits of students working individually or collaboratively were analyzed through participant observation and a set of structured interviews in order to ask additional probe questions related to the reasons behind participants' answers. On the other hand, knowledge retention was assessed through a pre-test (see Annex A: Pre-test Questionnaire) and post-test questionnaire (see

Annex B: Post-test Questionnaire), which involved statistical analysis to compare learning outcomes. The post-test questionnaire also included a set of questions related to the instructional material itself to understand if the material was understandable, logical, and relatable to their previous knowledge. Furthermore, answers given in the individual (see Annex C: Individual Exploration Guide) and collaborative exploration guides (see Annex D: Collaborative Exploration Guide) were also analyzed. Prior to collecting either quantitative or qualitative data, participants were informed about the aim of the study and about confidentiality of the involved data. Since research participants were underage, for us to be able to record the interviews that took place via Microsoft Teams, we obtained the students' legal representatives authorization through adequate informed consent protocol (see Annex E: Informed Consent Protocol).

1.4.3 Data Analysis Techniques

After collecting data from participant observations, exploration guides, questionnaires and interviews, the software used to analyze quantitative data was "IBM SPSS Statistics" (version 27.0.1), whilst to analyze qualitative data the software used was "Atlas.ti"[5].

1.4.3.1 Statistical data

The assumptions for the normality of the data were tested. Kolmogorov-Smirnov and Shapiro-Wilk tests were calculated. When $p > .05$ in both tests, the null hypothesis stating that data are taken from a normally distributed population is accepted. For all the variables in the study, the p-value obtained was < .05 for both tests, meaning that the null hypothesis was rejected, thus data were not normally distributed (Field, 2013). Skewness (a measure of asymmetry) and kurtosis (a measure of the peakedness) were also calculated. For small-to-moderate sample size (i.e., $n < 300$) is recommended to apply a z-test for normality test using skewness and kurtosis, to adjust the standard error (as the sample size increases, the standard error decreases). A z score is obtained by dividing the skewness and kurtosis values by their standard errors. A z value ± 1.96 is sufficient to establish the normality of the data. In our data, almost all variables obtained a z value superior to 1.96 in both skewness and kurtosis, suggesting the nonnormality of the data

[5] https://atlasti.com/qualitative-data-analysis-software/

(Field, 2013). Normality assessment was also inferred by visualizing the histograms of each variable in the study. The graphs obtained were not approximately bell-shaped and symmetric about the mean, thus we could assume non-normally distributed data. Given the results obtained through these methods of assessing normality, we concluded that our data were not normally distributed, therefore we opted to use non-parametric tests.

Descriptive statistics were calculated to provide information about the sample and the measures. Measures of central tendency (mean and median), dispersion (standard deviation, minimum and maximum) and distribution (frequency and percentages) were calculated.

The Chi-Square test of independence was used to determine whether two categorical variables are related, comparing the frequency of cases found in the various categories of one variable across the different categories of another variable. When the expected frequency in any cell is lower than 5 in 2x2 tables, it was used the Fisher's Exact Probability Test (Field, 2013).

A Mann-Whitney U test was used to test for differences between two independent groups on a continuous measure.

Spearman's Rank Order Correlation (r_S) was used to calculate the strength of the relationship between two continuous variables. According to Cohen (1988), a correlation up to .29 is considered small in magnitude, between .30 and .49 is medium, and above .50 is large.

Regarding the reliability of a scale, the internal consistency was examined using the Cronbach's alpha (α) coefficient. This coefficient indicates if the items of the scale are measuring the same underlying construct. Ideally, Cronbach's alpha coefficient of a scale should be above .70. The item-total correlation should also be taken into consideration, which indicates the degree to each item correlates with the total score. Low values (less than .30) indicate that the item is measuring something different from the scale as a whole. If an item presents a low item-total correlation and the alpha value, if that item is deleted, is higher than the final alpha value, it could be considered to remove the item from the scale.

Statistical significance was considered when the p-value was less than .05.

1.4.3.2 Qualitative data

As previously mentioned, the Computer Assisted Qualitative Data Analysis Software (CAQDAS) used to analyze this data was "Atlas.ti" which allowed coding multimedia elements, so transcripts were waived. Some authors advocate that working with data in its original state allows for greater reliability as well as thicker descriptions and more informative reporting (Markle *et al.*, 2011). By analyzing this information we achieved "data saturation", which indicates that at some point in the qualitative research data have a propensity to be redundant

(Grady, 1998). So again, transcription seemed inefficient in a time consuming-cost benefit perspective.

Interviews were undertaken on Microsoft Teams, since (a) students from "escolaglobal" were used to this platform and (b) it allowed for audio and video recording. Interviews took place one and two weeks after the on-site activity, respectively, with a three-fold goal: (a) assessing their knowledge on the covered topics, (b) identify the benefits of working collaboratively and individually, and (c) understand what they know about Engineering careers. Participants were selected on the final post-test questionnaire and were asked to provide their emails in case they were available for an interview. Ultimately, from 47 invitations sent by email, only 12 students ended up participating in the interviews. Moreover, some students did not even reply to the email asking for scheduling an interview, although several attempts of contacting them were made. Others replied that they could not participate because their legal representatives did not allow it. From 12 interviewees, 5 were assigned to the individual activity and the other 7 were assigned to the collaborative activity. It was a semi-structured interview that assigned characteristics from Socratic questioning and clinical interviews. The interview's main questions were outlined (see Annex F: Students' Interview), however, the interviews were designed to allow the emergence of new questions according to student's answers, motivating them to think critically and relatively freely on their answers. Questions were organized in three core clusters. The first one was responsible for collecting data regarding the knowledge retention on 3D printing. Students were encouraged to think out loud with the purpose of rejecting misconceptions and thus assessing the availability of relevant ideas on their cognitive structure. Additionally, and when suitable, some images were shown to help students externalize their knowledge. The second core cluster focused on the advantages and disadvantages of each working mode – individual *versus* collaborative. The third core cluster sought to identify whether students knew what an Engineer does and how can one link the activities made with Engineering in general. This latest cluster aimed at understanding the obtained results in the post-test questionnaire in terms of the motivation levels to eventually pursue a career in Engineering.

During the interview, key ideas were written down and registered simultaneously. After that, we familiarized ourselves with the data collected in its entirety as the body of material was relatively small. This process consisted of playing the videos one by one, registering the frequency of certain events directly in the "Atlas.ti" software (i.e., the number of times each interviewee managed to obtain the correct answer and simultaneously could explain the reason why that answer was correct). The interview itself was designed already thinking in preliminary categories that were likely to be helpful for coding the data (the core clusters above mentioned). This process is quite usual among researchers (Leedy & Ormrod, 2015). So, by playing the videos we identified noteworthy patterns that were thoroughly examined and synthesized into subcategories (or subcodes). A code is "a word or short phrase that symbolically assigns a summative, salient essence-capturing, and/or evocative attribute for a portion of language-based or visual data." (Saldana, 2009, p. 3) whilst a category consists of groups of codes that share some characteristic

(Saldana, 2009). Ultimately, information was interpreted considering the research questions. For this, it was necessary to revisit the interviews multiple times, which according to some authors is an advantage as the researcher may retain the participants' perspectives accurately (Markle *et al.*, 2011).

1.5 Dissertation Structure

This dissertation contains an introductory chapter in which context, motivation, research objectives, problems, hypotheses and research methodology is presented.

The following chapter is allocated to the LR that identifies technological trends, teaching approaches, competencies needed for (I4.0) and explores the theory of David Ausubel and other related and more recent theories and its assessment methods.

Chapter 3 clearly presents the problem, the proposed solutions and implementation procedures.

On chapter 4, the results from the activities held with students are presented, namely from the data collected through the participant observation, questionnaires, interviews, and explorations guides. Ultimately, this chapter presents a results' discussion.

The last chapter - chapter 5 - presents the main conclusions, final remarks and points out possible optimizations to the proposed approach and future work.

2. Literature Review

This chapter presents a narrative LR that identifies and presents existing research and relevant debates on how technologies related to I4.0 are being taught around the world, which skills are required for I4.0 professionals, and what are the most effective and used evaluation methods. Furthermore, this chapter includes a review of the main tools and concepts adopted within this research project. The LR allowed us to identify patterns and trends in the literature and, as a result, we were able to identify loose ends and objectively understand what needs to be done next.

Narrative reviews aim to build theory through a comprehensive narrative synthesis of previously published information (Adams *et al.*, 2006). They are helpful in presenting a broad perspective on a topic and often describe the history or development of a problem (Slavin, 1995). According to Greenhalgh *et al.*, (2018) it also consists of "providing interpretation and critique; their key contribution is deepening understanding." (p. 2). Today, it is a widely adopted review method and it has been used by researches in several areas, including I4.0 and Engineering education (Hernandez-de-Menendez *et al.*, 2020; Rauf *et al.*, 2016; Tillinghast *et al.*, 2020; Wichmann *et al.*, 2019). LRs greatly contribute to adequately address emergent research issues, which is the case of I4.0. In this sense, and given that our research main goal was to understand what was the best architecture to teach and engage 5th grade students about smart manufacturing, this LR ought to find out the best teaching approaches, emerging technologies and skills required for future Engineers. The LR process held is summarized in Figure 2 and was extracted from Juntunen & Lehenkari (2021).

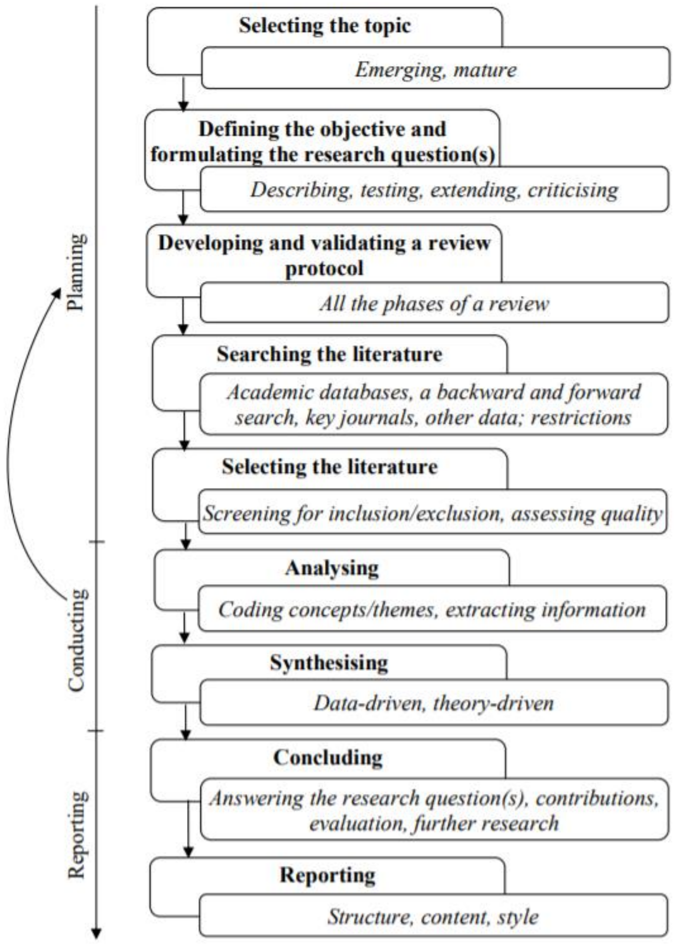


Figure 2. Literature review process.
Extracted from Juntunen & Lehenkari (2021)

2.1 Introduction

Three different industrial revolutions followed the first one and, thereby, significant changes in manufacturing have occurred. To make it clearer, according to the Skills Panorama (2019):

> The manufacturing sector involves activities that for the most part are concerned with transforming materials, substances, or components into new products - in other words, making goods. (…) Manufacturing includes a wide range of sub-sectors including, amongst others, the manufacture of food and drink products, textiles, clothing, pharmaceuticals, chemicals, computers and electrical equipment, metals, vehicles (e.g. cars, trains and ships), furniture, etc. (p. 1).

Manufacturing processes are growing in its complexity, automation and sustainability, which means people can operate machines in a simpler and more efficient manner (Wahlster, 2012 *apud* Qin *et al.*, 2016). The first industrial revolution took place at the end of the 18th century with the introduction of mechanical production facilities using steam and water power (Rüßmann *et al.*, 2015). In the 19th century, the second revolution led to mass production of electricity to support the division of labor and the discovery of the assembly line. This revolution was marked by efficient and mechanized production requiring smaller expenditure of human energy. The third industrial revolution began in the 1970s when the first Programmable Logistic Controller (PLC) was built. It was marked by the automation in production of Information Technology (IT) and electronic systems. This one was followed by I4.0 that led to the development of novel technologies based on heterogeneous data and knowledge integration (Basir *et al.*, 2019; Lu, 2017; Lukac, 2015)(Figure **3**). Lukac, (2015) further argues that implementing I4.0 demands change in many technologies namely automation, identification, computer, network communication, digital manufacturing, production process, production control management, decision making, judgment, sensing and analysis.

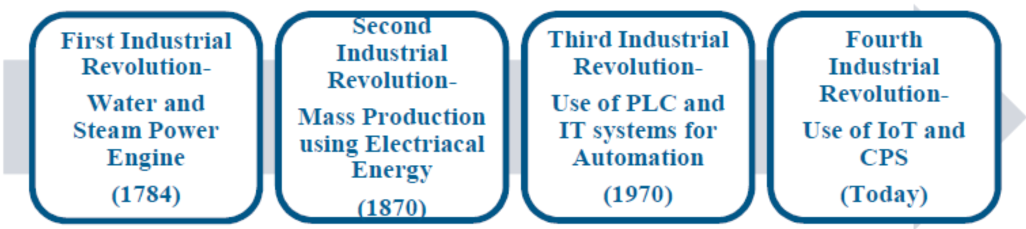


Figure 3. Industrial revolutions timeline.

Extracted from Vaidya (2018)

This way, the transition process from the third industrial revolution to I4.0 presents a range of challenges for organizations to tackle. Fourth revolution differs from previous ones in the possibilities it provides, challenges, scope and complexity. Concepts such as Internet of Things (IoT), Digital Twin (DT), Big Data, Virtual and Augmented Reality emerged and have become an integral part of the industrial value chain (Bongomin *et al.*, 2020; Lu, 2017; Mogos *et al.*, 2018; Turcu & Turcu, 2018). The exponential growth of these technologies is the foundation for the currently undergoing industrial revolution, called Industry 4.0. With the technologies that came with Industry 4.0. also came significant changes, instigating Engineering education to adapt to those changes. As stated by Mogos *et al.* (2018), such changes "(…) require setting tangible Engineering skills both in processing and thinking that can apply to emerging technologies" (p. 431). Some researchers claim that the transition to the I4.0 requires, for instance, greater investments in the education of Engineers as certain competencies are required to implement and maintain the latest technologies (Baygin *et al.*, 2016; Mogos *et al.*, 2018). According to the report of McKinsey (2016), one of the most significant barriers to implement I4.0 is the lack of the necessary talent, as emphasized by the producers at the first stages of implementation. This step forward in learning culture is becoming known as Education 4.0 (Ed 4.0).

2.2 Towards Industry 4.0

Industrial revolutions together may be seen as a set of sequential events building upon innovations of the previous revolutions and leading to more advanced forms of production. "(…) they redefine the levels of industrial performance and the degree of productivity in the value creation, that's why they are known as revolutions" (Wichmann *et al.*, 2019, p. 2130). The development of an integrated and intelligent production capable of interacting autonomously with the major corporate players is the foundation of the fourth industrial revolution.

> Coined by Klaus Schwab, founder and executive chairman of the World Economic Forum, describes a world where individuals move between digital domains and offline reality with the use of connected technology to enable and manage their lives, as part of a wider culture shift. (Miller, 2016, p. 3).

The term has quickly become a buzzword on a global scale since then. It includes a set of enabling technologies that facilitate the automation of processes and the exchange of huge amounts of data along the production chain. These technologies, explored below, can transform a traditional factory into a smart factory.

2.2.1 Technological Trends of Industry 4.0

Technology is an area that experiences constant growth. In production, particularly, systems have been continuously evolving under the influence of information and communication technology. According to Alqahtani *et al.* (2019) the transition to I4.0 always results in the implementation of new technologies and in a substantial change in manufacturing and human resource management. These technologies together give rise to a new generation of systems which primary goal is to achieve an active collaboration among hardware devices (e.g., machine tools, robots, measuring instruments), software systems and human resources on a real-time basis by exchanging the required data, information, and knowledge (Monostori, 2014). In order to achieve this goal, a set of relevant technologies have been introduced, namely, Augmented Reality, Industrial Internet of Things (IIoT), Cyber-Physical Systems (CPS), (Mogos *et al.*, 2018; Morales-menendez *et al.*, 2020), Cloud computing, additive manufacturing (AM), machine learning (ML), artificial intelligence (AI), robotics, among others (Basir *et al.*, 2019; Fettermann *et al.*, 2018). Some studies summarize technological advancements in nine pillars (Chong *et al.*, 2018; Hernandez-de-Menendez *et al.*, 2020; Rüßmann *et al.*, 2015; Silvestri *et al.*, 2020; Tay *et al.*, 2018; Vaidya *et al.*, 2018) that are key enablers of I4.0 and drivers of improvement in the designated areas. These technologies include (1) IIoT (2) Big Data and Analytics, (3) Horizontal and vertical system integration, (4) Simulation, (5) Cloud computing, (6) Augmented Reality (AR), (7) Autonomous Robots, (8) AM and (9) Cyber Security. These pillars convert isolated production cells into a fully cohesive, automated and enhanced production process (Vaidya *et al.*, 2018). In addition, new opportunities were created for making information exchange more comprehensive. As a result, automation systems can become more complex.

Before getting into each pillar characterization, a notion of CPS must be provided. CPS is the core foundation of I4.0, its function consists in various embedded devices that are networked to sense, monitor and actuate physical elements (Morales-menendez *et al.*, 2020; Sisinni *et al.*, 2018). When applied directly in production processes it is called Cyber Physical Production Systems (CPPS) and its fundamental question is how to explore the relation of autonomy, cooperation, optimization and responsiveness along different manufacturing processes and practices to achieve high performance (Amaya *et al.*, 2020). In manufacturing processes, CPS comprises the machines used in manufacturing, transportation, robots, automatic guided vehicles (AGV), among others devices (Li *et al.*, 2017). The robust connection of both worlds - physical and the virtual - can improve the quality of information required for planning, optimizing and operating manufacturing systems. Data collected from CPSs, as well as the customer-management system, is the base of the Big Data analysis (Vaidya *et al.*, 2018). The proper use of sensors should find out failures occurring in machines and automatically prepare for fault repair actions on CPS. Integrating several different subsystems is time consuming, expensive and at the same time the whole system must be kept operational and functional – dealing with sensor networks, big amounts of data, information retrieval, representation, and interpretation – without compromising security aspects. The heterogeneity and complexity of CPS applications result in several challenges in developing and designing high-confidence, secure, and certifiable systems and control methodologies (Lee & Sangiovanni-Vincentelli, 2012).

2.2.1.1 IIoT

The Industrial Internet of Things (IIoT) is an extension of the concept of Internet of Things (IoT) to the industrial field. It consists in a network of objects with embedded technologies that allow them to interact with each other or the external environment (Morales-menendez *et al.*, 2020). A more complete definition given by Khan *et al.*, (2020) is the following: "(…) the network of intelligent and highly connected industrial components that are deployed to achieve high production rate with reduced operational costs through real-time monitoring, efficient management and controlling of industrial processes, assets and operational time." (p.2)

Today, every single connected physical object is uniquely identifiable on the Internet based on its virtual representation. In this scenario, the Internet represents the global networking of connected devices or "Things", enabling them to communicate with each other by exchanging and transforming information. IIoT is the basic technology of cyber-physical systems (CPSs).

2.2.1.2 Big Data and Analytics

Todays' rapid development of Internet results in a huge amount of data that is produced and collected daily. Consequently, processing and analysis is beyond the capabilities of most traditional tools (Witkowski, 2017). And this is when Big Data emerges.

This concept was coined by Forrester and according to it, Big Data consists of four dimensions: Volume, Variety, Velocity and Value (4V). Bellow the definitions of each dimension are presented (Witkowski, 2017)

- "Volume (amount of data) – by McKinsey Global Institute, "the concept of Big Data refers to datasets whose size exceeds the capacity of ordinary tools for collection, storage, management and analysis" – it is connected with the technological capabilities to manage these data.
- Variety (variety of data) – Big Data comes from a variety of sources, which are: transactional systems, social networking sites or the internet. These data change dynamically and are very unstructured, which means that they are not suited to traditional forms of analysis (they include, for example, images, video and content from social networking sites).
- Velocity (the speed of generation of new data and analysis) – data analysis is carried out on Big Data in real time, as the correct conclusions from the constantly flowing and changing data need to be implemented in an ongoing basis.
- Value (value data) – the general aim is to isolate the whole mass of information to what is most important for us – this is why it is so important that the results reflect the actual conditions and led to the most favorable business activities." (p.768)

Furthermore, new data supplied by the diffusion of sensors and IoT allow the development of Big Data Analytics and Machine Learning tools applicable in various fields such as trend analysis, process monitoring, quality prediction and control, fault diagnosis, fault classification, online soft sensing and process control (Ge *et al.*, 2017). A deep data analysis of an industry allows operators to find out threats occurred in different production cells in advance and also to anticipate upcoming issues.

2.2.1.3 Horizontal and vertical system integration

Horizontal and vertical system integration refers to an integration across the entire supply chain, reaching a total connection between all the actors in a highly dynamic system (Hernandez-de-Menendez *et al.*, 2020; Stock & Seliger, 2016).

Horizontal integration is the merging of several individual supply chains; as a result, businesses with similar goods cooperate and compete to become more competitive. Vertical integration, on the other hand, entails the linking of a company's value-added subsystems. The main benefit of horizontal and vertical integration is that the entire business network works autonomously, taking advantage of all the data generated, making processes optimum, reducing costs, and producing better products (Tay *et al.*, 2018). As a final conclusion, "It allows all the production elements involved, i.e., departments of the organization, suppliers, customers, and vendors, to function by communicating in real-time." (Hernandez-de-Menendez *et al.*, 2020, p. 791).

2.2.1.4 Simulation

Simulations, also referred to as "digital twins", have proven to bring benefits to the Industry field. It can be defined as "the use of high-fidelity models of real products, services, or processes to simulate their behaviors with the main objective of understanding their reactions when facing specific situations to improve performance." (Hernandez-de-Menendez *et al.*, 2020, p. 791). In manufacturing contexts, the main advantages of its use are the possibility to: (a) change variables and make tests without taking risks, (b) train workers before they operate the real machines, and (c) forecast problems in the real world machines by running the simulations at the same time (Hernandez-de-Menendez *et al.*, 2020). Siemens and a German machine tool vendor, for example, developed a virtual machine that can mimic the machining of parts using data from the physical machine. This lowers the setup time for the actual machining process by as much as 80 percent (Rüßmann *et al.*, 2015).

2.2.1.5 Cloud computing

Hernandez-de-Menendez *et al.* define Cloud Computing as "the use of internet servers that offer an accessible way of using computer resources such as networks, storage, applications, and diverse services" (Hernandez-de-Menendez *et al.*, 2020, p. 792). In manufacturing contexts, cloud supports the management of a huge amount of data in open systems and allows real-time communication for production systems (Chong *et al.*, 2018). In recent years it began to be used to perform Big Data analytics such as identifying preferences from users, which is controversial. Nevertheless, cloud computing in manufacturing fields have proven to improve the efficiency of processes, offering essential information that can be shared with different partners rapidly. This consequently reduces costs and improve systems performance (Hernandez-de-Menendez *et al.*, 2020).

2.2.1.6 Augmented Reality

Augmented Reality (AR) is a human-machine interaction that combines 3D virtual objects with a 3D real environment in real time. This technology superimposes digital information onto reality, mixing them (Figueiredo *et al.*, 2014) with the help of a mobile device. It can provide operators with real time information for maintenance, logistics, and other common operating procedures (Chong *et al.*, 2018). One of the benefits is the possibility to accelerate training of staff and technical experts (Silvestri *et al.*, 2020).

2.2.1.7 Autonomous Robots

Robots have long been used by manufacturers to execute difficult tasks, but they are now evolving to become much more useful. They are increasingly getting more autonomous, cooperative and progressively involving more applications (Silvestri *et al.*, 2020). Today robots can perform tasks like welding, painting, bonding, gluing, screw-driving, assembling, inspecting, packaging, palletizing, transferring, and transporting, among several others (Bayegan & Elisson, 2012). They can execute tasks with accuracy and high repeatability when continuous re-calibration is made, ensuring product quality (Bayegan & Elisson, 2012). In I4.0, autonomous robots can work together, interacting with one another or helping operators executing their tasks - robots for collaborative interaction are generally named "cobots" (Oberc *et al.*, 2019; Rüßmann *et al.*, 2015). Additionally, they can also substitute workers in risky tasks and hazardous settings.

2.2.1.8 Additive manufacturing

There are three core fabrication processes, namely subtractive, additive and formative. In the subtractive process, fabrication starts with a block of solid material which is then shaped by removing material until the desired form is attained. Forming processes make use of stresses like compression, tension, shear, or some combination to cause the plastic deformation of a material into a desired shape (Zivanovic *et al.*, 2020). Additive Manufacturing (AM) consists of creating an object by sequentially adding material in successive layers, one stacked upon another. For this, a digital model/design is needed to be converted into a physical object by a 3D printer (Chong *et al.*, 2018). The AM contrasts with traditional object creation, where it is often necessary to remove material through milling, machine, carving, shaping or other means. AM is suitable for producing small lots of customized products or complex lightweight designs of prototypes (K. Jones & Mendez, 2021; Rüßmann *et al.*, 2015). Some of the types of AM technologies are Stereolithography (SLA), Selective Laser Sintering (SLS) and Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM) (Chong *et al.*, 2018; Hernandez-de-Menendez *et al.*, 2020). SLA printers use lasers to solidify, while SLS use lasers to fuse the photopolymer resin and powder in order to create an object. FFF, on its turn, builds objects by extruding molten thermoplastics that solidify later. Most used 3D printing materials are Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Nylon, and Acrylic Styrene Acrylonitrile (ASA). PLA, is great for beginners as it allows printing stiff pieces with good dimensional accuracy and shelf life, it is inexpensive, environmentally friendly and most importantly biodegradable (3D HUBS B.V., 2021; MakerBot Industries, 2021). Additionally, as it is derived from crops such as corn and sugarcane, it exudes a sweet aroma during printing.

The AM process is shown in Figure **4** and includes the following phases: (1) CAD modeling, (2) Exporting STL file from CAD software (3) Slicing - STL file is divided into layers by a proper software (4) Generating a G-code file, (5) Printer setup, (6) Simulation of 3D printing, (7) Object fabrication, (8) Additional postproduction techniques such as curing, surface polishing, finishing, etc. (Zivanovic *et al.*, 2020). The latest is an auxiliary operation to improve the look.

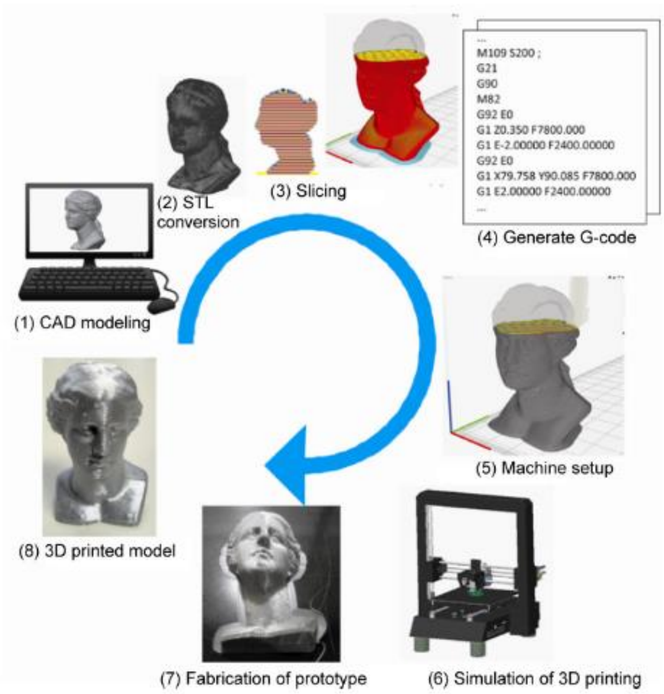


Figure 4. Phases to create an object through AM
(Extracted from Zivanovic *et al.*, 2020)

For the empirical component of this dissertation, students learned the basics of 3D modeling, such as how can one draw a desired object by combining different shapes, controlling perspectives, drag and drop, duplicate and moving, using *TinkerCad*[6] and the steps to print in 3D through additive processes. Due to its plainness, this software is suitable for beginners. Some

[6] https://www.tinkercad.com/

studies have encouraged CAD to prepare students with the necessary skills for developing students' professional skills of the future (Chong *et al.*, 2018; K. Jones & Mendez, 2021; Seiersten & Berg, 2017) based on interdisciplinary teamwork. It has proven to increase students' engagement. Chong *et al.* (2018) highlight, however, some of the limitations of integrating 3D printing into teaching, namely (1) limited choice of colors, materials and finishing surfaces (2) small size of printers, which makes them unsuitable for large structures and (3) lack of guidance of how the technology works.

2.2.1.9 Cyber Security

The last pillar here presented is Cyber Security. Regarding it, Vaidya *et al.*, (2018) states "With the increased connectivity and use of standard communications protocols that come with Industry 4.0, the need to protect critical industrial systems and manufacturing lines from cyber security threats increases dramatically" (p.236). Cyber Security is the technology that enables the protection of shared information and CPSs from cyber-attacks (Wells *et al.*, 2014).

By protecting information, cyber security, ensures stable operation of systems as well as data accuracy and a more reliable manufacturing.

2.2.2 Teaching Approaches of Industry 4.0

With the aim of understanding how concepts related to I4.0 are being taught all over the world, some key approaches were identified. Table **2** identifies those approaches and the respective teaching methodologies and countries/educational contexts.

Table 2 Teaching approaches of Industry 4.0

Teaching methods	**Country / Educational Institution**	**Reference**
Learning Factory	Faculty at NTNU, Norway	(Ogorodnyk *et al.*, 2017)
	Austria, TU Wien	(Erol *et al.*, 2016)
	University of Applied Sciences Darmstadt, Germany	(Simons *et al.*, 2017)
	RWTH Aachen University, Germany	(Schuh *et al.*, 2015)
	Learning factory of the Ruhr-University of Bochum, Germany	(Oberc *et al.*, 2019)
	Germany	(Tisch *et al.*, 2013)

	Educational Foundation of Ignatius (FEI) University Center, Brazil	(Maia *et al.*, 2017)
Project Based Learning	Private Primary School in Ankara, Turkey	(Somyürek, 2014)
	Taiwan	(Jou *et al.*, 2010)
	Israel	(Verner & Greenholts, 2017)
	University of Applied Sciences Darmstadt, Germany	(Simons *et al.*, 2017)
Problem oriented scenarios / Scenario Based Learning	Learning factory of the Ruhr-University of Bochum, Germany	(Oberc *et al.*, 2019)
	Private Primary School in Ankara, Turkey	(Somyürek, 2014)
	Universitat Politècnica de València (UPV) and the IES Gonzalo Anaya	(Peiró-Signes *et al.*, 2020)
	Middle-school in Israel	(Kaloti-Hallak *et al.*, 2019)
	Austria, TU Wien	(Erol *et al.*, 2016)
	Israel	(Zadok & Voloch, 2018)
	Educational Foundation of Ignatius (FEI) University Center, Brazil	(Maia *et al.*, 2017)
Work Based Learning	RWTH Aachen University, Germany	(Schuh *et al.*, 2015)
	Faculty at NTNU, Norway	(Ogorodnyk *et al.*, 2017)
Flipped classroom	Malaysia	(Chong *et al.*, 2018)
e-learning	Southern Italian company	(Clarizia *et al.*, 2021)
	University of Applied Sciences Emden/Leer, Germany	(Wermann *et al.*, 2019)
	Taiwan	(Jou *et al.*, 2010)
	Malaysia	(Chong *et al.*, 2018)

Learning Factories (LF) have been used all over the world (Tisch *et al.*, 2013). The main reason for using LF lies in the possibility of providing a realistic environment of production systems with their technical equipment. Furthermore, process modifications can be safely tested. As stated by Tisch *et al.*, (2013) “Learning Factories pursue an action-oriented approach with participants acquiring competencies through structured self-learning processes in a production-technological learning environment." (p. 580) Thus, it is possible to teach the curriculum's contents in a very practice-oriented manner. The advantages of a real-world manufacturing environment are mostly used for academic education contexts (Erol *et al.*, 2016; Maia *et al.*, 2017; Oberc *et al.*, 2019; Ogorodnyk *et al.*, 2017; Schuh *et al.*, 2015; Simons *et al.*, 2017) or for training employees (Tisch *et al.*, 2013). From this LR, we could realize LFs may combine different assessment methods and types of what we entitled in Table **2** as teaching approaches. Moreover, LFs may include high tech machinery or not. For example, the roller skis assembly developed at the NTNU in Norway aimed at teaching practical skills and theoretical knowledge on topics like waste reduction and push/pull production systems without technological appliances (Ogorodnyk *et al.*, 2017). However the LF built at RWTH Aachen University (Germany), which consisted of sheet metal forming, joining of automotive body structures and a manual assembly section, represented authentic industrial requirements in terms of complexity level and quality specifications (Schuh *et al.*, 2015). Prominent approaches used when building a LF are project, scenario, and work-based learning. All of them are related to an action-oriented and "learning by making" method. According to Ogorodnyk *et al.* (2017) this latter method allows students to retain information for a longer time. The same authors decided to adopt a "push" method which consists of the introduction of theory before the problem, to avoid students advancing to the concrete activity without having knowledge on basic and fundamental related concepts (Tisch *et al.*, 2013). On the flip side, the activity may start with a presentation of the problem to the participants before they know the theory, an approach known as the "Problem Pull". Accordingly, the participants are eager to learn how to solve the presented problem (preferably a real-life one) and hence pull for the theory needed (J Cachay & Abele, 2012). Concerning the concrete activity organization, all reported activities involved interdisciplinarity and teamwork. In Ogorodnyk *et al.* (2017) work, students were given different roles during the learning factory activity (the roles were related to the work stations they were working on) and, at first, they were supposed to work alone to figure out the process at the work station and in the factory as a whole. Moreover, they were not supposed to discuss anything with the others. During the next rounds they were allowed to have team discussions. In the interviews conducted in this work, students emphasized the importance of teamwork in order to acquire a holistic picture; the individual process alone would be limited from their point of view. It seems that I4.0 jobs and skills are strongly linked with physical interaction and collaboration between individuals. But with the current worldwide pandemic, one question arises: Is it possible to learn meaningfully by executing tasks individually and still have access to a holistic view? Today's educational technologies might allow a kind of a holistic comprehension through other means beyond physical, in-person interaction.

Even though LFs are excellent means for disseminating knowledge for students, when it involves implementing machines, new software and licenses, it is a rather costly approach (Maia *et al.*, 2017). Next, we will present and describe other alternative approaches found in the literature review. Besides the literature already mentioned – directly related to LFs - there are other approaches mentioned in Table **2** that should be highlighted as they became useful for our research process.

The work of Chong *et al.* (2018) which consisted in evaluating the benefits of integrating 3D printing and I4.0 into Engineering undergraduate programs, suggests a blended learning model (online learning and face to face teaching) incorporating a flipped classroom approach (Figure **5**). Online learning, in this case, refers to the use of tools like “Moodle” or “Blackboard” for students’ self-learning, assessment, and evaluation. Face-to-face teaching refers to the traditional approach consisting of lectures and workshops, as well as some group activities to develop students’ soft skills. Finally, the flipping classroom, refers to the hands-on projects managed and driven by students. The authors suggest the “Bring Your Own Device” (BYOD) pedagogical trend (i.e. the use of open source software or arduino chips for automation or control system learning) and the “Do It Yourself” (DIY) pedagogical strategy (i.e. making a robotic arm via additive manufacturing) - which motivates the “learning by making” - for enhancement of active learning. Some of the main conclusions attained from surveys and interviews were that 3D printing helps Engineering students learn via rapid prototyping and enhances CAD skills and optimization and that self-education is important as it creates proactive and lifelong learners who can frame and troubleshoot any problem that may arise.

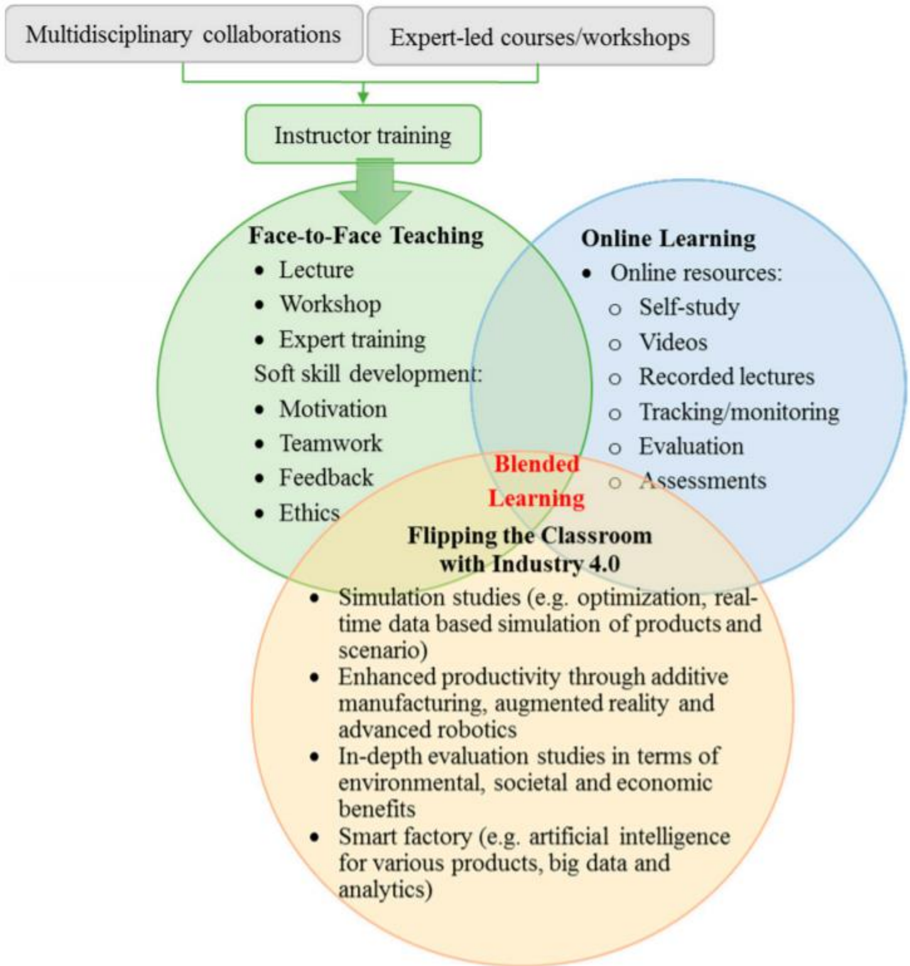


Figure 5. Model to teach Industry 4.0 pillars into engineering teaching. Extracted from Chong *et al.* (2018)

In its turn, the work of Kaloti-Hallak *et al.* (2019) targets middle school students and relies on the meaningful learning theory - just like this dissertation - to teach Engineering design process by the means of robotic activities through a Problem based Learning (PBL) approach. The first robotic activity of the First Lego League (FLL) contained missions that simulated assisting senior citizens in areas that they might find difficult; the second one containing missions that simulated helping people prepare, stay safe and rebuild in case of natural disasters. Zadok and Voloch (2018) consider this approach - PBL - to be one of the most important pedagogic milestones in the development of meaningful learning throughout educational history because student learn in a meaningful context. In this situation, the student feels committed to the success of his work and aspires to develop her/his ideas. Despite sharing similarities, PBL and Project based Learning (PrBL) are two distinct approaches. While in PrBL students design, plan and develop a product, in PBL a specific open ended and authentic real-world problem is specified by the instructor and students have to present a solution. The latest is a subset of PrBL, meaning that the project may or may not address a specific problem. The work of Peiró-Signes *et al.* (2020) also used the PBL approach. It targeted vocational students in the area of mechatronics and took into account the concept of meaningful learning. This empirical investigation focused on the acquisition of competencies in the areas of basic robot programming and the communication interface between robots and external devices. With this purpose, a bowling game simulation was developed using robots (machines), arduinos (basic PLCs) and cell phones (interface design) to develop an activity focused on communication and programming concepts and skills. The objective of the students was to make the robot grab a ball and leave it on a ramp which could be oriented towards a set of bowling pins. The orientation of the ramp could be controlled by a servo motor connected to an Arduino and to govern the mechanism, the students needed to use a cell phone. Results obtained through a Likert scale questionnaire encourage the development of this activity which results in a positive perception of students concerning their learning outcomes. Challenging students with a game that they know and in which they can compete, proved to be a powerful motivator to encourage the learning of certain concepts and skills of interest.

Lastly, the work of Verner & Greenholts (2017) targeted teachers and its primary goal was to foster meaningful learning by engaging them in the analysis of design solutions through the approach "learning by making". They had to choose, disassemble and analyze a technology system of their choice (functionality, mechanism, sensors etc.), and develop an idea on how to redesign that technology (i.e. a mouse) for other use cases. Results attained through a questionnaire and a free-form reflection, found that all the respondents appreciated the opportunity to learn about Reverse Engineering (RE) and its use in design education. It allowed them to think like Engineers and understand the mechanism and operation of technological systems used in everyday life and to learn new aspects of Engineering design. Students also noticed that the practice of RE engaged them in learning new digital technology tools (such as *TinkerCad* and *Arduino*) and in mastering technical skills that are important for teaching technology in schools. Critical comments pointed out the limited time to complete the design of the new system and to present and discuss their prototypes.

All the insights and conclusions above mentioned will be taken into account when designing our empirical case. A complex subject such as I4.0, requires a deep understanding in what competencies are needed for future Engineers. Industry 4.0 gathers various fields such as mechatronics, information, communication, computer networks, data and information processing and also the integration of all these hardware and software technologies into the industrial environment (Wermann *et al.*, 2019). For this reason, Engineering education framed in the I4.0 era, requires a multi-disciplinary knowledge.

Active learning refers to innovative student-centered instructional approaches that dynamically involve students in the learning process. The main constructs of active learning are the participation and the engagement of students with concrete learning experiences, knowledge construction of students via meaningful learning activities, and some degree of student interaction during the process. In many studies, active learning has been implemented in the context of problem-based, inquiry-based, discovery, collaborative, cooperative, team-based, and inductive learning methods (Erol *et al.*, 2016; Jou *et al.*, 2010; Maia *et al.*, 2017; Ogorodnyk *et al.*, 2017). In contrast to active learning, passive learning usually involves teacher-centered methods that favor direct instruction in which students often learn through listening to and observing lectures presented by an instructor.

To address the lack of a framework and taxonomy about active learning, Chi (2009) proposed the Differentiated Overt Learning Activities (DOLA) framework that proposes that engagement behaviors can be categorized and differentiated into one of four modes: Interactive, Constructive, Active, and Passive (ICAP). Table **3** presents these four modes of activities and the cognitive processes addressed to each mode. Furthermore, this hypothesis predicts that as students become more engaged with the learning materials, from passive to active to constructive to interactive, their learning will increase.

Table 3 Differentiated Overt Learning Activities.
Extracted and adapted by Chi & Wylie (2014)

Passive	**Active**	**Constructive**	**Interactive**
Storing new information directly, without assimilating it with relevant knowledge.	Search for existing knowledge. Strengthen knowledge. Encode or assimilate new information.	Create & infer new knowledge. Integrate newly created knowledge with old knowledge. Re-organize knowledge Repair or accommodate old knowledge.	Co-construct new knowledge that is novel to both partners; Build on each other's Knowledge; Solve own conflicts based on partner's comment.

On the passive mode, activities promote a transactional notion of education, where students receive information with no expectation of interaction. At this stage, students watching a video or receiving a lecture.

Regarding active mode, Chi & Wylie (2014) characterize an activity as so if students evidence direct manipulation of instructional materials or activities. These behaviors certainly appear more active than the first stage, although students have yet to create original thought or wording of concepts in their own terms. At this stage, the teacher would observe students taking verbatim notes, highlighting a text, or perhaps rewinding or pausing a video. According to Chi (2009), students who engage in active learning activities learn better than students who are more passive and not engaging in any observable learning activities, even though these passive students are oriented toward instruction and are receiving the learning materials.

In the constructive mode, students undertake activities in which they generate knowledge that extends beyond the presented materials. Examples of these type of activity are: selfexplaining, or explaining aloud to oneself a concept presented in a text, drawing a concept map, taking notes in one's own words from a lecture, generating self-explanations, comparing and contrasting different situations, asking comprehension questions, solving a problem that requires constructing knowledge, justifying claims with evidence, designing a study, posing a research question, generating examples from daily lives, using analogy to describe certain cases, monitoring one's comprehension, making strategic decisions in a video game, converting text based information into symbolic notation, drawing and interpreting graphs, or hypothesizing and testing an idea. The cognitive processes hypothesized to accompany constructive activities can generate new ideas, insights, and conclusions in a way that allows learners not only to infer new knowledge but also to repair or improve their existing knowledge. Repairing one's existing knowledge makes it more coherent, more accurate, and better structured, which serves to deepen one's understanding of new information.

Finally, interactive mode refers to two or more learners undertaking activities that develop knowledge and understanding extending beyond the materials being studied - similar to the constructive mode -, but the interaction of the learners further enables them to build upon one another's understanding. The main difference between the interactive and constructive mode is that learners in the latter engage in activities alone. Chi & Wylie (2014) cautions, however, "simply asking students to work together does not automatically make an activity interactive." (p.235). For example, if one group member dominates the discussion or if one member does not contribute to the discussion or product, then the group is not fully interacting.

Engineering education must be continuously developed in line with the current and future requirements of the industry. With this, emerges a more specific question: What are the most suitable teaching methods to educate on I4.0 concepts, considering the skills required for the professionals in this industry?

2.2.3 Education 4.0 and Competencies Needed

The fast development of Industry 4.0 implies that Engineering graduates acquire new competencies to adapt to the digital transformation. Here it is worth mentioning STEM (Science, Technology, Engineering and Mathematics) concept, which is an acronym that stands for Science, Technology, Engineering and Mathematics. Aiming to reach technology development and consequently, economic competitiveness, some countries are increasing their investment in STEM related industries, such as information technology and Engineering. Mohr-Schroeder *et al.* (2020) states:

> While a single, consensus definition of integrated STEM still does not exist, certain characteristics have been shown to be important in integrated STEM. These include (a) the need to address a complex, authentic, or real-world problem; (b) shared skills, practices, and concepts from across disciplines; (c) student-centered teaching strategies, including an

emphasis on collaboration and teamwork; and (d) integration of at least two or more disciplines. (p. 30).

STEM education involves viewing the above mentioned disciplines as an integrative whole in the process of teaching and learning (Breiner *et al.*, 2012; Havice *et al.*, 2018) instead of receiving knowledge from a single specialized teacher and consequently acquiring fragmented and isolated knowledge from each discipline. However, a gender gap in STEM industries persist. A study taken in 67 different countries found that boys expressed a stronger interest in broad science topics than girls did (Mostafa, 2019). In Portugal, according to PORDATA (2020), only 24% of students attending higher education in Engineering, manufacturing and construction correspond to female. Silva (2018) stresses the same issue for STEM and ICT roles in Portugal, both in education and workforce. Portugal is one of the countries that would have a substantial positive impact if improving gender equality. A study by the European Institute for Gender Equality (EIGE) gives strong evidences related to the economic benefits of gender equality in the EU (Morais Maceira, 2017). As indicated "the employment rate in the EU will make a substantial leap if women have more equal opportunities in STEM education and the labor market" (p. 181). The lower numbers of girls in STEM education may be motivated by gender stereotypes (Carlana, 2019; Silva, 2018) which consequently reduces girls' confidence and interest in this field (Ferreira, 2017). Women who pursue careers in STEM, have reported to face male dominated workplaces with high rates of discrimination (Funk & Parker, 2018); their contributions are often ignored (Sherbin, 2018); they experience isolation caused by "lack of access to women peers, role models, and mentors" (Madgavkar *et al.*, 2019, p. 39; Silva, 2018); and they are paid less than their male co-workers (Carlana, 2019; Silva, 2018).

(Leung, 2020) developed a boundary crossing framework for the four disciplines of STEM education. Similarly with Priemer *et al.* (2019), Leung emphasizes that problem solving plays a central role in STEM education. Building upon an inquiry based and problem-solving approach of STEM education, Leung (2020) conceptualizes STEM education as:

> "situated contextual teaching and learning where participants from educational Communities of Practice (e.g. teachers, students) socially co-construct solutions and knowledge for addressing relevant real-world problems through boundary crossing dialogical and problem-solving processes that involve more than one STEM discipline". (p. 5)

Therefore, STEM education is a process of inquiry educating students as problem solvers with critical and analytical thinking to find innovative and creative answers themselves in the natural and man-made world. Recently, the term STEAM which stands for Science, Technology, Engineering, Arts and Mathematics emerged aiming to engage students in STEM learning and to enhance creativity, problem-solving skills and to encourage students to explore new ways of knowing (Perignat & Katz-Buonincontro, 2019). However, the definition of "Arts" in STEAM acronym lacks agreement. The different definitions can be grouped into three categories: (1) non-STEM that refers to covering any subject that is not featured by STEM subjects (often used to refer to things like the humanities) (Peppler & Wohlwend, 2018; Quigley *et al.*, 2017), (2) Arts education that refers to diverse kinds of arts like visual or performing (Glass & Wilson, 2016; Grant & Patterson, 2016) and (3) Pedagogical approaches like project-based learning or problem-based learning (Choi & Behm-morawitz, 2017; Gates, 2017).

Developing and enhancing competencies through education and meaningful learning are key drivers of economic success, of individual well-being and societal cohesion. Kinkel *et al.* (2017) claim that a competency is "the individual dispositional ability and readiness to act successfully and self-organized when facing novel, unstructured or complex situations or tasks and the ability to develop solutions for future situations" (p. 324).

Analysts predict that between 2020 and 2030 employment growth in Manufacturing sector in Portugal will lead with 6.1% while EU27 follows with -2.9% (Skills Panorama, 2019). The Automation and the future of work in Portugal study (McKinsey & Company, 2018) assessing the country's automation potential until 2030 was presented in January 2019. It highlights the upcoming and profound technological transformations and the need to reskill and requalify workers.

According to Erol *et al.* (2016), Industry 4.0 propagates the idea of workers increasingly focusing on creative, innovative, and communicative activities. Routine and monitoring activities will be mostly replaced by automated systems.

The Accreditation Board for Engineering and Technology, Inc. considers that successful professionals must have the following abilities: (1) to identify, formulate, and solve complex Engineering problems by applying principles of Engineering, science, and mathematics; (2) to apply Engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors; (3) to communicate effectively with a range of audiences; (4) to recognize ethical and professional responsibilities in Engineering situations and make informed judgments, which must consider the impact of Engineering solutions in global, economic, environmental, and societal contexts; (5) to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives; (6) to develop and conduct appropriate experimentation, analyze and interpret data, and use Engineering judgment to draw conclusions; (7) to acquire and apply new knowledge as needed, using appropriate learning strategies.

Through the development of a LR, a group of researchers identified competencies that new candidates must have to implement I4.0, as shown in Table **4** (Hecklau *et al.*, 2016).

Table 4 Competencies required for the Industry 4.0. Extracted and adapted from Hecklau *et al.* (2016)

Technical competencies	**Methodological competencies**	**Social competencies**	**Personal competencies**
State-of-the-Art knowledge	Creativity	Intercultural skills	Flexibility
Technical skills	Entrepreneurial thinking	Language skills	Ambiguity tolerance
Process understanding	Problem-solving	Communication skills	Motivation to learn
Media skills	Conflict-solving	Networking skills	Ability to work under pressure
Coding skills	Decision-making	Ability to work in a team	Sustainability mindset
Understanding IT security	Analytical skills	Ability to compromise and cooperate	Compliance
	Research skills	Ability to transfer knowledge	
	Efficiency orientation	Leadership skills	

As may be observed, technical basics are merely one of the attributes for professionals of the future as they must be supplemented with skills so far perceived as soft ones.

"Annex G: Industry Profile" presents a Table where it is summarized an Advanced Manufacturing profile generated by the World Economic Forum (2020) based on 26 countries. From this profile, five topics were extracted:

1. Emerging skills identified as being in high demand within their organization.
2. Current skills in focus of existing reskilling/upskilling programs.
3. Technology adoption in Industry.
4. Barriers to adoption of new technologies.
5. Emerging and redundant jobs in 5 years. This provides an overview of expected developments in industry-specific job roles.

It is noteworthy that in the future, manufacturing sector will need individuals with hybrid skills who can apply technical, digital, and personal skills and knowledge across a range of contexts and applications.

Simons *et al.* (2017) presents Figure **6**, which gathers the crucial aspects of production, crucial technologies and required competences of Engineers - and states that Engineers "need an interdisciplinary understanding of systems, production processes, automation technology, information technology, ergonomic principles and of business processes. In addition, the skills for cooperation and communication in interdisciplinary groups are of crucial importance." (p. 83) Furthermore, the author suggests that to acquire an holistic perspective of complex production systems and to effectively instruct future Engineers, educational institutions might use problem-based or project-based learning in Learning Factories.

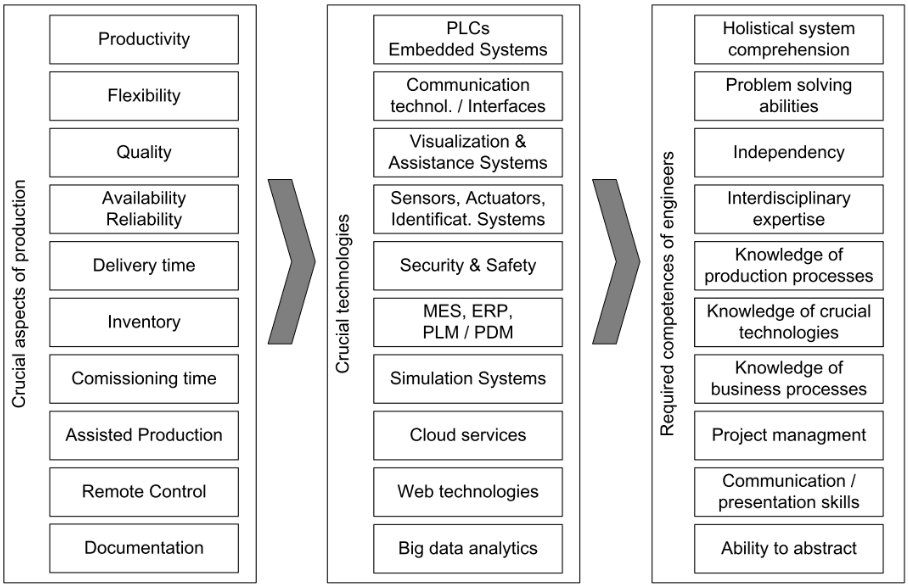


Figure 6. Crucial aspects of production, technologies and required competencies. Extracted from Simons *et al.* (2017)

The defined competencies required to adapt to the current industrial revolution reported in different papers/projects and various industrial sector surveys differ slightly among themselves. However, the critical competencies rely on technology use, monitoring and control, analytical thinking and innovation, complex problem-solving and active learning.

2.2.4 David Ausubel Theory and Related Views

The term "meaningful learning" became prominent in science education through the work of the educational psychologist David Joseph Ausubel and his use of this concept in the 1960s. According to this theory:

> The essence of the meaningful learning process is that new symbolically expressed ideas (the learning task) are related in a nonarbitrary, and nonverbatim fashion, to what the learner already knows (his cognitive structure in a particular subject-matter field), and that the product of this active and integrative interaction is the emergence of a new meaning reflecting the substantive and denotative nature of this interactive product (Ausubel, 2000, p. 67).

Nonarbitrary means that it does not interact with any previous knowledge that exists in the cognitive structure (this knowledge is called "subsumer"), but with specifically relevant knowledge. Nonverbatim means nonliteral, the learner does not make an "ipsis verbis" internalization, but rather merged with personal meanings. However, the author cautions that 1) the learner must have the disposition to relate the new material to be learned and 2) the material they learn should be relatable to their particular structures of knowledge on a nonarbitrary and nonverbatim basis (Ausubel, 2000). Considering the learners' disposition to learn, Novak (2009) stresses

> A learner can begin learning a new concept by memorizing a definition of the concept, this being representational learning. However, meaningful learning requires further effort; the learner must choose to relate the concepts and proposition(s) of the definition in some substantive way to what relevant knowledge already exists in the learner's cognitive structure (p. 62).

This author provides an example of a teacher or book that defines vapor as "water in the form of an invisible gas." If the student chooses to learn the concept meaningfully, he needs to relate the meaning of vapor to concepts and propositions he already knows in a substantive, nonarbitrary, non-verbatim manner. This is illustrated in Figure **7**. If he chooses to learn by rote, the definition of vapor would be learned verbatim and not assimilated substantively and non-arbitrarily into his existing knowledge framework – Figure **8**. In this case, propositions are not related to, nor incorporated into, his prior conceptual framework, and would likely be soon forgotten.

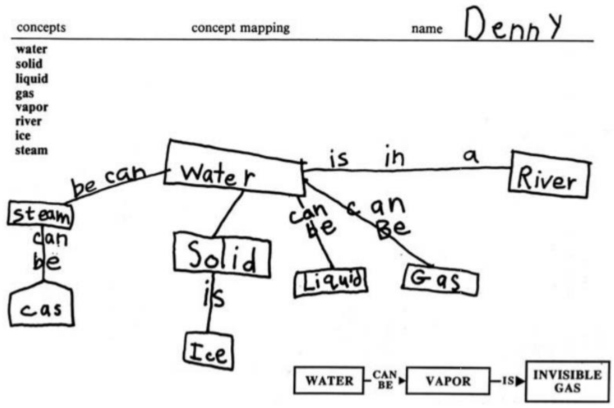


Figure 7. Concept map showing the definition of
"vapor" as learned by rote. Extracted from Novak (2010)

Regarding the instructional material, it must be sufficiently non-arbitrary - nonrandom, plausible, sensible - so that it can be related on a nonarbitrary and nonverbatim basis to correspondingly relevant ideas that at least some human beings are capable of learning if given the opportunity to do so. This aspect of the learning task - that determines whether the material is potentially meaningful - can be called logical meaningfulness. The other factor which determines whether learning material is potentially meaningful, depends on the quantity and quality of the organization of the relevant knowledge held by the learner - relevant ideational content should be available in the cognitive structure of the learner to serve this subsuming and anchoring function.

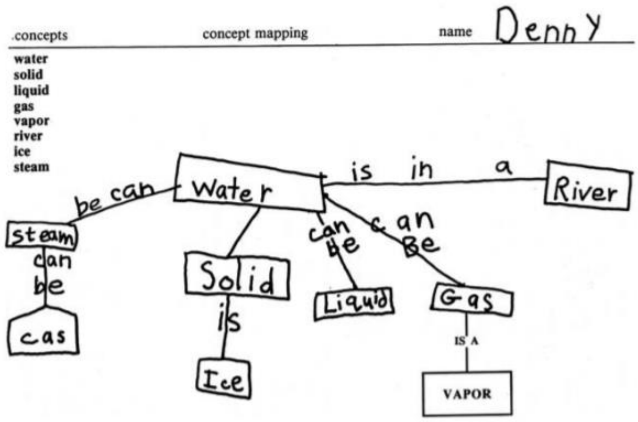


Figure 8. Concept map in which the definition of "vapor"
might have been incorporated following meaningful learning.
Extracted from Novak (2010)

The potential meaningfulness of learning materials varies also with factors like age, IQ, occupation, social class, and cultural membership (Ausubel, 2000).

According to Ausubel, some principles may be followed to facilitate transfer of meanings. During the expository teaching, the instructor should use progressive differentiation and integrative reconciliation in instructional materials. Ausubel's definition of progressive differentiation states that: "most learning, and all retention and organization, of subject matter is hierarchical in nature, proceeding from the top downwards in terms of level of abstraction, generality, and inclusiveness" (Ausubel, 2000, p. 6). The sequential assimilation of new meanings from successive exposures to new, aided by potentially meaningful materials results in progressive differentiation of concepts or propositions. In turn, Integrative reconciliation is a strategy that consists in anticipating and thwart the mistakeable similarities and differences between new ideas and established relevant existing ideas already present in learners' cognitive structures. Another relevant principle has to do with consolidation. It should occur before a new learning material is introduced, making sure previous meanings are clear and stable. This is achieved, for example, through confirmation, clarifications, feedback, frequent tests with items demanding explanation among various alternatives varying in degree of correctness (Ausubel, 2000).

According to Ausubel, the availability of relevant ideas in cognitive structure may be assessed by multiple choice or essay pre-tests, Piaget-type clinical interviews, Socratic questioning and "cognitive mapping". Evaluation/rating by subject matter by experts/teachers may also be used to judge its usefulness to teach a particular subject.

This is the classical view of meaningful learning. In this view, the most important factor influencing learning is what the learner already knows. Therefore, teachers must necessarily take into account the student's previous knowledge. Since then, other views based on this urged.

2.2.4.1 Novak's Humanistic View

Novak first presented this thesis in his book "A Theory of Education" (Novak, 1977). It proposes that meaningful learning is subjacent to the constructive and positive, integration of thinking (cognitive learning), feeling (affective learning), and acting (psychomotor learning), leading to human empowerment for commitment and responsibility (Novak, 2009). The learner and mentor interaction seeks to exchange meanings and feelings between them. Regarding this subject matter, Novak (2009) says "When learner and teacher are successful in negotiating and sharing the meaning in a unit of knowledge, meaningful learning occurs" (p. 18). This exchange is positive and constructive when the learner enhances or acquires an understanding of a segment of knowledge, going beyond rote learning. On the other hand, the exchange is negative when the understanding is obfuscated, or feelings of inadequacy emerge.

For Novak (2009), the willingness to learn stands as one of the two necessary conditions to acquire meaningful learning. The other condition has a direct relation with the four known "commonplaces" proposed by Joseph Schwab in 1973. For educators it is seen as a checking list of all necessary elements to understand and propose any educational intervention. Novak suggests adding a fifth element, being them (1) learner; (2) teacher; (3) knowledge; (4) context; and (5) evaluation (added by Novak). For evaluation purposes, Novak suggests concept maps and Vee diagrams (Novak, 2009).

Moreover, in Novaks' view (2009), technology mediated education might reduce errors or biases by the teacher, however the author advocates teaching and learning requires interactive events that machines are not able to provide because they do not express emotions or an excitement that a human teacher may provide.

2.2.4.2 Gowin's Social Interactionist View

Gowin (1981) supports that teaching-learning process underlies a triadic relationship - between teacher, educative materials and student - that occurs in a context. Teaching requires reciprocity of responsibilities. The teacher is responsible to present – the number of times and ways necessary - meanings and to look for evidence that the learner is grasping them. The learner is responsible to verify whether the meanings he/she is grasping are those that are accepted in the subject matter context. In this process of negotiation of meanings, language plays a crucial role. If sharing meanings is achieved, the student is ready to decide whether or not to learn significantly. To do so, the student has to manifest a disposition of relating, in a non-arbitrary and non-literal way, to their cognitive structure, the meanings that it captures from the potentially significant educational materials of the curriculum.

2.2.4.3 Contemporary Cognitive View

Johnson-Laird's mental models theory (1983) suggest that when facing a new knowledge, a mental model is constructed by the learner - which reflects an intentionality to assign meanings to the new knowledge. A mental model in Johnson-Laird's view is a reasoning mechanism that exists in a person's working memory and can represent physical or conceptual entities. Depending on the circumstances, this representation can get stabilized and can evolve to an assimilation scheme (Greca & Moreira, 2002). According to Vergnaud (2009), a scheme "is the invariant organization of activity for a certain class of situations" (p. 88). Therefore, assimilation schemes are more stable; the subject constructs a certain scheme and uses it to assimilate a certain class of situations. Peoples' ability to represent the world accurately though, is different from individual to individual. Thus, mental models are considered incomplete representations of reality (N. A. Jones *et al.*, 2011). Moreover, they are characterized as inconsistent representations because they may depend on contexts, changing according to the situation in which they emerge (N. A. Jones *et al.*, 2011). On the other hand, mental modeling is recursive, thus mental models may be changed as much as it is necessary along the negotiation of meanings, and it should constitute an essential step to meaningful learning, as it might even evolve to assimilation schemes (Moreira, 2002).

2.2.4.4 Complexity and Progressiveness

For Vergnaud, knowledge is organized in conceptual fields, whose mastery by the learner occurs over a long period of time, through experience, maturity and learning (Vergnaud, 1982 *apud* Moreira, 2002; Vergnaud, 2009). Concept fields can be defined as a set of situations and concepts (Vergnaud, 2009). This way, the learners' knowledge is constructed based on situations they encounter, having the possibility to master them progressively, through increasingly complex situations (new knowledges). Thus, the acquisition, or domain, of a conceptual field is a progressive process, with continuities and discontinuities (Moreira, 2002) which result in a continuum between rote learning and meaningful learning. Consequently, it might require much time (and many situations) to achieve a high degree of meaningfulness.

Moreira (2002) draws a comparison between the meaningful learning theory of David Ausubel and Vergnaud's theory of conceptual fields. Although Vergnaud's theory is not for teaching explicit and formalized concepts, it shares the idea that knowledge-in-action - largely implicit - can evolve over time into scientific knowledge - explicit. Ausubel's theory, on the other hand, deals exactly with the acquisition of explicit and formalized concepts, proposing programmatic principles - such as progressive differentiation, integrating reconciliation and consolidation - for the organization of teaching (Moreira, 2002). Vergnaud stresses that most of our physical and mental activity (behavior) is made up of schemes and these are mostly operative invariants (theorems and concepts-in-action) represented by implicit knowledge (Vergnaud, 1994 *apud* Moreira, 2002). Students often solve the situations, but do not explain the theorems in action that were used, this constitutes the difference between the action and the formalization of the action.

2.2.4.5 Autopoietic View

Autopoietic theory was developed by Maturana & Varela (1980) to provide explanations of the characteristics of living systems, as opposed to non–living systems. Maturana, (2001) advocates that each individual is an autopoietic system that determines the meaningfulness of his/her learning. The theory's main thesis is that the components of a system (e.g. pieces of existing knowledge) are used to produce new components (e.g. pieces of new knowledge) and relationships so as to recreate the system. This means that an autopoietic system is self-referential, which means, in turn, that the components accumulated by the system themselves affect the components of the system. In this process, the teacher and educative materials are disturbing agents and meaningful learning takes place, in the domain of disrupting interactions that generate changes of state, that is, structural changes that do not modify the autopoietic organization and maintain identity (Maturana, 2001).

According to the author, students' prior knowledges are explanations that are, in fact, reformulations of their experiences. Such clarifications might be accepted, or not, within the scientific context. This seems coherent with Ausubel's original proposal that emphasized that the subject's willingness to learn is one of the essential conditions for the occurrence of meaningful learning.

2.2.4.6 Computational Theory of Mind

Warren McCulloch and Walter Pitts (1943) were the first to suggest that neural activity is computational. However recent studies in the field have been made. Paul Thagard, for example, states "the central hypothesis of cognitive science is that thinking can best be understood in terms of representational structures in the mind and computational procedures that operate on those structures" (Thagard, 2005, p. 10). This theory supports that the human mind is seen as a computational and representational system. The mind receives sensorial information from the world and processes it, in other words, computes and generates representations of the world. So, people construct mental representations instead of understanding it directly.

This view is close to the Ausubel one to the extent that if the individual is predisposed to learn, he/she constructs mental representations of these knowledges, such as mental models (when the situation is new) or the student activates assimilation schemes in case the situation presented seems familiar. However, instead of talking about subsumers, which often are interpreted as discrete knowledges, this view focuses on mental representations that result from mental computations, which are not conscious.

Meaningful learning is therefore, being mediated not only by the teacher (human mediation) and by the language (semiotic mediation) but by the computer (machine mediation), as well. Examples of this use are simulations and computational modeling. They are used not only as pedagogical resources, but as also as mechanisms that lead to another kind of cognition, to new cognitive processes, and perhaps to another kind of meaningful learning.

2.2.4.7 Critical View

In a contemporary view, learning must be meaningful as well as critical, subversive, and anthropological. Teaching, because of this, has to follow the principles (Moreira, 2010, pp. 20–21):

1. Previous knowledge (we learn from what we already know)
2. Questions instead of answers (stimulate questioning instead of providing ready answers)
3. Diversity of educational materials (abandonment of the manual, of the unique textbook)
4. Learning through the error (it is normal to error; we learn by correcting our mistakes)
5. Student as a representationist perceiver (the student represents what perceives; the teaching-learning process implies presentation, reception, negotiation, and the sharing of meanings, for which language is crucial. Meaningful learning demands the sharing of meanings)
6. Semantic consciousness (the meaning is in the person, not in the words)

7. Uncertainty of knowledge (the human knowledge is tentative, evolutionary. The best models we have today will generate others that might be richer, more elaborate, and better)
8. Unlearning (sometimes previous knowledge works as an epistemological obstacle)
9. Knowledge as language (all that we call knowledge is a language)
10. Diversity of strategies (abandonment of the chalk board)
11. Disclaiming the narrative (relying just on the narrative does not stimulate comprehension)

An overview on these theories was important to realize the concept of meaningful learning underlies or complements some theories later created. It allowed us to understand meaningful learning in a deeper way, considering every kind of implications, and concepts such as representation, reception, negotiation and the sharing of meanings. It made clear that prior knowledge is the variable that has the most influence in the learning process. The most relevant views for today's world are probably complexity, progressiveness and criticalness. For education 4.0 it is an imperative to think critically about new upcoming views, we could not restate all the principles the exact same way Ausubel proposed. Summing up the main ideas, in todays' world the construction of meanings are progressive. Meaningful learning depends on the grasping of meanings that result from the negotiation (of meanings) between the learner and the teacher and this is not a fast process. Moreover, when it is forced upon the learner, it will motivate rote learning. Even when the acquisition of knowledge happens meaningfully, in today's world that knowledge should be continuously questioned. The human knowledge changes quickly. By learning meaningfully and critically, the learner is able to deal with a large amount and uncertainty of knew knowledges.

2.2.5 Assessment Based on Meaningful Learning

Along with the articles read and the theories presented, some assessment methods were mentioned. We will go through them in the next subtopics.

2.2.5.1 Concept Maps

Joseph Novak, based on the ideas of Ausubel, elaborated a technique which he named "Concept Mapping" or "Concept Maps", which is a cognitive mapping technique. A Concept Map represents students´ knowledge as a hierarchical structure of concepts through which the learners relate new information to ideas that the learners already know (Novak, 2009). So, by this means, the general knowledge goes to the upper part and the most specific one goes to the lower. Through the years, concept mapping has revealed to be a highly applicable technique that allows people to acknowledge what they know and have learned for a specific discipline. It has earned a great deal of attention (Novak, 2009; Young *et al.*, 2018) including in manufacturing Engineering education (Ullah, 2016). Concept maps allow to orderly portray thoughts and ideas, analyze what people know and don’t know and, consequently, broaden their existing knowledge.

To construct concept maps it is important to be somehow familiar with the subject. Novak e Cañas (2008) point that a segment of a text, a laboratory or field activity, or a particular problem or question that one is trying to understand, should be identified, creating a context. They highlight “Focus Questions” as a good way to clearly specify the issue, avoiding that students build a concept map that may be related to the domain but which does not answer the question. Given a Focus Question, students should then identify about 15 to 25 key concepts that may respond to the answer and order it from the most general to particular. This list of concepts is entitled by the authors as “parking lot” because concepts are supposed to be transferred to a concept map, determining where they fit. Some concepts may be excluded, however, if no logical connection is found. After this, a software which allows moving concepts together with cross links should be used to see if the learners understand the relationships between the sub-domains in the map. As students identify cross-links, they are likely to reach the idea that every concept is related to every other concept, being required to identify the most important cross links. This process involves what Bloom *et al.*, (1956) identified as high levels of cognitive performance, namely evaluation and synthesis of knowledge.

This approach to assess domain-specific knowledge has a number of benefits like (a) assessing the students’ levels of development of expertise in a domain, (b) having no ceiling effect, (c) assessing higher levels of thinking rather than memory and comprehension and (d) offering an alternative to the usual multiple choice standardized tests or grades for assessing domain-specific ability and understanding (Erdimez *et al.*, 2017; Maker & Zimmerman, 2020).

2.2.5.2 Vee Diagram

Vee diagrams were first presented by Gowin (1977) as an efficient tool to aid students in understanding research reports (Novak, 2009). Providing the following guiding questions can help students to successfully use Vee Diagrams (Figure **9**) to generate new knowledge (Gowin, 1977 *apud* Novak, 2009):

1. What are the telling questions? These are questions that “tell” what the inquiry seeks to find out.
2. What are the key concepts? These are the dozen or so disciplinary concepts that are needed to understand the inquiry.
3. What methods of inquiry (procedural commitments) are used? These are the data gathering or data interpreting methods used.
4. What are the major knowledge claims? These are the answers claimed by the researcher as valid answers to the telling questions.

5. What are the value claims? These are claims, explicit or implied, about the worth or value of the inquiry and the answers found in the inquiry.

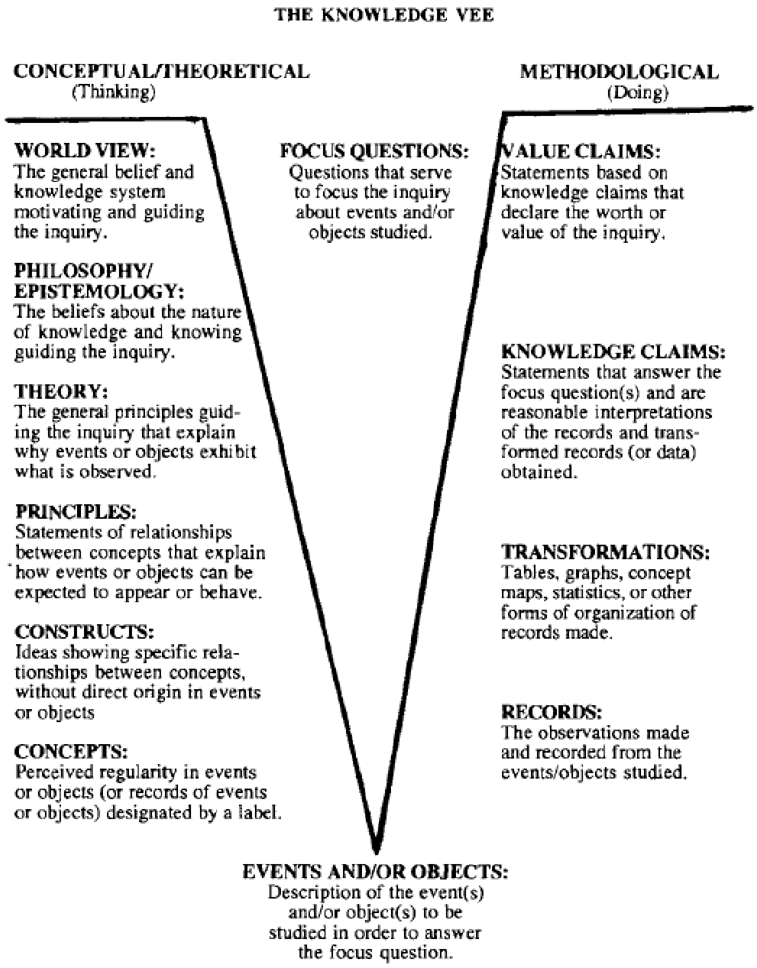


Figure 9. Vee diagram with the 12 elements involved in the construction of knowledge and value claims. Extracted from Novak (2009)

As we can see, there are 12 “epistemic elements” that are involved in constructing or examining a piece of knowledge. This structure helps to illustrate how each of these elements function. In short, the focus question drives the overall investigation; objects or events that occur are described at the point of the Vee; the right arm of the Vee is the doing side (methodological); data and records include all tables, graphs, and observations; analysis is where sense is made of the data and records; knowledge claims describe an individual’s new understandings that arise from completing the task; the thinking (conceptual/theoretical) component of the Vee is on the left; concepts are the main ideas that are embedded in the learning activity and principles are concepts that are synthesized and transformed into broader unifying statements (Novak, 2009).

2.2.5.3 Multiple choice or essay pre-tests

According to Hartley & Davies (2019),

> a pretest may be defined as any set of related questions, given before instruction, that is directly relevant to the knowledge, attitude, or skill domain to be acquired. The questions or items making up the test may be the same as, a selection from, or parallel versions of questions to be posed as a posttest or even as a retention test to be given after all the teaching has long been concluded (p. 241).

The authors further explain that pretests demonstrate what is already known and what new material can be keyed into prior knowledge. Along with a posttest, information can be obtained concerning the success of both the learner and teacher. Beckman (2008) investigated the effect of pre-testing in a sample of undergraduate students taking a science course. In this study, one class was given a pre-test with questions derived from unit learning objectives before an instructional unit, whereas the second class was given a list of learning objectives instead of a pre-test before an instructional unit. Results of the post-test revealed that participants in the treatment group scored significantly higher than those in the control group on both the unit post-tests and the final exam. Students also reported that the pre-tests motivated them to monitor their own learning (Beckman, 2008).

According to Ausubel (2000) the simplest way to prove that meaningful learning has occurred is through multiple choice tests, where the student should differentiate between similar ideas or to choose the identifying elements of a concept or proposition from a list that contains related concepts/propositions. DeMara *et al.* (2019) entitled it as a "multiple dropdown data" mainly due to its use on technological devices. In this particular case, it was used to assess the "Remember" processes (of Blooms' Taxonomy model). On the other hand, Erdimez *et al.*, (2017) argue that multiple choice tests are limited on assessing higher level skills such as judgement, analysis and reflection. The same authors advocate that concept mapping has the potential to show greater gains in scores of the students than the multiple-choice items.

2.2.5.4 Socratic questioning

Based on Delic & Bećirović (2016), the Socratic method is

> a pedagogy that uses guided questions, dialog, and refutation to help learners critically reflect on their understanding of a particular issue. As learners reflect, the instructor's questions stimulate them to reject misconceptions and gain an understanding of what they know and also what they do not know (pp. 516–517).

So rather than the teacher filling the mind of the student, both are responsible for pushing the dialogue forward and uncovering truths. Socratic questioning in teaching leads to greater learning than didactic lectures (Rosé *et al.*, 2001). DeMara *et al.* (2019) used this method to evaluate higher levels of cognitive structure using the "Bloom Taxonomy" (this framework is further explained on 2.2.6 topic).

Ogorodnyk *et al.* (2017) work – which consisted of the creation of an assembly line of roller skis aiming at improving students' practical and theoretical knowledge on topics of waste types, efficiency, push/pull production systems etc. - also assessed the students' learning outcomes via interviews (although it is not mentioned if it consisted only in asking or if it involved some kind of dialogue as the Socratic questioning entails). Between other conclusions, answers have proved that students could define the major concepts and were able to distinguish different types of waste and production systems. A week after the activity, interviews were conducted again - in order to understand whether the knowledge was really gained during the activity - and they still remembered the terms and claimed to be able to use them in practice.

2.2.5.5 Clinical interviews

Piagets' qualitative research method "clinical interviews" consists of providing materials/tools to the learner and ask them to perform specific tasks (i.e. Providing a small stone and plasticine and ask the child why one is heavier than another). During this process, he asks questions and records the child's answers (Piaget, 1929). The interviewer then asks a series of follow-up questions, tailored to the responses given by the child, until the interviewer has determined not only what conclusions the child has reached about the problem presented, but also the logic behind those conclusions. Piaget argued these patterns reflect the logic of children's thinking at certain cognitive levels. In short, it is actually the research method of loud thinking and today this tool stills being used (Kaloti-Hallak *et al.*, 2019). Kaloti-Hallak *et al.*, (2019) used this assessment method by providing tools (i.e. image, and physical construction) to help students externalizing their knowledge and understanding during interviews. The students were asked to draw the design of a robot that could perform the First Lego League (FLL) missions. In follow-up questions, the students were asked to explain the drawing and the purpose of the various parts of the robot. If a student could not draw the design, pictures of the robot they had used in the competition were presented and the students were asked to explain.

2.2.6 Bloom Taxonomy

Since "Bloom Taxonomy" was mentioned in some of the scientific articles gathered (DeMara *et al.*, 2019; Kaloti-Hallak *et al.*, 2019), and revealed to be a useful tool to set learning objectives according to different levels of mastery, we will also deepen our knowledge about this. According to Bloom *et al.*, (1956) it is a framework that comprises three learning domains: the cognitive, affective, and psychomotor, and assigns to each of these domains a hierarchy that corresponds to different levels of learning. The cognitive one organizes learning into six hierarchical levels: knowledge, comprehension, application, analysis, synthesis, and evaluation and was originally conceived to be used as an aid in developing precise definitions and classifications of broad terms like "thinking" and "problem solving" (Bloom *et al.*, 1956). It is focused on intellectual skills such as critical thinking, problem solving, and creating a knowledge base. It was the first domain created by the original group of Bloom's researchers.

Below are the authors' definitions/explanations of these main categories (Bloom *et al.*, 1956):

- Knowledge "involves the recall of specifics and universals, the recall of methods and processes, or the recall of a pattern, structure, or setting." (p. 201)
- Comprehension

  > "refers to a type of understanding or apprehension such that the individual knows what is being communicated and can make use of the material or idea being communicated without necessarily relating it to other material or seeing its fullest implications." (p. 204)

- Application refers to the "use of abstractions in particular and concrete situations." (p. 205)
- Analysis represents the "breakdown of a communication into its constituent elements or parts such that the relative hierarchy of ideas is made clear and/or the relations between ideas expressed are made explicit." (p. 205)
- Synthesis involves the "putting together of elements and parts so as to form a whole." (p. 206)
- Evaluation engenders "judgments about the value of material and methods for given purposes." (p. 207)

In its turn, the affective domain focuses on the attitudes, values, interests, and appreciation of learners. The psychomotor domain encompasses the ability of learners to physically accomplish tasks and perform movement and skills (Bloom *et al.*, 1956). In short, it is a method used for improving the exchange of ideas and materials among test workers.

Educators often use this framework to create learning outcomes that target not only subject matter but also the depth of learning they want students to achieve, and to then create assessments that accurately report on students' progress towards these outcomes (Anderson *et al.*, 2001).

David Krathwohl and Lorin Anderson (2001) published a revision to the cognitive dimension of the Blooms' Taxonomy. This new revised version changes nouns to verbs, deviating attention from acquisition and focusing on the active performance of the types of learning involved in each stage of the hierarchy (Figure **10**). This revised model has two dimensions: the cognitive process - with the six categories of remembering, understanding, applying, analyzing, evaluating, and creating - and the knowledge - with the three categories of factual, conceptual, procedural and meta-cognitive dimension. So "synthesis" was abolished and "create" was moved to the highest level of the domain. Kaloti-Hallak *et al.* (2019) uses this latter model to support the analysis of meaningful learning. To evaluate the influence of the activities on students' learning, the authors divided the activities in phases and distributed them into the six hierarchical levels of the "Bloom Taxonomy". Later, interviews were guided using a representational model (i.e. image or physical construction) to help students externalizing their knowledge. Results proved that most of the groups demonstrated the understanding/applying level during each of the design process phases (searching and decision making, construction and testing, diagnosing, and debugging), some demonstrated the analyzing/evaluating level, but only a few demonstrated the higher level of creating.

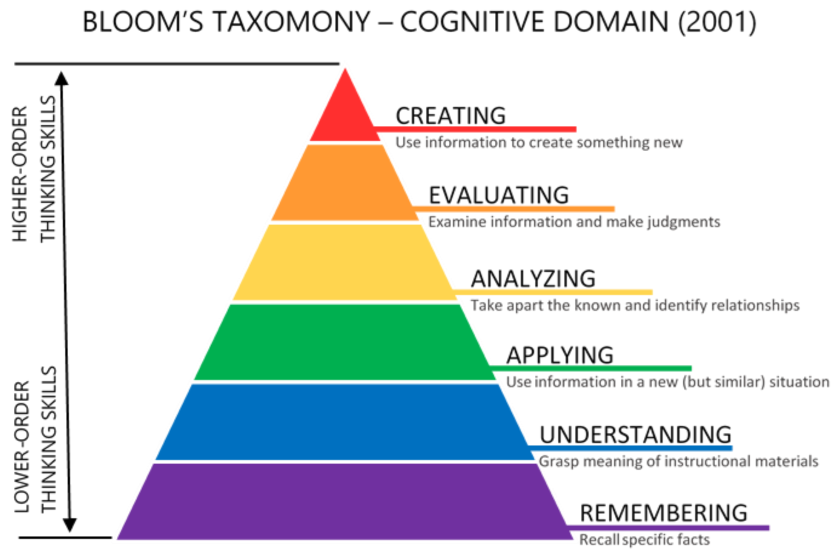


Figure 10. Revised Bloom Taxonomy.
Extracted from Kurt (2020)

2.3 Conclusions

I4.0 differs from previous revolutions in pace, range and complexity. Exponential disruptive technologies are emerging and changing radically education and industrial processes, accelerating it and making everything more flexible. This raises a two-fold problem. One is related to the lack of competencies to meet the demand and needs of I4.0. The other one has to do with a gender bias, tending to a higher number of men studying and working on STEM related fields. Educational institutions have the responsibility of raising the interest for young students with a special emphasis on girls, striving to reach a qualified and equal – or at least, minimized gender gap - workforce in the future. They should also foresee the potentials of this revolution to take the necessary actions wisely. So, educational institutions have the chance to turn technology trends into opportunities, creating the awareness among young students.

A number of projects have emerged worldwide to engage students or upskill trainees. The projects mentioned had different capabilities in terms of resources, knowledge, and finances to implement I4.0 technologies. In general, this LR was valuable in allowing us to identify the main I4.0 technologies, teaching approaches, competencies, and tools to assess meaningful learning considering, at the same time, several concerns and implications in the future of the next set of manufacturing Engineers.

3. Problem and Implementation

This chapter presents the scientific problem addressed by our research project and the proposed solution, also providing an overview of our methodological design and related procedures.

3.1 Problem

The exponential growth of digital technologies urges the need to upskill current workers and to endow future ones with a new skillset, assuring a qualified workforce capable of solving complex and unstructured problems. This study focuses on reskilling rather than upskilling. The earlier the students start to interact with the novel technologies presented in chapter 2.2.1, while experiencing challenges related to I4.0 environments, the easiest will be for them to acquire the necessary competencies to succeed in the future as I4.0 Engineers. Our field work was conducted at “escolaglobal”. “escolaglobal” has embarked on an educational technology project, becoming a Microsoft Showcase School in 2015 and an Acer Innovative School in 2018, which means that this school already adopts strategies to drive transformation that focuses on the digital area. For example, this school offers STEAM classes for students. Even so, most of the 5th grade students had never seen a 3D printer, did not knew basic concepts about it or broader concepts such as smart manufacturing. With this, we have identified a gap to further explore in this research project. As part of the “ShapiNG” project, it was possible to gather some information at Gondomar Secondary School that turned out to be useful in terms of establishing adequate requirements and references to execute our core activity. In Gondomar, 11 students from the 11th grade of a professional course were asked about their preferences regarding the topic that was most interesting for them and the most voted were robotics and 3D printing (see Figure **11**). Despite this question, this activity covered all the topics presented in the following figure, and we understood that talking about these topics through video conferencing was not effective as most of them lost their motivation as there were no practical tasks to perform. Therefore, one requirement of the proposed activity was to be presential and practical. Therefore, 3D printing seemed to be a good topic to motivate young students to explore smart manufacturing technologies and concepts. From all the technologies presented in the LR, this seemed to be the most attracting and understandable for such a young age. Even though it might not be immediate, it can encourage them to consider a career in Engineering later in their lives, as they acquire knowledge and expertise on related topics.

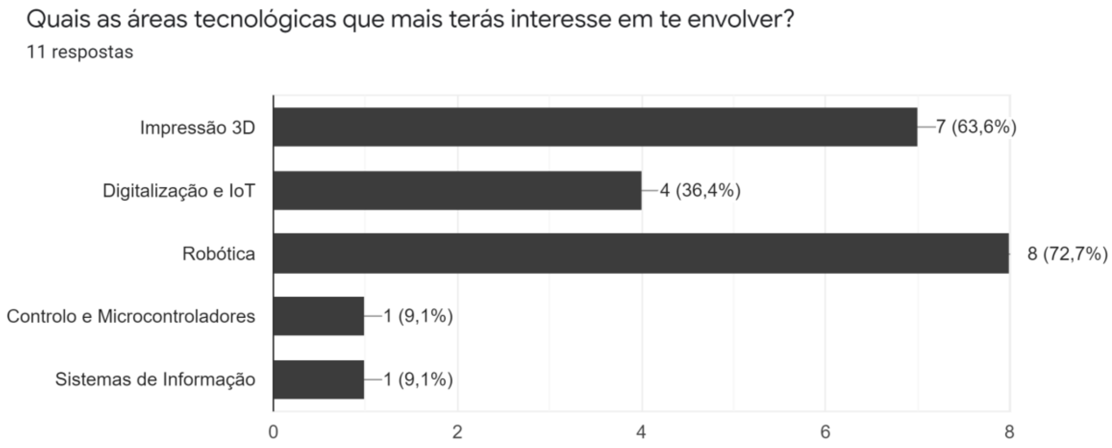


Figure 11. Most interesting areas for high school students

The activity's main purpose, besides raising students' interest in the Engineering field, with focus on young girls, was to find out which dynamic – collaborative *versus* individual – most benefits retention of knowledge in a potential meaningful manner and what are the benefits of each approach. Students assigned to the collaborative activity had to solve challenges together using shared docs and *TinkerCad*, whereas the individuals assigned to the individual activity had to perform tasks alone. This differentiation allowed to determine which of the dynamics is more susceptible of resulting in rote learning or, on the opposite end, meaningful learning. According to Vygotsky' social constructivism theory, one important aspect of the learning process is that it creates the Zone of Proximal Development (ZPD), which is an area where one can learn under adult guidance or aided by more capable peers (Vygotsky, 1979). From this point of view, learning is a social process, therefore, there are tasks that one can do on one's own, tasks that can only be done with the guidance from more knowledgeable individuals and tasks that go beyond the learners' capabilities despite any effort. This theory raises crucial questions, such as, (a) is it really peer working as effective as adult-children guidance? (b) is guided learning always more effective than individual learning? Even if the tasks are precise and learning objectives are well-defined? (c) Does this theory suits any age the same way? (d) What if an individual, instead of guided learning, searches for information on websites, books, or technological tools? Does it still be less effective than the individual who learns under the guidance of an adult or his/her peers?

In this sense, this study will focus on the "constructive" mode for the individual activity and on the "interactive" mode for the collaborative activity, considering the ICAP hypothesis (Chi & Wylie, 2014). Thus, at the end it will be possible to understand whether the research supports the ICAP hypothesis. In case of supporting this hypothesis, interactive activities are the ones to enhance better learning processes than the constructive ones.

3.2 Proposed Solution

Aiming to address the previously mentioned gap and corresponding problem, this research proposes a pedagogical approach to introduce smart manufacturing concepts and technologies to 5th grade students. This approach adopted a "push" method, which means an introduction of the theory was made before introducing the problem, assuring that students have the basic knowledge when advancing onto the main challenges (Tisch *et al.*, 2013). The activities took place during two STEAM classes of one hour each. The first one started with a presentation of the four industrial revolutions and its main technologies, focusing then on 3D printing - advantages, disadvantages, and applications (see Annex H: First Class Presentation). After this theoretical introduction, students had to follow the individual exploration guide (see Annex C: Individual Exploration Guide) or the collaborative exploration guide (see Annex D: Collaborative Exploration Guide) according to the dynamic which was previously assigned to the student in a randomize experience. Although both contained the same tasks, the collaborative one had additional instructions for an harmoniously interaction. The exploration guides had two parts – one for the first class and another for the second class – and were action-oriented, aiming at driving students' work so they could work autonomously. As a first task, students were challenged to model a pizza base and its ingredients on *TinkerCad* and at the end they learnt how to export it in .STL file (see Figure **12**). Students working collaboratively had to share the workplane (see Figure **13**), while students working individually had the whole workplane to work alone.

The second class took place one week after and started by asking students how did the previous class ended up (by exporting an .STL file) and then we explained how that .STL file could be configured in *Ultimaker Cura*, exporting to a .Gcode file that went then to the 3D printer by using a mini SD card (see Figure **14**). When setting up the printer some concepts such as the infill and the adhesion types where explained, relating it to the desired final quality and printing time - the more infill percentage, more time is needed to print (see Annex I: Second Class Presentation). Before printing, the names of some components of the printer were mentioned (i.e., nozzle, bed, and extruder) and the calibration process was explained. The material used was PLA, given the advantages mentioned before (see topic 2.2.1.8). As there were only two printers, students could see at the same time how it is made and then, five students at a time could come close to see the printing process. In the meanwhile, students had to finish answering the questions of the exploration guide (the ones planned to be answered in the second class). While students working collaboratively could talk with each other, students assigned to individual work had to answer these questions autonomously. They could though, search for the answers in the internet. Regardless of the dynamic that was assigned, students could ask the instructor some help, receiving some tips to find out the solution. These activities are close to the PBL approach once students are given a challenge, however, they did not need to brainstorm to find a creative solution as in these cases it was already defined in the exploration guides. This oriented approach was understood to be more suitable as it was students' very first contact with the 3D modeling and 3D printing topics. This way, we could ensure the main tasks could be accomplished within an hour and that the covered concepts were the same to every student.

Figure 12. First class

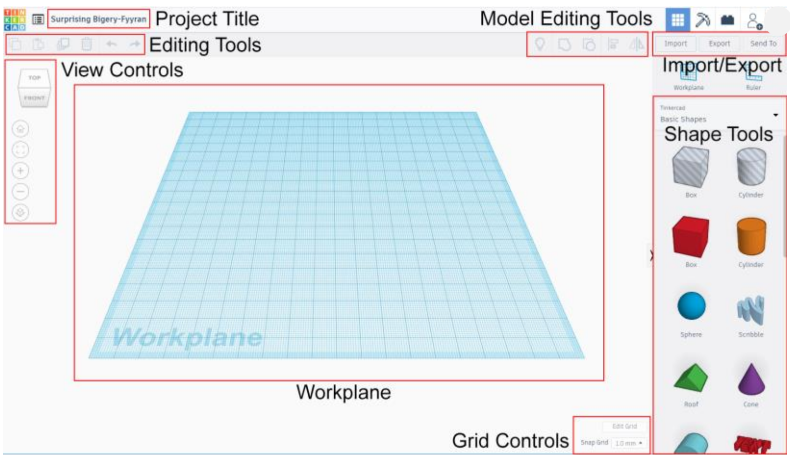


Figure 13. *ThinkerCad* Interface

Figure 14. Second class

These tasks are part of a larger activity intitled *Teaching Factories for Kids* (TF4K), held as part of the EIT Manufacturing "ShapiNG" project, that plans to build a portable Learning Factory (LF) based on a 3D pizza assembly line aiming to teach middle and high school students, concepts related to automation and reconfigurable systems. In short, our study focuses on the first stage of this project, consisting of modeling and printing the ingredients to be used at the already mentioned assembly line.

3.3 Implementation

Considering the thesis of David Ausubel (Ausubel, 2000), some conditions were established for meaningful learning to take place:

1) Activities were assigned to STEAM classes, which might assure the disposition of the learner to relate the new material to be learned;
2) The instructional material presented followed straight to point guidelines to be relatable to their particular structures of knowledge on a nonarbitrary and nonverbatim basis, attempting to integrate new material with previously presented information through comparisons and cross-referencing of new and old ideas:
    a. Before explaining what each industrial revolution consists of, students should be asked what they already know about this topic. In case some student already knows anything, he/she should share it with the whole class and then the instructor provides a definition of it which encompasses and refines the definition given by the student.
    b. When exporting the .STL file from *TinkerCad*, students should be asked what other file formats they know.

c. When explaining what calibration is, students should be asked if they ever heard of it, and again, the instructor should provide a definition that encompasses and refines the students' definition.

3) The instructional material presented had logical meaning and concepts were presented from the most general to progressively differentiated and more specific so that the learner properly assimilates the new knowledge.

Ausubel's theory does not include specifications for the role of the teacher. However, he outlines three variables that influence meaningful verbal learning: (1) the availability, stability and clarity of relevant anchoring ideas (2) the discriminability of new learning material from previously learned concepts in cognitive structure, and (3) the stability and clarity of subsuming concepts (Ausubel, 2000). This work assumes then, that the role of the teacher is to consider these variables by exploring and providing the appropriate subsumers to facilitate meaningful learning.

Such activity provided the opportunity to bring industrial concepts into the classroom, enhancing students' theoretical knowledge and practical experience.

3.4 Conclusions

The technology exposure young students have nowadays is unprecedent and as a result, teaching approaches must be updated. With the rising popularity of STEAM education, 3D printing is getting attention across the world. Today's world demand to study the theory and apply it in a short period of time, providing the possibility for students to experiment and learn by making.

The solution found to solve the mentioned problem was drawn from a thorough literature review. 3D printing was identified as the most suitable pedagogical content for introducing smart manufacturing concepts to young people as it allows understanding and acquiring I4.0 skills in a very action-oriented manner. Topics such as robotics, automation, IoT among others are perceived as way too complex to be covered for 5th grade students.

A number of benefits may be identified. 3D printing:

1) Fosters creativity as students can design something that do not yet exist.
2) Increases engagement within the classroom.
3) Makes them realize their digital responsibility
4) Helps increase students' interest in STEAM disciplines by allowing them to grasp complex topics.
5) Demands students to think about problem-solving, spacial skills, and critical thinking.

Concerning the specific underlying goal of reducing gender gap, a rationale of inclusion was attached, and the main requirement was to have a female instructor, so students could take it as a role model. This way, we hope the stereotype that engineering fields are for men, is reduced.

Ultimately, it should be stressed that the transition from STEM to STEAM is still ongoing and does not yet truly meet the needs of the fourth industrial revolution. By merging the Arts with STEM subjects, STEAM education accentuates the role of arts and creativity to generate technological and scientific breakthroughs. We believe that the chosen topic – 3D printing and 3D modeling – is capable of creating a gateway for STEAM to express its advantages by means of diverse innovative teaching approaches.

4. Result Analysis

In this chapter we will present the results obtained in our study. Complementing theory and empirical knowledge, it is our intention to present the data collected, discuss it, and interpret it in light of the theoretical assumptions set in the second section of this thesis, always taking into account our main research objectives.

4.1 Pre and Post-test Questionnaires

Pre and post-test questionnaires (see Annex A: Pre-test Questionnaire and

Annex B: Post-test Questionnaire) had two sections in common, one regarding knowledge questions and another regarding motivation. In the Post test, besides the mentioned sections, some statements regarding the pedagogical material were presented so that students evaluated them in a *Likert Scale,* which is a continuum of possible responses (Leedy & Ormrod, 2015) and some questions regarding the group and individual activity were added.

Regarding the advantages and disadvantages of each dynamic collected in the Post test questionnaire did not differ much from the data collected in the interviews. Students who were assigned to individual work mentioned that it was positive once they did not have to deal with other peoples' opinion and could thus, orient the work the way they desired, with more focus. Nevertheless, some mentioned that in group it would be more advantageous as they could finish the task faster and could be helpful to ask others in case they had doubts. On the other hand, students who were assigned to group activity mentioned they took longer to finish the task as there were some disturbing group elements and they had to discuss the topics until they reach a final agreement. The advantages mentioned were related to the possibility of allocating tasks to each group element and it was more engaging as they could discuss the topics together.

4.1.1 Learning Outcomes

4.1.1.1 Descriptive Statistics of Scores in Pre and Post-tests

Students' learning outcomes regarding 3D printing was assessed both in pre- and post-tests. For that, six questions were administered, namely: 1) Identify one advantage of 3D printing; 2) 3D printing is a technology of…; 3) One of the materials used in 3D printing is…; 4) The calibration of the printing…; 5) Nozzle should be…; 6) To export a graphic from a modeling software I should choose a file with the extension… For each question, only one option was correct. The knowledge score was calculated summing the correct answers given in the six questions. The knowledge score ranged from 0 (no correct answer on the six questions) to 6 (answered correctly to all the six questions).

As presented in Table **5**, the mean of the knowledge score in the pre-test was 0.98 (*SD* = 1.17), and in the post-test was 4.52 (*SD* = 1.50).

Table 5. Descriptive statistics of knowledge scores in pre and post-tests

	Mean	***SD***	***Median***	***Min***	***Max***
Knowledge score pre-test	0.98	1.17	1	0	5
Knowledge score post-test	4.52	1.50	5	0	6

Regarding the frequency of each score in pre and post-tests, 27 (45%) students did not have any correct answer in the pre-test, but in the post-test, only 2 (3.3%) students presented a score of 0. On the other hand, in the pre-test, no one was able to answer all the questions correctly, but in the post-test 17 (28.3%) students had the highest score. Figure **15** presents the number of students for each number of corrected answers.

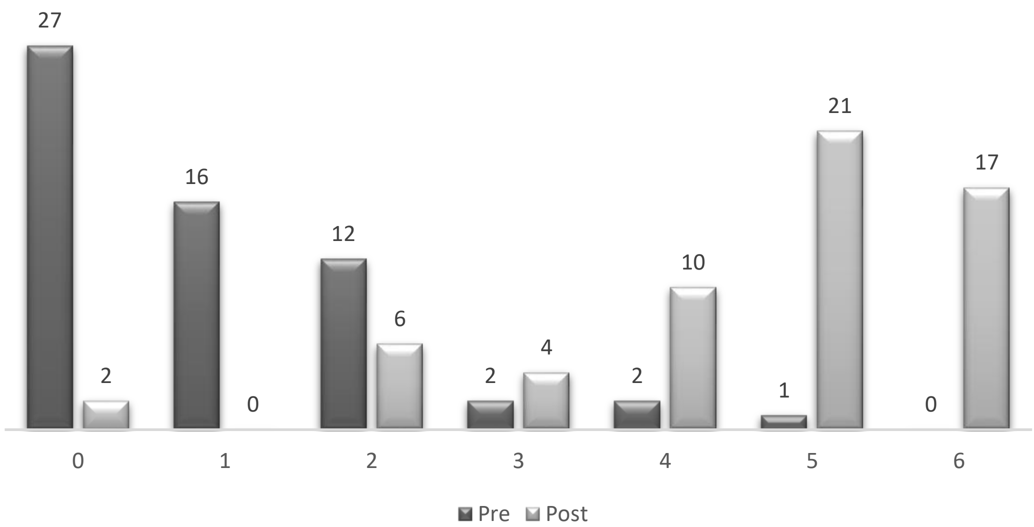


Figure 15. Frequency of scores in pre and post-tests

4.1.1.2 Is There a Difference in the Score for Students who Learned in Individual and in Collaborative Dynamics?

As showed in Figure **16**, in the pre-test, students who learned in a collaborative dynamic presented a score mean of 1.27 (*SD* = 1.34; *Median* = 1), and students who learned in an individual dynamic presented a score mean of 0.70 (*SD* = 0.92; *Median* = 0.5). In the post-test, the mean obtained for students assigned to a collaborative dynamic was 4.47 (*SD* = 1.43; *Median* = 5) and for students assigned to an individual dynamic was 4.57 (*SD* = 1.59; Median = 5).

There was no statistically significant difference in the score between students that were in collaborative and individual learning dynamics in the pre-test (U = 342.50, p = .091) and the post-test (U = 409.50, p = .534) (see Table **6**).

Table 6. Mann-Whitney test between the dynamics in pre and post-test score

	Collaborative (*n* = 30)	**Individual (*n* = 30)**	***U***	***p***
	Mean Rank	***Mean Rank***		
Knowledge score pre-test	34.08	26.92	342.50	.091
Knowledge score post-test	29.15	31.85	409.50	.534

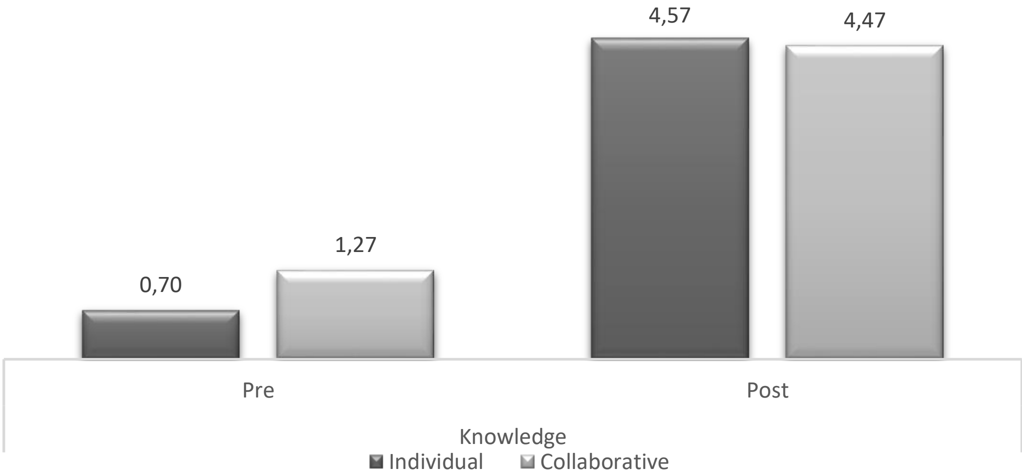


Figure 16. Means of scores in pre and post-tests for students who learned in collaborative and individual dynamics

4.1.2 Students' Mastery Perception About 3D Printing

4.1.2.1 Descriptive Statistics of Students' Mastery Perception

Regarding the frequency of students' perceived mastery in the pre-test, the majority of the students (n = 29; 48.3%) reported that they did not know anything about 3D printing (null knowledge), and 22 (36.7%) students reported that they know a little about 3D printing (basic knowledge). About the frequency of perceived mastery in the post-test, most of the students (n = 29; 48.3%) reported that they knew several things about 3D printing (medium knowledge) and 24 (40%) students reported that they knew a little concerning 3D printing (basic knowledge).

Figure **17** presents the frequency of students' mastery perception in both pre and post-tests.

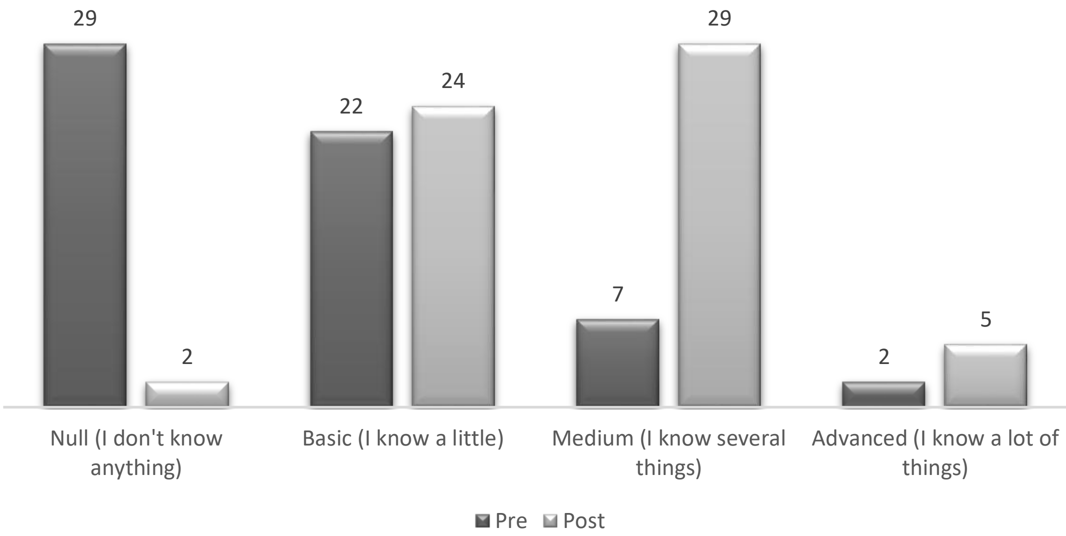


Figure 17. Frequency of students' mastery perception in pre and post-tests

4.1.2.2 Is There a Relationship Between Students' Mastery Perception About 3D Printing and Learning Dynamics?

We observed a higher number of cases in the 'null' and 'advanced' mastery perception from the individual to collaborative dynamic. On the other hand, we observed a smaller number of cases in the 'medium' mastery perception from the individual to collaborative dynamic, and an equal number of cases in the 'basic' mastery perception in both dynamics (cf. Figure **18**). However, we found that the mastery in the post-test was independent of the learning dynamics [$\chi^2(3) = 2.51$, $p = .473$)], suggesting that the students' perceived mastery in the post-test was not dependent on whether they learned in a collaborative or an individual dynamic (Table **7**).

Table 7. Chi-square test of independence between dynamics and post-test mastery

	Dynamics		χ^2
	Collaborative n **= 30 (50%)**	**Individual** n **= 30 (50%)**	
Post-test Mastery			
Null (I don't know anything)	0 (0.0%)	2 (6.7%)	
Basic (I know a little)	12 (40.0%)	12 (40.0%)	
Medium (I know several things)	16 (53.3%)	13 (43.3%)	2.51 (p = .473)
Advanced (I know a lot of things)	2 (6.7%)	3 (10.0%)	

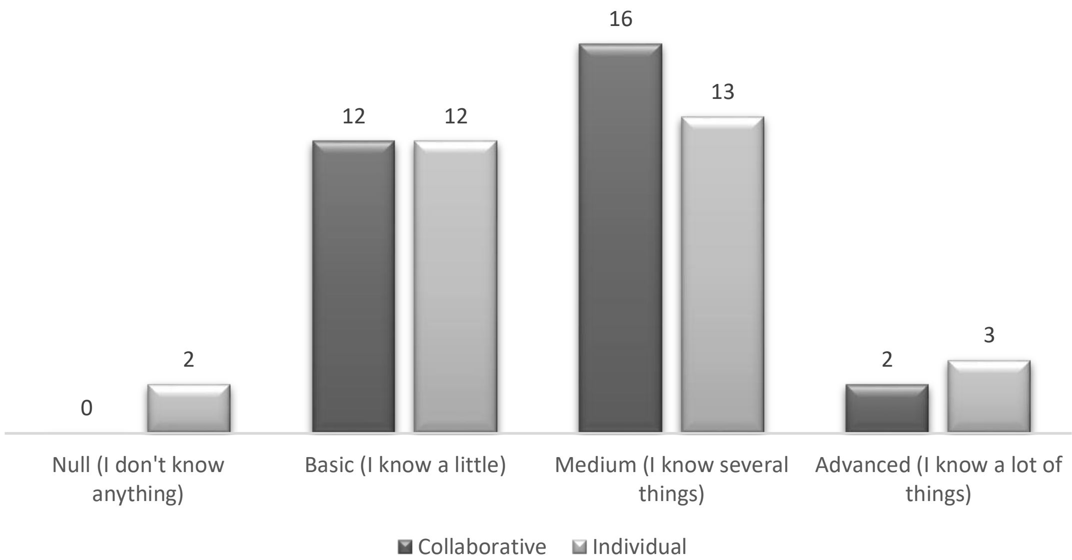


Figure 18. Frequency of students' mastery perception in a collaborative and individual dynamics

4.1.3 Motivation to Learn

4.1.3.1 Descriptive Statistics of Motivation to Learn

As regards the frequency of the motivation to learn about smart manufacturing, modeling and 3D printing in the pre-test, the majority of the students (n = 29; 48.3%) reported that were extremely motivated to learn, and 28 (46.7%) students reported that they were very motivated to learn. Concerning the frequency of the motivation to learn in the post-test, most of the students (n = 28; 46.7%) reported that they were very motivated to learn, and 20 (33.3%) students reported that they were extremely motivated to learn. Figure **19** presents the frequency of students' motivation to learn in both pre- and post-tests.

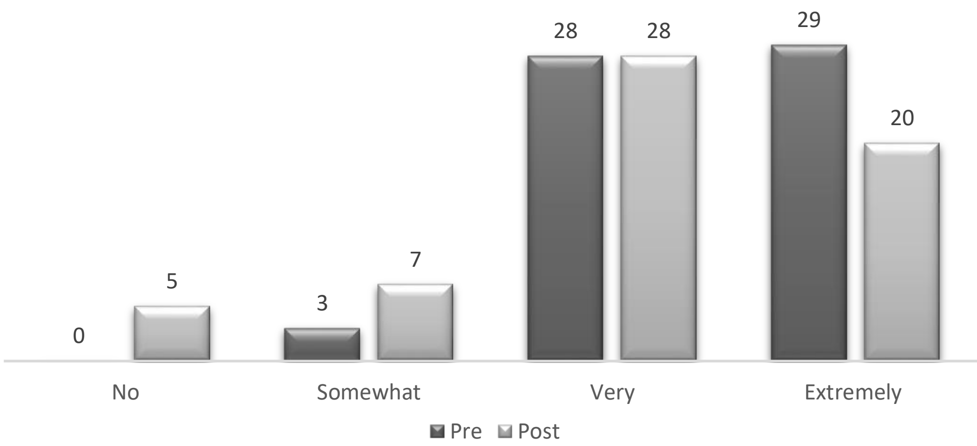


Figure 19. Frequency of the motivation to learn in pre- and post-tests

For the following analyses, we created two main categories for motivation to learn. The category called 'unmotivated' was composed of the 'no motivation' and 'somewhat motivated' answers. The category called "motivated" was composed of the 'very motivated' and 'extremely motivated' answers.

4.1.3.2 Is There a Relationship Between Gender and Motivation to Learn?

In the pre-test, we observed a higher number of unmotivated cases in female students (n = 3; 11.5%) than in male students (n = 0; 0%), but more male students reported motivation to learn compared to female students. The relationship between motivation to learn in pre-test and gender was not statistically significant [$\chi^2(1) = 4.13$, $p = .076$), indicating that motivation to learn in pre-test was not dependent on the students' gender.

In the post-test, we observed the same number of unmotivated cases in female and male students, and a higher number of motivated cases in male students ($n = 28$; 82.4%) than in female students. However, the statistic test was not significant, suggesting that motivation to learn in the post-test was independent of the gender of the students [$\chi^2(1) = 0.27$, $p = .602$)].

Figure **20** shows the distribution of cases for gender in pre and post-tests and Table **8** presents the test statistic for motivation to learn both in pre- and post-tests.

Table 8. Chi-square test of independence between gender and motivation to learn at pre and post-tests

	Gender		χ^2
	Male *n* **= 34 (56.7%)**	**Female** *n* **= 26 (43.3%)**	
Motivation to learn: pre-test			
Unmotivated	0 (0.0%)	3 (11.5%)	4.13 ($p = .076$)
Motivated	34 (100.0%)	23 (88.5%)	
Motivation to learn: post-test			
Unmotivated	6 (17.6%)	6 (23.1%)	0.27 ($p = .602$)
Motivated	28 (82.4%)	20 (76.9%)	

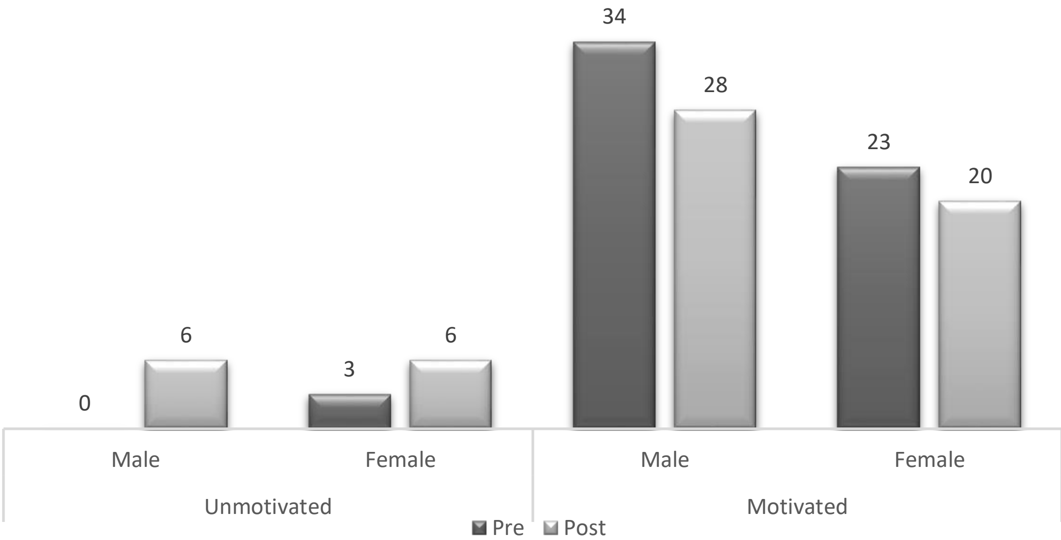


Figure 20. Frequency of the motivation to learn for female and male students in pre- and post-tests

4.1.3.3 Is There a Relationship Between Motivation to Learn in the Pre-test and Motivation to Learn in the Post-test?

Of the 60 students, from pre-test to the post-test, no student maintained no motivation to learn, but 45 (75%) students maintained the motivation to learn. However, 12 (20%) students that were motivated in the pre-test, in the post-test reported that were unmotivated to learn. On the other hand, 3 (5%) students that were unmotivated to learn in the pre-test, reported that were motivated to learn in the post-test. The chi-square test of independence showed that the motivation to learn in the post-test was not dependent on the motivation to learn in the pre-test [$\chi^2(1) = 0.79$, $p = 1.000$)] (cf. Table **9**).

Table 9. Chi-square test of independence between gender and motivation to learn at pre-test and post-test

	Motivation to learn: post-test		χ^2
	Unmotivated	Motivated	
Motivation to learn: pre-test			
Unmotivated	0 (0.0%)	3 (5.0%)	0.79 (*p* =
Motivated	12 (20.0%)	45 (75.0%)	.1.000)

4.1.4 Knowledge Questions

Concerning the first cluster of questions – which were exactly the same six questions already answered in the Pre and Post Tests – it was possible to realize which concepts were retained and which were not (Figure **21**). Concepts concerning advantages of printing in 3D (question 1), calibration (questions 4 and 5) and the material used to print (question 3), were retained properly. Most of the students were able to explain how and why calibration was made and remembered how the material used looked like. Images showed revealed to be crucial though. It helped them externalize their knowledge, revealing whether concepts were anchored to the cognitive structure and if so, how they had organized these concepts. For example, some of them were not able to remember what calibration was, however, when the image of the calibration was displayed, most of the students could immediately remember they had to insert a card between the nozzle and the bed, even though the printer displayed in the image was an "Ultimaker" and the ones used in the activity were "Creality". On the other hand, many of them were not able to identify the correct manufacturing process addressed to 3D printing (question 2). None of them could point the right answer without seeing the images and some of them, despite knowing that 3D printing is made layer upon layer, would mention "formative manufacturing" instead of "additive manufacturing". Another frequently incorrect answer is related to the name of the file format used to export a 3D modelled design (question 6), even though all of them were able to mention other file formats they knew (relating it to their previous knowledge, this is, the subsumer in David Ausubel's theory of learning (Ausubel, 2000)).

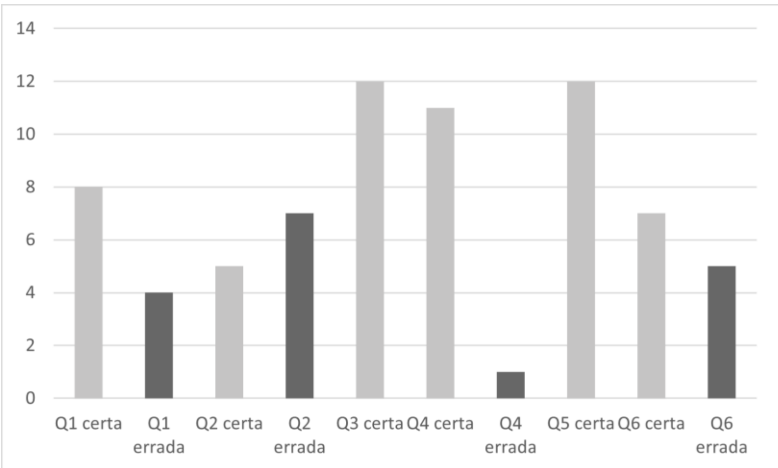


Figure 21. Knowledge Questions

4.1.5 Motivation to Pursue a Career in Engineering

4.1.5.1 Descriptive Statistics of Motivation to Pursue Engineering

As regards the frequency of the motivation to pursue Engineering in the pre-test, the majority of students (n = 35; 58.3%) reported that pursuing a career in Engineering could be a possibility. Relating to the frequency of the motivation to pursue Engineering in the post-test, most of the students (n = 28; 46.7%) continued to report that could be a possibility. Figure **22** presents the frequency of students for each motivation to pursue Engineering.

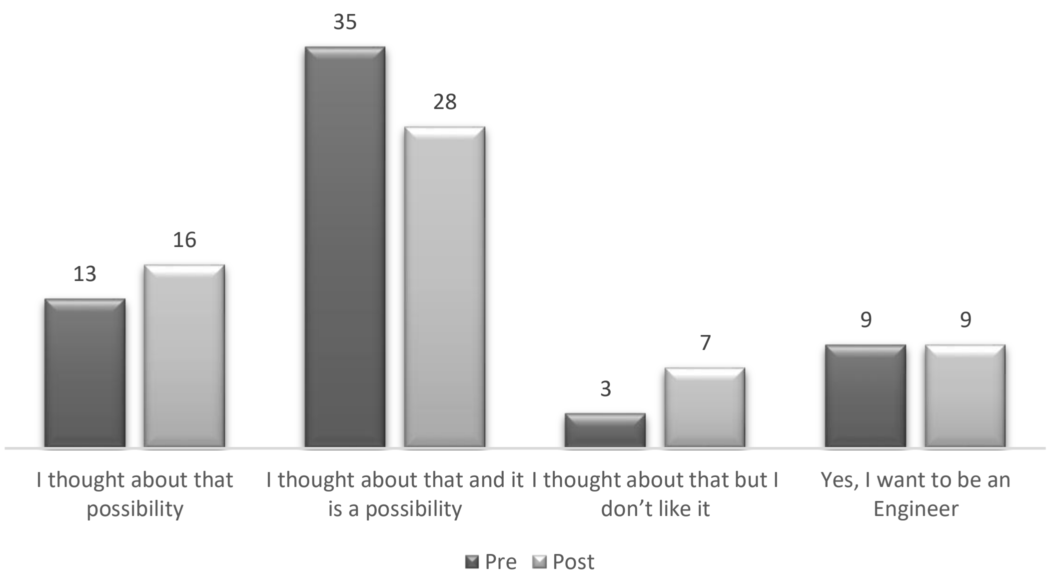


Figure 22. Frequency of the motivation to pursue Engineering in pre and post-tests

For the following analyses, we created two main categories for motivation to pursue a career in Engineering. The category called 'unmotivated' was composed of the 'I've never thought about that possibility' and 'I thought about that but I don't like it' answers. The category called "motivated" was composed of the 'I thought about that and it is a possibility' and 'Yes, I want to be an Engineer' answers.

4.1.5.2 Is There a Relationship Between Gender and Motivation to Pursue a Career in Engineering?

In the pre-test, we observed a higher number of 'unmotivated' (*n* = 11; 32.4%) and 'motivated' (*n* = 23; 67.6%) cases in male students than in female students. The relationship between motivation to pursue a career in Engineering in pre-test and gender was not statistically significant [$\chi^2(1) = 1.30$, $p = .255$), meaning that motivation to pursue Engineering in pre-test was independent of the students' gender.

In the post-test, we observed a higher number of 'unmotivated' cases in female students (*n* = 14; 53.8%) than in male students, but more male students (*n* = 25; 73.5%) reported motivation to pursue Engineering compared to female students. The relationship between motivation to pursue Engineering in the post-test and gender was statistically significant [$\chi^2(1) = 4.67$, $p = .031$), indicating that motivation to pursue Engineering in the post-test was dependent on the students' gender.

Figure **23** shows the distribution of cases for gender in pre and post-tests and Table **10** presents the test statistic for motivation to pursue Engineering both in pre and post-tests.

Table 10. Chi-square test of independence between gender and motivation to pursue Engineering at pre-test and post-test

	Gender		χ^2
	Male ***n* = 34 (56.7%)**	**Female** ***n* = 26 (43.3%)**	
Motivation to pursue Engineering: pre-test			
Unmotivated	11 (32.4%)	5 (19.2%)	1.30 ($p = .255$)
Motivated	23 (67.6%)	21 (80.8%)	
Motivation to pursue Engineering: post-test			
Unmotivated	9 (26.5%)	14 (53.8%)	4.67 ($p = .031$)
Motivated	25 (73.5%)	12 (46.2%)	

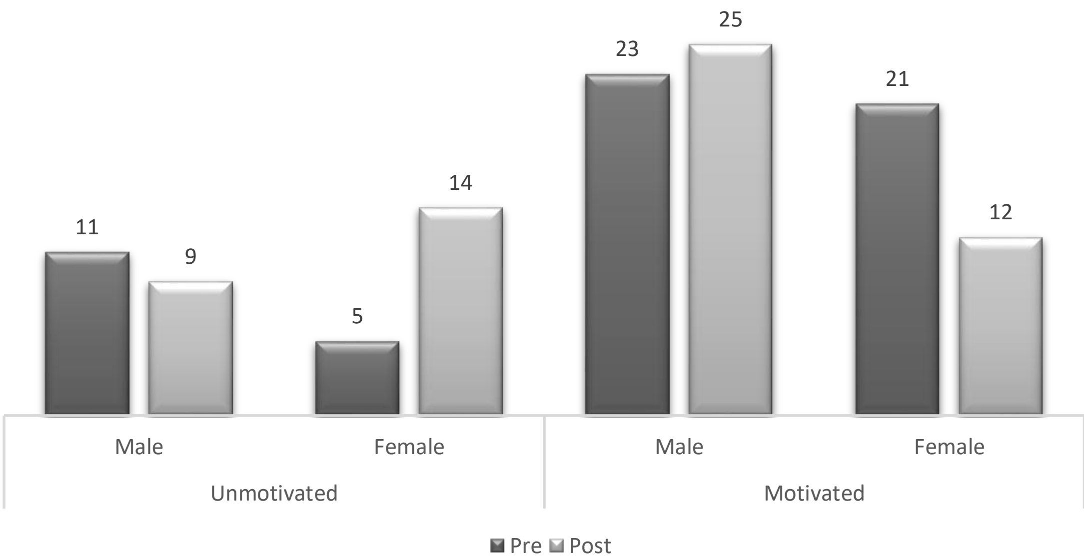


Figure 23. Frequency of the motivation to pursue Engineering for female and male students in pre and post-tests

4.1.5.3 Is There a Relationship Between Motivation to Pursue Engineering in the Pre-test and Motivation to Pursue Engineering in the Post-test?

Of the 60 students, from pre-test to the post-test, 30 (50%) students maintained an interest in Engineering or want to pursue a career in Engineering and 9 (15.0%) students maintained that never thought about that possibility or did not like that possibility. However, 14 (23.3%) students that in the pre-test thought about the possibility of pursuing an Engineer career, in the post-test reported that they did not like that possibility. On the other hand, 7 (11.7%) students that in the pre-test reported never thought the possibility to pursue a career in Engineering or they did not like it, in the post-test reported that pursue a career in Engineering is a possibility or they want to be an Engineer (cf. Table **11**). The chi-square test of independence showed that the motivation to pursue Engineering in the post-test was not dependent on the motivation to pursue Engineering in the pre-test [$\chi^2(1) = 2.96$, $p = .085$)].

Table 11. Chi-square test of independence between motivation to pursue Engineering at pre-test and post-test

	Motivation to pursue Engineering: post-test		χ^2
	Unmotivated	Motivated	
Motivation to pursue Engineering: pre-test			
Unmotivated	9 (15.0%)	7 (11.7%)	2.96 (p = .085)
Motivated	14 (23.3%)	30 (50.0%)	

4.1.6 Quality of the Instructional Material

4.1.6.1 Internal Consistency and Descriptive Statistics

The ‘quality of the instructional material’ scale is composed of 7 items using a 5-point Likert scale ranging from 1 (Totally disagree) to 5 (Totally agree).

To investigate the internal consistency of the ‘quality of the instructional material’ scale, the Cronbach’s alpha (α) value obtained was .78, suggesting that the items of the scale have acceptable internal consistency.

The item-total correlation was computed for each item of the scale to assess the correlation between the designated item with the sum of scores for all other items. Item 4 presented an item-total correlation of .19, which is inferior to the acceptable value of .30. If this item was removed from the scale, the alpha coefficient value would be higher as can be seen in Table **12**.

Table 12. Mean, standard deviation, item-total correlation and Cronbach's alpha if item 4 is deleted for each item of the 'quality of the instructional material' scale

Item	*M*	*SD*	Item-Total Correlation	α if item 4 is deleted
1. The materials presented are suitable for learning modeling and 3D printing	4.37	0.90	.55	.74
2. The materials are understandable and logical	4.18	0.79	.52	.75
3. The materials presented are relevant to me	4.00	1.13	.61	.73
4. The materials presented are related to real environments	3.95	1.00	.19	.81
5. The materials presented can help me to solve day-to-day problems	3.67	1.30	.57	.74
6. The materials presented help me to recall the previous knowledge I learned	3.98	1.03	.51	.75
7. The materials presented help me link new concepts with previous experiences	4.12	0.99	.63	.73

Therefore, item 4 was removed from the 'quality of the instructional material' scale, and the Cronbach's alpha obtained for the scale with 6 items, was .81, indicating that the items presented a good internal consistency. Table **13** depicts the mean, standard deviation, median, minimum and maximum of the 'quality of the instructional material' scale for the 6 items.

Table 13. Descriptive statistics of quality of instructional material

	Mean	*SD*	*Median*	*Min*	*Max*
Quality of instructional material	4.05	0.74	4.17	1.67	5.00

4.1.6.2 Is There a Difference in Perceived Quality of Instructional Material Scores for Unmotivated and Motivated Students to Learn?

Students that were motivated to learn in the post-test showed a mean of 4.22 (SD = 0.57) in the quality of instructional material, whereas students that felt unmotivated to learn reported a mean of 3.37 (SD = 0.97) (Table **14**). There was a statistically significant difference (U = 132.50; p = .004) in the perceived quality of instructional material of unmotivated and motivated students, which means that motivated students presented higher scores in the quality of instructional material than the unmotivated students (Table 15).

Table 14. Descriptive statistics of Quality of instructional material for unmotivated and motivated students to learn

	Mean	*SD*	*Median*	*Min*	*Max*
Unmotivated to learn (n = 12)	3.38	0.97	3.17	1.67	4.83
Motivated to learn (n = 48)	4.22	0.57	4.25	3.00	5.00

Table 15. Mann-Whitney test between the motivation to learn in perceived quality of instructional material

	Unmotivated (n = 12)	**Motivated (n = 48)**	***U***	***p***
	Mean Rank	***Mean Rank***		
Quality of instructional material	17.54	33.74	132.50	.004

4.1.6.3 Is There an Association Between Perceived Quality of Instructional Material and Knowledge Scores at Post-test?

The Spearman's Rank Order Correlation coefficient was calculated to test the relationship between perceived quality of instructional material and knowledge score at post-test. There was no significant correlation ($r_S = .15$, $p = .265$), which means that the levels of perceived quality of instructional material were not associated with knowledge scores in the post-test. As we can see in Figure **24**, the scatterplot shows the distribution of points, with no pattern evident.

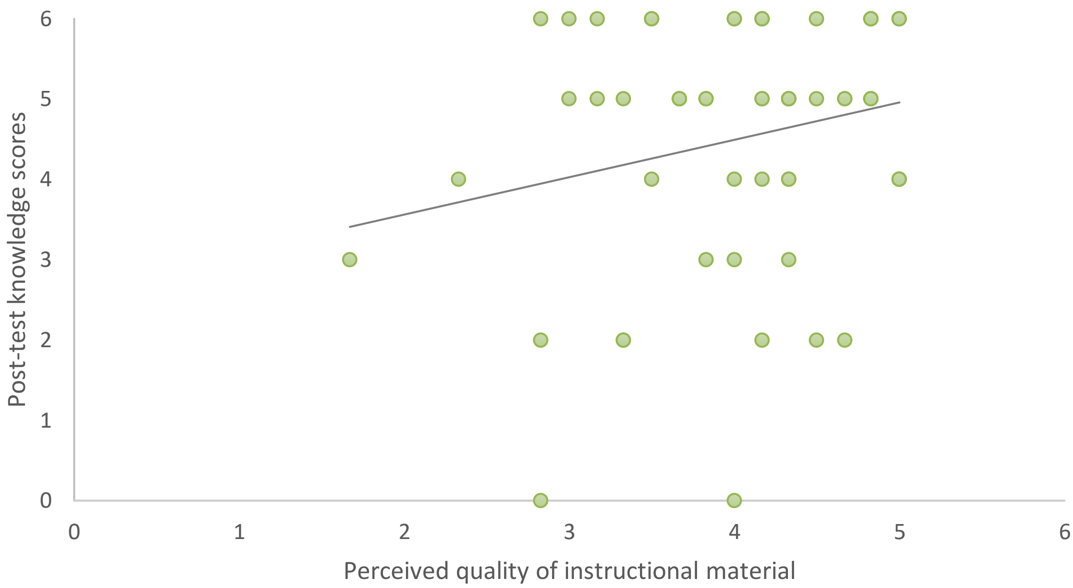


Figure 24. Association between perceived quality of instructional material and post-test scores

4.2 Observation

Participant observation was led aiming to (a) understand how students interrelate, (b) familiarize with the students thereby facilitating involvement in the proposed activities, (c) get the feel for how things are organized and prioritized, (d) understand what students deem to be important in learning process and (e) provide the possibility of raising new questions that should be addressed with participants in the interviews to obtain a holistic understanding of the phenomenon. This research method is used to help answer descriptive research questions, to develop new theories and to generate or test hypotheses (DeWalt & DeWalt, 2010). The same authors stress this strategy should be complemented with other forms of collecting data, to understand different aspects and factors of the topic under study, hence improving accuracy.

The data registered, most of the times, reinforces what has been discovered through other research methods used in this study but, most importantly, it introduced new aspects. By observing, we could understand that the discussion environment created among students working collaboratively, arose socio-emotional challenges because students had to work with people who did not share the same point of view, other times they had to defend point of views and persuade the others, dealing with frustration sometimes. As a result, not all groups worked harmoniously. Moreover, by observing the activity, we could realize that, at least one group decided to model one big pizza instead of four or five in the same workplane. This denotes that groups organized themselves in different ways, which might influence their productivity and knowledge attainment in different ways. Besides that, they might be developing different skills from the students who decided to split the workplane for each group element to work in different spaces.

Working individually, students often ask for help, instead of looking for an answer on the internet as suggested. However, we realized the sense of responsibility and attention was way bigger when compared to the collaborative dynamic.

Most of the students looked excited about the topic and the proposed tasks, nevertheless, a few revealed to be frustrated for not being able to complete the tasks and we noticed it was most frequent with girls working individually. This may also be related to their sense of responsibility and lack of interest in the topic.

Exploration guides revealed its efficiency as a lot of students managed to execute the proposed tasks autonomously. Without it, students could have demotivated as they could not keep on the work while the others were a step behind. Some students preferred to discover the interface and tools of *ThinkerCad* without reading the exploration guide and often those students asked the instructor for help - as they wanted a quick and more effortless way to execute the tasks - but in those cases, students were encouraged to follow the exploration guide rather than providing a ready answer.

4.3 Interviews

This chapter presents the main findings of the research as derived from interview data with fourteen students that participated in both activities carried out at “escolaglobal”. Each subchapter is focused on the core clusters mentioned in the topic 1.4.3.2.

4.3.1 Collaborative *versus* Individual

Concerning the second cluster of questions, main findings pointed out that collaborative interaction was considered an advantage as students could share their knowledge and doubts, allocate tasks to each group element and compare the answers. The main argument used by those who allocated tasks to each group element, was to complete the activity faster, which from the pedagogical point of view is not so advantageous. Some mentioned a disadvantage was to be less focused, take more time to finish tasks and dealing with other perspectives, opinions and behaviors caused troubles sometimes. Some of them decided to disturb the whole group which might have influenced results.

In its turn, benefits from individual activity are related to focus, self-overcoming, being able to bring their own ideas, take their own decisions without being influenced by others and they don’t have the need to share the file with others, taking the plunge that some students unformat it, no communication problems and thus, less confusion. Creativity could be observed in real time as, for example, one of them decided to do a squared pizza, instead of a round one. Disadvantages were related to not being able to share the doubts with others and not being able to conclude the activities on time as they had no help. Some advantages mentioned by the interviewees, were converted into a more educational language, because spontaneously, interviewees mentioned advantages like "being able to ask my doubts to my colleagues" and for this study purpose, such response was converted into "the possibility of negotiating concepts", also when they mentioned "Do what I want without the influence of others" was converted into "confidence to take autonomous decisions" (Table 16).

Beyond this, most of the interviewees agreed that group activity suited best the second part of the activity than the first one as they could discuss the questions proposed. In their perspective, for modeling in *TinkerCad*, collaborative activity could cause some hassles as the disturbing elements would delete the work done by other students. However, one of the interviewees mentioned that being in group in the first class helped her to understand how she/he could model a certain object, by seeing how the other group elements were doing it.

Table 16. Benefits of individual and collaborative work

Individual	Collaborative
• The possibility of creating things without influence of others (creativity)	• Being able to ask doubts to the peers
• More focus	• More engaging
• Less stressful	• Learn how to do by seeing how one peer has already made
• Self-overcoming problems is challenging	• Negotiating concepts
• Creating confidence to take autonomous decisions	• Leadership and socio-emotional skills

4.3.2 Perceived Understanding of Engineering as a Job

Most of the students (8 out of 12) had a broad and fuzzy idea of the work done by an Engineer and thus, could not relate properly the activity with the question regarding the motivation to pursue a career in Engineering, which might explain results obtained in the post-test Questionnaire. Anyway, some of them, after thinking deeper on it, could relate it during the interview, mentioning it is important to learn about technology of the future and that modeling softwares and 3D printing is something Engineers might have to know in their future jobs. It seemed though that before the interview they had never thought of it, although they knew Engineer had different fields of operation. This might explain the decrease in the number of students who wanted to pursue a career in Engineering from the pre to the post-test.

4.4 Exploration Guides

At the end of the second class, students were asked to send the exploration guide via email so we could analyze answers. All the received exploration guides were incomplete which probably means it was too long to be solved within an hour. Most incorrect answers were related to the exercise they had to fill in the captions to the image of a printer. Probably because it was different from the printer showed in school. The one in the image had two filaments and the printed piece had a support, which might have raised some doubts and misunderstandings. Despite this, in the majority of the received exploration guides, we verified students were able to identify the main adhesion types and the reason why calibration should be made.

4.5 Results Discussion

David Ausubel conditions for learning to occur in a potentially meaningful manner was established (see topic 3.3) and so, a set of variables were analyzed aiming to understand the impact of the activities on students' learning and motivation. None of the students reported to have null motivation to learn in the pre-test, so we may assume that all of them were predisposed to learn. We will now discuss and answer the research questions previously defined:

1. **Is 3D printing a suitable topic for introducing smart manufacturing to 5th grade?**

Although the school already had 3D printers, students had never seen or printed anything in 3D, so this topic revealed to be suitable and capable of creating engagement. Besides this, many of them revealed to be very motivated in the beginning.

2. **Are the activities proposed capable of creating potential meaningful learning on the covered topics?**

Scores obtained in the administered pre and post-tests and the mastery perception lead us to believe that there were significant learning outcomes. However, interviews administered one/two weeks later, aiming to assess their knowledge, raised the possibility of not being fully or well organized in their cognitive structure. Some answers could be correctly provided by them, however, when asked why they chose such option, some of them were not able to explain and others could do it only after raising following questions and rejecting misconceptions.

3. **What are the benefits of working collaboratively *versus* individually to acquire potential meaningful learning on the covered topics?**

Regarding the benefits associated to each dynamic, we could report that students assigned to individual activities, naturally assumed a different behavior and thus, worked different skills. Whilst the individual dynamic encouraged students to take a more responsible position, leaving room to be more creative and self-overcome the fear of making a mistake, students assigned to the collaborative dynamic could negotiate concepts, and acquire leadership and socio-emotional skills. Results lead us to think though, that one set of benefits is not more powerful than another set of benefits. This might mean that both sets of benefits are essential for a potential acquisition of meaningful learning.

4. **Which of the dynamics – individual or collaborative – has contributed to a more potentially meaningful retention of knowledge?**

The dynamic that registered higher scores, when learning outcomes were assessed, was the individual one. However, statistics revealed that the difference between scores registered in each dynamic was not significant, meaning there is no reason to believe one dynamic contributes more to a potentially meaningful retention of knowledge when compared to the other. At this stage, we may say that this study does not support the ICAP hypothesis once the "interactive" mode was not more effective – from the learning perspective - than the "constructive". One could assume that such activities could be equally effective regardless the dynamic chosen. Nevertheless, one interviewee reported that despite being assigned to the individual activity, he/she asked the colleague next to him/her, some questions. Such interaction was not noticed by the time of the activity and that might have influenced individual results.

5. **How does female motivation to pursue a career in Engineering differ from male?**

Results show that females' motivation to pursue a career in Engineering is significantly lower than male students. On one hand this may be due to the lack of familiarity with the word "Engineering", as some of the interviewees reported that they did not know in what Engineering profession consists of. Also, it may be premature to evaluate their motivation to pursue a career in this area right after the activity end up or at such an early age, as many of them are still getting in touch with different areas. On the other hand, it may though be taken as an alert to create awareness and thus further effort in order to reduce the gap of female gender in Engineering.

Additional data collected provided a more in-depth understanding of the activities proposed. For example, according to the interviewees, first class was more engaging than the second one, because it was more practical. The second one required that students look for the answers on the internet and they considered this a more traditional and tiresome task.

Concerning the perceived quality of the instructional material, we may assume that the material was suitable for creating conditions for meaningful learning to occur as the majority of the students agreed the material was understandable, relevant and helped them link new concepts with previous knowledge. It is noteworthy that they did not agreed that these activities were related to real environments, which might also be associated with their lack of knowledge regarding Engineering professions and its application.

We also attempted to understand the relation between instructional material and motivation. Results demonstrate that motivated students higher ranked the instructional material affirmations when compared to unmotivated students. However, their perceived quality was not dependent on the scores obtained in the administered pre and post-tests.

Finally, and answering to the main research question "What defines the design of a pedagogical architecture capable of creating awareness and motivation among young students in order to pursue a career in engineering?", a suitable pedagogical architecture might be then an approach that gathers together the fundamentals of David Ausubel - which are strongly oriented toward the verbal learning methods - with an action-oriented approach activity based on an attractive and easy to understand technology. Such activity may be done individually or collaboratively, remembering however that, according to it, students will be training different skills. This architecture consider the student as an active participant in the learning process and is three-fold, embedding: a) A theoretical introduction that attempts to contextualize, providing possible applications of 3D printed pieces and explaining the importance of such activity in the Engineering field; b) Instructional material that is relatable to their particular structures of knowledge on a nonarbitrary and nonverbatim basis and c) An action-oriented activity that stimulates structured self-learning and helps students internalize the concepts presented previously (see Figure **25**). This approach considers students as "social agents" that have tasks to execute in a specific context and field of action (Council of Europe, 2001). The activity should stimulate the learning by doing as much as possible and students should strive to complete the tasks autonomously, following an exploration guide that presents tasks that increase in complexity.

> A task is defined as any purposeful action considered by an individual as necessary in order to achieve a given result in the context of a problem to be solved, an obligation to fulfil or an objective to be achieved (Council of Europe, 2001, p. 10).

Besides stimulating autonomy, exploration guides allow each student to keep up its own learning pace. Moreover, they should also contain application exercises that stimulate reflection, and results report (if applicable), aiding students hierarchize concepts in their cognitive structures. The instructor should act as a moderator, enhancing students' skills to draw their own conclusions and take decisions (Jan Cachay *et al.*, 2012). Ultimately, the instructor should provide questions instead of ready answers.

Figure 25. Architecture for teaching Smart Manufacturing to 5th grade students

5. Final Remarks and Future Work

The research question that motivated this study was "What defines the design of a pedagogical architecture capable of creating awareness and motivation among young students in order to pursue a career in engineering?". Aiming to answer this question, we defined a set of sub research questions (see Table **17**) and we planned, designed, and tested two activities with 5th grade students. The first activity entailed presenting the smart manufacturing concept and 3D printing and was followed by a hands-on activity consisting of modeling a pizza base and its ingredients on an online CAD software named *TinkerCad*. The second activity consisted of learning how to print a 3D model, which encompassed (a) configuring an .STL file in U*ltimaker Cura*; (b) exporting a .Gcode file; (c) setting up the printer; (d) learning the names of the printer' components and (e) learning how to calibrate the printer. These pedagogical activities propose a structured self-learning process, meaning all students were instigated to execute the provided tasks autonomously, following the instructions provided in an exploration guide. A case study was conducted with two different dynamics of working: collaborative and individual. The goals aimed at understanding (1) if 3D printing is a suitable topic for introducing smart manufacturing to 5th grade students; (2) if the activities proposed are capable of creating a potential meaningful learning on the covered topics; (3) what are the benefits of working collaboratively *versus* individually to acquire potential meaningful learning on the covered topics; (4) which of the dynamics – individual or collaborative – has contributed to a more potentially meaningful retention of knowledge and (5) how does motivation to pursue a career in Engineering differs from male and female students. Results are presented in Table **17**. Additionally, the conducted case study and data collected allowed to evaluate other parameters that could influence the effectiveness of the activity such as motivation, and instructional material. As a response to the main research question the architecture presented in Figure **25** was created, involving three components considered crucial for a meaningful learning experience on smart manufacturing: contextualization, instructional material and an oriented-approach. Such design architecture is expected to provide a gateway to further explore and analyze how students should be trained and encouraged to pursue a career in Engineering. Moreover, other studies may be conducted to evaluate the effectiveness of this architecture in different fields of study.

The ultimate objectives were, firstly, to give students the possibility to gain practical knowledge in addition to theoretical through their participation in the proposed pedagogical activities and secondly, to provide procedure guidelines for development of activities that aim at teaching smart manufacturing to young students, with special emphasis on young girls. The goals were reached, and the main research question and sub-questions were discussed and answered.

Concerning possible improvements, a more effective way to evaluate retention of knowledge might be handy as post tests and interviews did not allow to do it ostensibly. Using the *Bloom Taxonomy* as an aiding tool during interviews might be a good option. Additionally, to a more in-depth analysis, focused on learning outcomes, one can also think about conducting paired sample tests in the future, instead of independent ones. Ultimately, exploration guides can acquire a different format such as video, instead of *.word* or *.pdf* as some students demonstrated dullness to read it.

Regarding future work, besides the improvements just mentioned, we intend to (a) involve more schools in the proposed activities; (b) deepen a STEAM - Science, Technology, Engineering, Arts, Mathematics approach; (c) continue exploring and creating instructional material to cover 3D printing topics and (d) introduce a PBL approach, containing missions like assisting impaired people. The idea is that by providing means to the students to "socialize" with smart manufacturing challenges and career opportunities in early ages, they will be encouraged to consider a career in manufacturing-related fields and therefore help ensure a future with an available and well-qualified workforce. Concerning this goal, *Teaching Factories for Kids* (TF4K) project is performing activities such as a 3D pizza assembly line aiming to teach middle and high school students, concepts related to automation and reconfigurable systems (see Figure 26). These activities stimulate the "learning by doing" which we believe is the right way to retain meaningfully concepts related to this topic of smart manufacturing. In this regard it should be mentioned that there is a project on the way named "DISCOVER MANUFACTURING" - also supported by the EIT-Manufacturing - which main goal is to change the negative and outdated perception students, their teachers and parents have of manufacturing sector. It proposes a teachers' training which aims to provide the necessary guidelines, tools and instructional material so that teachers feel confident in guiding their students through the Design Thinking methodology to devise and 3D print a health-related object/product to assist someone or help their local community. However, teachers will continue to be supported by trainers, researchers and industry personnel. Finally, the activity will culminate in a competitive final.

Educational institutions have the responsibility of raising the interest of young students striving to reach a qualified and minimized gender gap workforce in the future, thus addressing key factors aligned with a STEM (Science, Technology, Engineering and Mathematics) educational approach (Mohr-Schroeder *et al.*, 2020). Hence, students will acquire the required skills of I4.0, such as interdisciplinarity (Maia *et al.*, 2017), communication and analytical skills, and creativity, among others (Hecklau *et al.*, 2016), tackling the greatest challenges of our time. And if we allow education to change, it will become the key source of our future competitiveness. The opportunity is too great to miss.

Ultimately, the topics of this dissertation have resulted in two paper publications in conference proceedings. The first one was developed under the scope of the "11th Conference on Learning Factories"[7] and is intitled "New Pedagogical Approaches to Shaping the Next Generation of Portuguese Manufacturing Professionals", the other one was developed under the scope of the "PRO-VE Conferences"[8] and is intitled "Education 4.0 and the smart manufacturing a conceptual gateway for learning factories".

Table 17. Research sub-questions, hypotheses and final results

	Sub-questions	**Hypotheses**	**Results**
1.	Is 3D printing a suitable topic for introducing smart manufacturing to 5th grade students?	The attractiveness and easy to grasp concept of 3D printing make it a suitable topic for introducing smart manufacturing to 5th grade students.	3D printing revealed to be suitable and capable of creating engagement.
2.	Are the activities proposed capable of creating potential meaningful learning on the covered topics?	Activities based on Computer-Aided Design (CAD) and problem solving can create potential meaningful learning experiences.	It is inconclusive as interviews were only conducted with twelve students and some of the interviews raised the possibility of not being fully or well organized in their cognitive structure.
3.	What are the benefits of working collaboratively *versus* individually to acquire potential meaningful learning on the covered topics?	Individual performance allows students to learn meaningfully because they can learn at their own pace which stimulates critical thinking and focus. Collaborative performance	Individual dynamic encouraged students to take a more responsible position, leaving room to be more creative and self-overcome the fear of making a mistake, students assigned to the

[7] https://www.tugraz.at/events/clf2021/home/
[8] https://pro-ve-2021.sciencesconf.org/

		fosters soft skills, such as negotiation and leadership.	collaborative dynamic could negotiate concepts, and acquire leadership and socio-emotional skills.
4.	Which of the dynamics – individual or collaborative – has contributed to a more potentially meaningful retention of knowledge?	Collaborative activities register more meaningful learning when compared to individual.	The difference between scores registered in each dynamic was not significant, meaning there is no reason to believe one dynamic contributes more to a potentially meaningful retention of knowledge when compared to the other.
5.	How does motivation to pursue a career in Engineering differs from male and female students?	Female motivation to pursue a career in Engineering is typically lower when compared to male.	Results show that females' motivation to pursue a career in Engineering is significantly lower than male students.

Figure 26. On going activities of TF4K

6. References

Accreditation Board for Engineering and Technology, Inc. (2021). Criteria for *Accrediting Engineering Programs, 2020 – 2021* | ABET. Https://Www.Abet.Org/. https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2020-2021/

3D HUBS B.V. (2021). *HUBS: A protolabs company*. https://www.hubs.com/guides/3d-printing/?utm_content=bufferc2ecf&utm_medium=social&utm_source=facebook.com&utm_campaign=buffer&fbclid=IwAR3IrDMPAPqXeOkpyfSWBOImfYsdrWuqVx52emuLVSTSeBPmmFNCPPfjS_k#fdm

Adams, A., Johnson, C. D., & Green, B. N. (2006). Writingn a rrative literature reviews for peer-reviewed journals: secrets of the trade. *CHIROPRACTIC MEDICINE*, *5*(3), 101–117. https://doi.org/10.1162/ling_a_00246

Alqahtani, A. Y., Gupta, S. M., & Nakashima, K. (2019). International Journal of Production Economics Warranty and maintenance analysis of sensor embedded products using internet of things in industry 4 . 0. *Intern. Journal of Production Economics*, *208*(December 2018), 483–499. https://doi.org/10.1016/j.ijpe.2018.12.022

Amaya, M. R. A., Ortega-jiménez, C. H., Machuca, J. A. D., & Alfalla-luque, R. (2020). *Industry 4.0: current trend and future scope for further research in High Performance Manufacturing*.

Anderson, L. W., Krathwohl Peter W Airasian, D. R., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., Raths, J., & Wittrock, M. C. (2001). *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*. https://www.uky.edu/~rsand1/china2018/texts/Anderson-Krathwohl - A taxonomy for learning teaching and assessing.pdf

Ausubel, D. P. (2000). *The Acquisition and Retention of Knowledge: A congnitive View*. Springer-Science+Business Media, B.V.

Basir, R., Qaisar, S., Ali, M., Aldwairi, M., Ashraf, M. I., Mahmood, A., & Gidlund, M. (2019). *Industry 4.0: A survey on technologies, applications and open research issue*. https://doi.org/10.3390/s19214807

Bayegan, M., & Elisson, B. (2012). Special Report: Robotics. *ABB Review*, 72. http://www05.abb.com/global/scot/scot271.nsf/veritydisplay/ef27d6c7e1c59be1c1256fc500385aed/$file/ABB SP 1-05_72dpi.pdf

Baygin, M., Yetis, H., Karakose, M., & Akin, E. (2016). An Effect Analysis of Industry 4 . 0 to Higher Education. *2016 15th International Conference on Information Technology Based Higher Education and Training (ITHET)*, 1–4. https://doi.org/10.1109/ITHET.2016.7760744

Beckman, W. (2008). Pre-Testing as a Method of Conveying Learning Objectives. *Journal of Aviation/Aerospace Education & Research*, *January 2008*. https://doi.org/10.15394/jaaer.2008.1447

Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., & Krathwohl, D. R. (1956). The Classification of Educational Goals: Handbook 1: Cognitive Domain. In *Taxonomy of educational objectives*. Longmans Geen and co ltd.

Bongomin, O., Gilibrays Ocen, G., Oyondi Nganyi, E., Musinguzi, A., & Omara, T. (2020). Exponential Disruptive Technologies and the Required Skills of Industry 4.0. *Journal of Engineering (United Kingdom)*, *2020*(February), 0–17. https://doi.org/10.1155/2020/4280156

Breiner, J. M., Johnson, C. C., Harkness, S. S., & Koehler, C. M. (2012). *What Is STEM? A Discussion About Conceptions of STEM in Education and Partnerships*. 3–11.

Cachay, J, & Abele, E. (2012). Developing Competencies for Continuous Improvement Processes on the Shop Floor through Learning Factories – Conceptual Design and Empirical Validation. *Procedia CIRP*, *3*, 638–643. https://doi.org/10.1016/j.procir.2012.07.109

Cachay, Jan, Wennermer, J., Abele, E., & Tenberg, R. (2012). *Study on action-oriented learning with a Learning Factory approach*. *55*, 1144–1153. https://doi.org/10.1016/j.sbspro.2012.09.608

Carlana, M. (2019). *Implicit stereotypes: Evidence from teachers' gender bias*. 1163–1224. https://doi.org/10.1093/qje/qjz008.Advance

Chi, M. T. H. (2009). Active-Constructive-Interactive: A Conceptual Framework for Differentiating Learning Activities. *Topics in Cognitive Science*, *1*(1), 73–105. https://doi.org/10.1111/j.1756-8765.2008.01005.x

Chi, M. T. H., & Wylie, R. (2014). The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes. *Educational Psychologist*, *49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823

Choi, G. Y., & Behm-morawitz, E. (2017). Computers in Human Behavior Giving a new makeover to STEAM : Establishing YouTube beauty gurus as digital literacy educators through messages and effects on viewers. *Computers in Human Behavior*, *73*, 80–91. https://doi.org/10.1016/j.chb.2017.03.034

Chong, S., Pan, G., Chin, J., & Show, P. L. (2018). Integration of 3D Printing and Industry 4.0 into Engineering Teaching. *Sustainability*. https://doi.org/10.3390/su10113960

Clarizia, F., De Santo, M., Lombardi, M., & Santaniello, D. (2021). E-learning and industry 4.0: A chatbot for training employees. *Advances in Intelligent Systems and Computing*, *1184*, 445–453. https://doi.org/10.1007/978-981-15-5859-7_44

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*.

Council of Europe. (2001). Comes: Learning, Teaching, Assessment (CEFR) European Framework of Reference for Languag. *Common European Framework*. https://rm.coe.int/1680459f97

Creswell, J. W. (2009). Research Design: Qualitative, Quantitative and Mixed Methods Approaches. In *Intercultural Education* (Vol. 20, Issue 2). https://doi.org/10.1080/14675980902922143

Creswell, J. W., & Clark, V. P. (2010). Choosing a mixed methods design. In *Designing and conducting mixed methods research* (pp. 53–106). http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Choosing+a+mixed+methods+design#0

Creswell, J. W., & Clark, V. P. (2018). *Designing and Conducting Mixed Methods Research*.

Delic, H., & Bećirović, S. (2016). Socratic Method as an Approach to Teaching. *European Researcher, 111*(10). https://doi.org/10.13187/er.2016.111.511

DeMara, R. F., Tian, T., & Howard, W. (2019). Engineering assessment strata: A layered approach to evaluation spanning Bloom's taxonomy of learning. *Education and Information Technologies*, *24*(2), 1147–1171. https://doi.org/10.1007/s10639-018-9812-5

DeWalt, K. M., & DeWalt, B. R. (2010). *Participant Observation: A Guide for Fieldworkers* (R. Altamira (ed.); Edition 2). AltaMira Press. https://books.google.pt/books?id=ymJJUkR7s3UC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=snippet&q=hypotheses&f=false

Digital, M. (2016). *McKinsey Digital 2016*.

Erdimez, O., Tan, S., & Zimmerman, R. (2017). The use of concept maps as a tool to measure higher level thinking skills in elementary school science classes. *Journal for the Education of Gifted Young Scientists*, *5*(2), 1–18. https://doi.org/10.17478/JEGYS.2017.60

Erol, S., Jäger, A., Hold, P., Ott, K., & Sihn, W. (2016). Tangible Industry 4.0: a scenario-based approach to learning for the future of production. *Procedia CIRP*, *54*, 13–18. https://doi.org/10.1016/j.procir.2016.03.162

Ferreira, E. (2017). *Gender and ICT: school and gender stereotypes*.

Fettermann, D. C., Gobbo, C., Cavalcante, S., Almeida, D. De, & Tortorella, G. L. (2018). How does Industry 4.0 contribute to operations management ? *Journal of Industrial and Production Engineering*, *35*, 255–268. https://doi.org/10.1080/21681015.2018.1462863

Field, A. (2013). *Discovering statistics using IBM SPSS statistics* (4th ed.). SAGE Publications.

Figueiredo, M. J. G., Cardoso, P. J. S., Goncalves, C. D. F., & Rodrigues, J. M. F. (2014). Augmented reality and holograms for the visualization of mechanical engineering parts. *18th International Conference on Information Visualisation*, 368–373. https://doi.org/10.1109/IV.2014.17

Funk, C., & Parker, K. (2018). Women and Men in STEM Often at Odds Over Workplace

Equity. *Pew Research Center*, *January*.

Gates, A. E. (2017). *Benefits of a STEAM Collaboration in Newark , New Jersey : Volcano Simulation Through a Glass- Making Experience Benefits of a STEAM Collaboration in Newark , New Jersey : Volcano Simulation Through a Glass-Making Experience*. *9995*. https://doi.org/10.5408/16-188.1

Ge, Z., Song, Z., Ding, S. X., & Huang, B. (2017). Data Mining and Analytics in the Process Industry: The Role of Machine Learning. *IEEE Access*, *5*(september), 20590–20616. https://doi.org/10.1109/ACCESS.2017.2756872

Glass, D., & Wilson, C. (2016). *The Art and Science of Looking: Collaboratively Learning Our Way to Improved STEAM Integration*. *3125*. https://doi.org/10.1080/00043125.2016.1224822

Gowin, D. B. (1981). *Educating*. Cornell University Press.

Grady, M. P. (1998). *Qualitative and Action Research: A Practitioner Handbook*. Phi Delta Kappa International. https://books.google.pt/books?id=JOr3-A3-LbwC&lpg=PA1&ots=hCURVdoIK-&lr&pg=PA1#v=onepage&q&f=false

Grant, J., & Patterson, D. (2016). Innovative Arts Programs Require Innovative Partnerships: A Case Study of STEAM Partnering between an Art Gallery and a Natural History Museum. *The Clearing House*, *89*(4–5), 144–152. https://doi.org/10.1080/00098655.2016.1170453

Greca, I. M., & Moreira, M. A. (2002). Além da detecção de modelos mentais dos estudantes : uma proposta representacional integradora. *Investigações Em Ensino de Ciências. Porto Alegre. Vol. 7, n. 1 (Jan./Mar. 2002), p. 31-53*, *7*(1), 31–53.

Greenhalgh, T., Thorne, S., & Malterud, K. (2018). *Time to challenge the spurious hierarchy of systematic over narrative reviews ?* *March*, 1–6. https://doi.org/10.1111/eci.12931

Hartley, J., & Davies, I. K. (2019). *Preinstructional Strategies: The Role of Pretests, Behavioral Objectives, Overviews and Advance Organizers*. *46*(2), 239–265.

Havice, W., Havice, P., Waugaman, C., & Walker, K. (2018). Evaluating the Effectiveness of Integrative STEM Education: Teacher and Administrator Professional Development. *Journal of Technology Education*, *29*(2), 73–90.

Hecklau, F., Galeitzke, M., Flachs, S., & Kohl, H. (2016). Holistic Approach for Human Resource Management in Industry 4.0. *Procedia CIRP*, *54*, 1–6. https://doi.org/10.1016/j.procir.2016.05.102

Hernandez-de-Menendez, M., Escobar Díaz, C. A., & Morales-Menendez, R. (2020). Engineering education for smart 4.0 technology: a review. *International Journal on Interactive Design and Manufacturing*, *14*(3), 789–803. https://doi.org/10.1007/s12008-020-00672-x

Johnson-Laird, P. N. (1983). *Mental Models*. Harvard University Press.

Jones, K., & Mendez, J. D. (2021). Enhancing learning with 3D print technology: A case study of problem based learning. *Journal of Education for Business*, *96*(3), 187–194. https://doi.org/10.1080/08832323.2020.1774735

Jones, N. A., Ross, H., Lynam, T., Perez, P., & Leitch, A. (2011). Mental models: An interdisciplinary synthesis of theory and methods. *Ecology and Society*, *16*(1).

https://doi.org/10.5751/ES-03802-160146

Jou, M., Chuang, C. P., & Wu, Y. S. (2010). Creating interactive web-based environments to scaffold creative reasoning and meaningful learning: From physics to products. *Turkish Online Journal of Educational Technology*, *9*(4), 49–57.

Juntunen, M., & Lehenkari, M. (2021). *Studies in Higher Education A narrative literature review process for an academic business research thesis*. *46*(2), 330–342. https://doi.org/10.1080/03075079.2019.1630813

Kaloti-Hallak, F., Armoni, M., & Ben-Ari, M. (2019). The effect of robotics activities on learning the engineering design process. *Informatics in Education*, *18*(1), 105–129. https://doi.org/10.15388/infedu.2019.05

Khan, W. Z., Rehman, M. H., Zangoti, H. M., Afzal, M. K., Armi, N., & Salah, K. (2020). Industrial internet of things: Recent advances, enabling technologies and open challenges. *Computers and Electrical Engineering*, *81*, 106522. https://doi.org/10.1016/j.compeleceng.2019.106522

Kinkel, S., Schemmann, B., & Lichtner, R. (2017). Critical Competencies for the Innovativeness of Value Creation Champions: Identifying Challenges and Work-integrated Solutions. *Procedia Manufacturing*, *9*(0), 323–330. https://doi.org/10.1016/j.promfg.2017.04.021

Kurt, S. (2020). *Bloom's Taxonomy*. Educational Technology. https://educationaltechnology.net/blooms-taxonomy/

Lee, E. A., & Sangiovanni-Vincentelli, A. L. (2012). *Modeling Cyber – Physical Systems*. *July 2015*. https://doi.org/10.1109/JPROC.2011.2160929

Leedy, P. D., & Ormrod, J. E. (2015). *Practical Research: Planning and design*.

Leung, A. (2020). *Boundary crossing pedagogy in STEM education*. *9*.

Li, X., Li, D., Wan, J., & Vasilakos, A. V. (2017). *A review of industrial wireless networks in the context of Industry 4.0*. 23–41. https://doi.org/10.1007/s11276-015-1133-7

Lu, Y. (2017). Journal of Industrial Information Integration Industry 4 . 0 : A survey on technologies , applications and open research issues. *Journal of Industrial Information Integration*, *6*. https://doi.org/10.1016/j.jii.2017.04.005

Lukac, D. (2015). *The fourth ICT-based Industrial Revolution "Industry 4.0" - HMI and the case of CAE /CAD innovation with EPLAN P8*. 835–838.

Madgavkar, A., Manyika, J., Krishnan, M., Ellingrud, K., Yee, L., Woetzel, J., Chui, M., Hunt, V., & Balakrishnan, S. (2019). *The future of women at work*. *May*.

Maia, R. F., Massote, A. A., & Lima, F. (2017). Innovative laboratory model based on partnerships and active learning. *Proceedings - Frontiers in Education Conference, FIE*, *2017-Octob*. https://doi.org/10.1109/FIE.2017.8190534

Maker, C. J., & Zimmerman, R. H. (2020). Concept Maps as Assessments of Expertise: Understanding of the Complexity and Interrelationships of Concepts in Science. *Journal of Advanced Academics*, *31*(3), 254–297. https://doi.org/10.1177/1932202X20921770

MakerBot Industries, L. (2021). *Makerbot*. https://www.makerbot.com/3d-printers/materials/method-asa/

Markle, D., West, R., & Rich, P. (2011). Beyond Transcription Technology, Change, and Refinement of Method Markle Forum Qualitative Sozialforschung Forum Qualitative Social Research. *Forum Qualitative Sozialforschung Forum Qualitative Social Research*, *12*(3), Art.21. http://www.qualitative-research.net/index.php/fqs/article/view/1564/3249

Maturana, H. R. (2001). COGNIÇÃO, CIÊNCIA E VIDA COTIDIANA. In UFMG (Ed.), *Designing Our Way to a Better World*. https://doi.org/10.5749/minnesota/9780816698875.003.0018

Maturana, H. R., & Varela, F. J. (1980). *Autopoiesis and Cognition: The realization of the Living* (Vol. 42, Issue 9). http://publications.lib.chalmers.se/records/fulltext/245180/245180.pdf%0Ahttps://hdl.handle.net/20.500.12380/245180%0Ahttp://dx.doi.org/10.1016/j.jsames.2011.03.003%0Ahttps://doi.org/10.1016/j.gr.2017.08.001%0Ahttp://dx.doi.org/10.1016/j.precamres.2014.12

McKinsey & Company. (2018). *Automação e futuro do emprego em Portugal*.

Miller, D. (2016). Natural Language: The User Interface for the Fourth Industrial Revolution. *Opusresearch Report*. https://opusresearch.net/wordpress/2016/11/04/opus-research-report-natural-language-the-user-interface-for-the-fourth-industrial-revolution/

Mogos, R. I., Bodea, C. N., Dascalu, M. I., Safonkina, O., Lazarou, E., Trifan, E. L., & Nemoianu, I. V. (2018). Technology Enhanced Learning for Industry 4.0 Engineering Education. *Revue Roumaine Des Sciences Techniques Serie Electrotechnique et Energetique*.

Mohr-Schroeder, M. J., Bush, S. B., Maiorca, C., & Nickels, M. (2020). Moving Toward an Equity-Based Approach for STEM Literacy. In *Handbook of Research on STEM Education* (Issue 49572, pp. 29–38). https://doi.org/10.4324/9780429021381-4

Monostori, L. (2014). Cyber-physical production systems: Roots , expectations and R & D challenges. *Procedia CIRP*, *17*, 9–13. https://doi.org/10.1016/j.procir.2014.03.115

Morais Maceira, H. (2017). Economic Benefits of Gender Equality in the EU. *Intereconomics*, *52*(3), 178–183. https://doi.org/10.1007/s10272-017-0669-4

Morales-menendez, M. H. R., Escobar, C. A., Mcgovern, M., & Hernandez-de-menendez, M. (2020). Competencies for Industry 4 . 0. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *july*, 1511–1524.

Moreira, M. A. (2002). A TEORIA DOS CAMPOS CONCEITUAIS DE VERGNAUD, O ENSINO DE CIÊNCIAS E A PESQUISA NESTA ÁREA. *Investigações Em Ensino de Ciências-V7*, *7*(1), 7–29.

Moreira, M. A. (2010). *Aprendizagem Significativa Crítica*. *Iii*, 83–101.

Mostafa, T. (2019). *Why don't more girls choose to pursue a science career?*

Novak, J. D. (2009). *Learning, Creating and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations* (Second Edi). Routledge. https://doi.org/https://doi.org/10.4324/9780203862001

Novak, J. D., & Cañas, A. J. (2015). The Theory Underlying Concept Maps and How to

Construct and Use Them. *IHMC CmapTools*, *August*. https://doi.org/Technical Report IHMC CmapTools 2006-01 Rev 2008-01

Oberc, H., Prinz, C., Glogowski, P., Lemmerz, K., & Kuhlenkötter, B. (2019). Human Robot Interaction - Learning how to integrate collaborative robots into manual assembly lines. *Procedia Manufacturing*, *31*, 26–31. https://doi.org/10.1016/j.promfg.2019.03.005

Ogorodnyk, O., Granheim, M., Holtskog, H., & Ogorodnyk, I. (2017). Roller Skis Assembly Line Learning Factory – Development and Learning Outcomes. *Procedia Manufacturing*, *9*(2351), 121–126. https://doi.org/10.1016/j.promfg.2017.04.045

Peiró-Signes, A., Trull-Dominguez, O., Segarra-Oña, M., & Cabrero, J. A. (2020). Bowling Game To Learn Communications Between Different Devices. *INTED2020 Proceedings*, *1*(March), 1490–1495. https://doi.org/10.21125/inted.2020.0493

Peppler, K., & Wohlwend, K. (2018). *Theorizing the nexus of STEAM practice Theorizing the nexus of STEAM practice*. *2913*. https://doi.org/10.1080/10632913.2017.1316331

Perignat, E., & Katz-Buonincontro, J. (2019). STEAM in practice and research: An integrative literature review. *Thinking Skills and Creativity*, *31*(July 2018), 31–43. https://doi.org/10.1016/j.tsc.2018.10.002

Piaget, J. (1929). *The Child s Conception of the World*. ROUTLEDGE & KEGAN PAUL LTD.

PORDATA. (2020). *Alunos do sexo feminino em % dos matriculados no ensino superior: total e por área de educação e formação*. https://www.pordata.pt/Portugal/Alunos+do+sexo+feminino+em+percentagem+dos+matriculados+no+ensino+superior+total+e+por+área+de+educação+e+formação+-1051

Priemer, B., Eilerts, K., Filler, A., Pinkwart, N., Tiemann, R., Upmeier, A., Belzen, Z., Priemer, B., Eilerts, K., Filler, A., Pinkwart, N., & Rösken-, B. (2019). A framework to foster problem-solving in STEM and computing education. *Research in Science & Technological Education*, *38*, 105–130. https://doi.org/10.1080/02635143.2019.1600490

Qin, J., Liu, Y., & Grosvenor, R. (2016). A Categorical Framework of Manufacturing for Industry 4.0 and Beyond. *Procedia CIRP*, *52*, 173–178. https://doi.org/10.1016/j.procir.2016.08.005

Quigley, C. F., Herro, D., & Jamil, F. M. (2017). *Developing a Conceptual Model of STEAM Teaching Practices*. 1–12.

Rauf, A. S., Daud, M. F., & Said, M. N. H. B. M. (2016). MOOCs in engineering education – A literature review. *6th Regional Conference on Engineering Education 2016*, *August*.

Rosé, C. P., Moore, J. D., Vanlehn, K., Allbritton, D., & Ros, C. P. (2001). A comparative evaluation of Socratic versus didactic tutoring. *Proceedings of Hte Twenty-Third Annual Conference of the Cogntive Science Quarterly*, *8*(June 2013), 897–902.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The Future of Productivity and Growth in Manufacturing

Industries. *The Boston Consulting Group*.

Saldana, J. (2009). The Coding Manual for Qualitative Researchers. In *SAGE Publications Ltd*. https://books.google.ca/books?id=ZhxiCgAAQBAJ&printsec=frontcover#v=onepage&q&f=false

Schuh, G., Gartzen, T., Rodenhauser, T., & Marks, A. (2015). Promoting work-based learning through industry 4.0. *Procedia CIRP*, *32*, 82–87. https://doi.org/10.1016/j.procir.2015.02.213

Seiersten, N., & Berg, A. (2017). Digital drawing demystified: Exploring a creative zone of proximal development. *Proceedings of the 19th International Conference on Engineering and Product Design Education: Building Community: Design Education for a Sustainable Future, E and PDE 2017*, *September*, 50–55.

Sherbin, L. (2018). Things Successful Women in STEM Have in Common. *Research in Science & Technological Education*, *april*.

Silva, S. M. (2018). *Closing the gender gap in digital technologies*.

Silvestri, L., Forcina, A., Introna, V., Santolamazza, A., & Cesarotti, V. (2020). Maintenance transformation through Industry 4.0 technologies: A systematic literature review. *Computers in Industry*, *123*. https://doi.org/10.1016/j.compind.2020.103335

Simons, S., Abé, P., & Neser, S. (2017). Learning in the AutFab – The Fully Automated Industrie 4.0 Learning Factory of the University of Applied Sciences Darmstadt. *Procedia Manufacturing*, *9*, 81–88. https://doi.org/10.1016/j.promfg.2017.04.023

Sisinni, E., Saifullah, A., Han, S., & Ulf, I. (2018). Industrial Internet of Things: Challenges , Opportunities , and Directions. *IEEE Transactions on Industrial Informatics*. https://doi.org/10.1109/TII.2018.2852491

Skills Panorama. (2019). *Manufacturing*. https://skillspanorama.cedefop.europa.eu/en/dashboard/browse-sector?sector=02&country=PT#10

Slavin, R. E. (1995). *Best evidence synthesis: an intelligent alternative to meta-analysis*. *48*(1), 9–18.

Somyürek, S. (2014). An effective educational tool: construction kits for fun and meaningful learning. *International Journal of Technology and Design Education*, *25*, 25–41. https://doi.org/10.1007/s10798-014-9272-1

Stock, T., & Seliger, G. (2016). Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP*, *40*(Icc), 536–541. https://doi.org/10.1016/j.procir.2016.01.129

Tay, S. I., Lee, T. C., Hamid, N. Z. A., & Ahmad, A. N. A. (2018). An overview of industry 4.0: Definition, components, and government initiatives. *Journal of Advanced Research in Dynamical and Control Systems*, *10*(14), 1379–1387.

Thagard, P. (2005). *Mind: Introduction to Cognitive Science* (2nd ed.). The MIT Press. https://www.bookboxpdf.com/paul-thagard-mind/

Tillinghast, R. C., Appel, D. C., Winsor, C., & Mansouri, M. (2020). STEM Outreach: A Literature Review and Definition. *2020 9th IEEE Integrated STEM Education Conference, ISEC 2020*, *67*. https://doi.org/10.1109/ISEC49744.2020.9280745

Tisch, M., Hertle, C., Cachay, J., Abele, E., Metternich, J., & Tenberg, R. (2013). A systematic approach on developing action-oriented, competency-based Learning Factories. *Procedia CIRP*, *7*, 580–585. https://doi.org/10.1016/j.procir.2013.06.036

Turcu, C. O., & Turcu, C. E. (2018). Industrial Internet of Things as a Challenge for Higher Education. *International Journal of Advanced Computer Science and Applications*, *9*(11), 55–60.

Ullah, A. M. M. S. (2016). On the interplay of manufacturing engineering education and e-learning. *International Journal of Mechanical Engineering Education*, *44*(3), 233–254. https://doi.org/10.1177/0306419016651948

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0 – A Glimpse. *Procedia Manufacturing*, *20*, 233–238. https://doi.org/10.1016/j.promfg.2018.02.034

Vergnaud, G. (2009). The theory of conceptual fields. *Human Development*, *52*(2), 83–94. https://doi.org/10.1159/000202727

Verner, I., & Greenholts, M. (2017). *Teacher Education to Analyze and Design Systems through Reverse Engineering* (Vol. 560, Issue April, pp. 122–132). https://doi.org/10.1007/978-3-319-55553-9

Vygotsky, L. S. (1979). Mind in Society: The Development of Higher Psychological Processes. In *American Anthropologist* (Vol. 81, Issue 4). https://doi.org/10.1525/aa.1979.81.4.02a00580

Wells, L. J., Camelio, J. A., Williams, C. B., & White, J. (2014). Cyber-physical security challenges in manufacturing systems. *Manufacturing Letters*, *2*(2), 74–77. https://doi.org/10.1016/j.mfglet.2014.01.005

Wermann, J., Colombo, A. W., Pechmann, A., & Zarte, M. (2019). Using an interdisciplinary demonstration platform for teaching Industry 4.0. *Procedia Manufacturing*, *31*, 302–308. https://doi.org/10.1016/j.promfg.2019.03.048

Wichmann, R. L., Eisenbart, B., & Gericke, K. (2019). THE DIRECTION OF INDUSTRY: A LITERATURE REVIEW ON INDUSTRY 4.0. *Proceedings of the International Conference on Engineering Design, ICED19*, *AUGUST*, 2129–2138. https://doi.org/10.1017/dsi.2019.219

Witkowski, K. (2017). Internet of Things, Big Data, Industry 4.0 - Innovative Solutions in Logistics and Supply Chains Management. *Procedia Engineering*, *182*, 763–769. https://doi.org/10.1016/j.proeng.2017.03.197

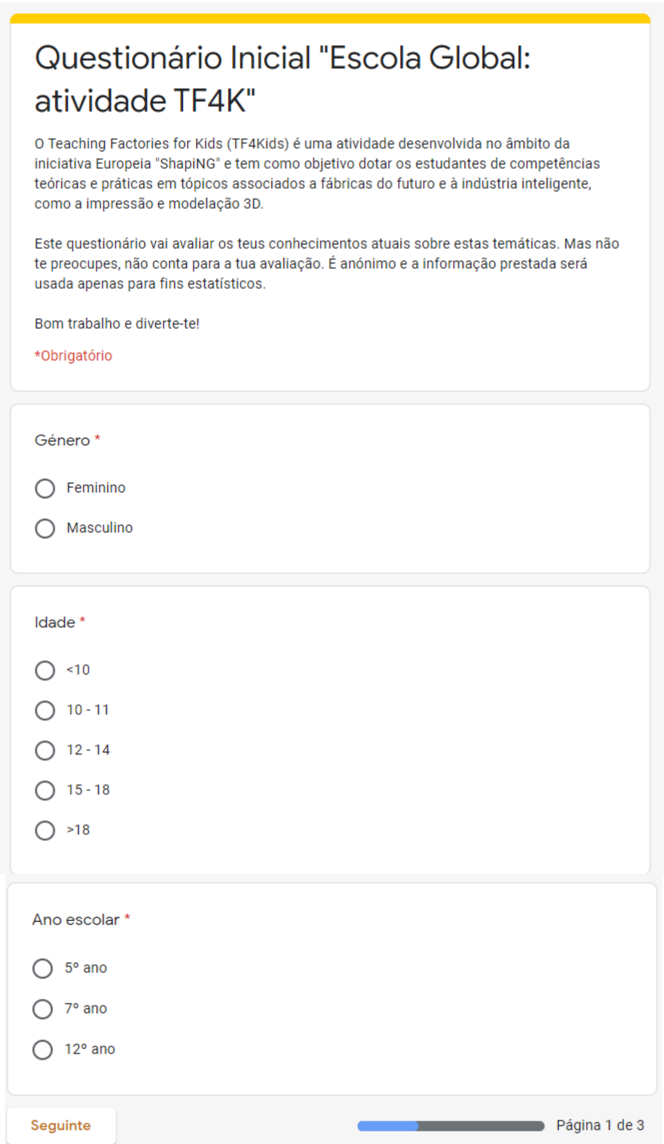
World Economic Forum. (2020). The Future of Jobs Report 2020 | World Economic Forum. *Research Report*, *October*. https://www.weforum.org/reports/the-future-of-jobs-report-2018%0Ahttp://reports.weforum.org/future-of-jobs-2016/shareable-infographics/%0Ahttp://reports.weforum.org/future-of-jobs-2016/chapter-1-the-future-of-jobs-and-skills/%0Ahttps://www.weforum.org/rep

Young, J., Young, J., Cason, M., Ortiz, N., Foster, M., & Hamilton, C. (2018). Concept raps versus concept maps: A culturally responsive approach to STEM vocabulary development. *Education Sciences*, *8*(july). https://doi.org/10.3390/educsci8030108

Zadok, Y., & Voloch, N. (2018). Applying PBL to teaching robotics. *International Journal of Innovation and Learning*, *24*(2), 138–151. https://doi.org/10.1504/IJIL.2018.094068

Zivanovic, S. T., Popovic, M. D., Vorkapic, N. M., Pjevic, M. D., & Slavkovic, N. R. (2020). An overview of rapid prototyping technologies using subtractive, additive and formative processes. *FME Transactions*, *48*(1), 246–253. https://doi.org/10.5937/fmet2001246Z

7. Annex A: Pre-test Questionnaire



Questionário Inicial "Escola Global: atividade TF4K"

O Teaching Factories for Kids (TF4Kids) é uma atividade desenvolvida no âmbito da iniciativa Europeia "ShapiNG" e tem como objetivo dotar os estudantes de competências teóricas e práticas em tópicos associados a fábricas do futuro e à indústria inteligente, como a impressão e modelação 3D.

Este questionário vai avaliar os teus conhecimentos atuais sobre estas temáticas. Mas não te preocupes, não conta para a tua avaliação. É anónimo e a informação prestada será usada apenas para fins estatísticos.

Bom trabalho e diverte-te!

*Obrigatório

Género *

- Feminino
- Masculino

Idade *

- <10
- 10 - 11
- 12 - 14
- 15 - 18
- >18

Ano escolar *

- 5º ano
- 7º ano
- 12º ano

Seguinte

Página 1 de 3

Motivação inicial: 5º ano

Sentes-te motivado(a) para aprender sobre o fabrico inteligente, modelação e impressão 3D? *

- ○ Nada motivado(a)
- ○ Um pouco motivado(a)
- ○ Muito motivado(a)
- ○ Extremamente motivado(a)

Sentes-te motivado(a) a seguir uma carreira na área de Engenharia? *

- ○ Nunca pensei nessa possibilidade.
- ○ Já pensei e vejo como uma possibilidade.
- ○ Já pensei nessa possibilidade mas não gosto.
- ○ Sim, quero muito.

Anterior | Seguinte | Página 2 de 3

5º ano: Impressão 3D

Farei a atividade *

- ○ sozinho
- ○ em grupo

0. Como classificas os teus conhecimentos em Impressão 3D? *

- ○ Nulo (não sei nada)
- ○ Básico (sei pouco)
- ○ Médio (sei várias coisas)
- ○ Avançado (sei muitas coisas)

1. Identifica uma vantagem da impressão 3D *

- ○ Custos de manutenção
- ○ Personalização de peças
- ○ Uso de softwares específicos
- ○ Não sei

2. A impressão 3D é uma tecnologia de *

- ◯ Produção formativa
- ◯ Produção aditiva
- ◯ Produção subtrativa
- ◯ Não sei

3. Um dos materiais utilizados na impressão 3D é *

- ◯ metal
- ◯ plástico PLA
- ◯ resina epóxi
- ◯ Não sei

4. A calibração da impressora *

- ◯ só se aplica a alguns modelos de impressora
- ◯ evita que o objeto modelado tenha irregularidades
- ◯ não é importante
- ◯ Não sei

5. O nozzle deve estar *

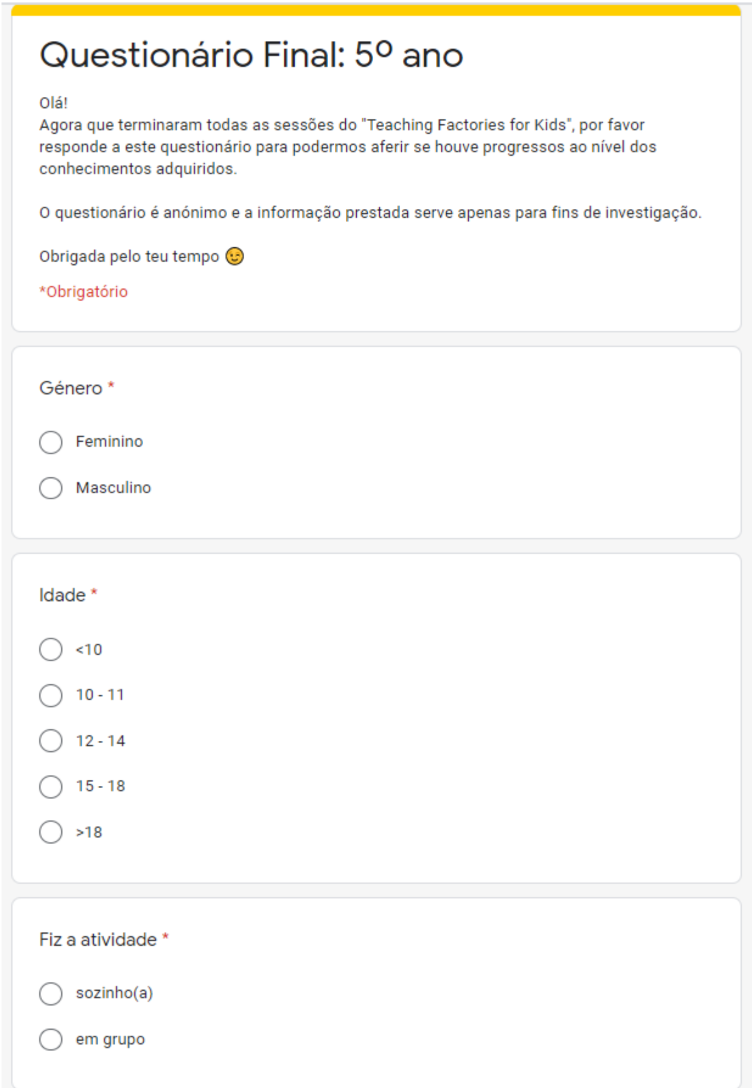
- ◯ muito junto à plataforma
- ◯ muito distante da plataforma
- ◯ perto da plataforma mas sem raspar nela
- ◯ Não sei

6. Para exportar um gráfico de um software de modulação devo escolher um ficheiro *

- ◯ .STL
- ◯ .jpg
- ◯ .pdf
- ◯ Não sei

Anterior | Submeter | Página 3 de 3

8. Annex B: Post-test Questionnaire



Questionário Final: 5º ano

Olá!
Agora que terminaram todas as sessões do "Teaching Factories for Kids", por favor responde a este questionário para podermos aferir se houve progressos ao nível dos conhecimentos adquiridos.

O questionário é anónimo e a informação prestada serve apenas para fins de investigação.

Obrigada pelo teu tempo 😉

*Obrigatório

Género *

- Feminino
- Masculino

Idade *

- <10
- 10 - 11
- 12 - 14
- 15 - 18
- >18

Fiz a atividade *

- sozinho(a)
- em grupo

Modalidade da atividade: individual

Gostaste de fazer a atividade sozinho(a) ou preferias em grupo? Que vantagens ou desvantagens achas que tem fazer a atividade sozinho(a)? *

A sua resposta

Anterior Seguinte Página 2 de 7

Modalidade da atividade: grupo

Gostaste de fazer a atividade em grupo ou preferias individual? Que vantagens ou desvantagens achas que tem fazer a atividade em grupo? *

A sua resposta

Anterior Seguinte Página 3 de 7

Motivação final: 5º ano

Sentes-te motivado(a) para aprender mais sobre o fabrico inteligente, modelação e impressão 3D? *

- Nada motivado(a)
- Um pouco motivado(a)
- Muito motivado(a)
- Extremamente motivado(a)

Sentes-te motivado(a) a seguir uma carreira na área de Engenharia? *

- Nunca pensei nessa possibilidade.
- Já pensei e vejo como uma possibilidade.
- Já pensei nessa possibilidade mas não gosto.
- Sim, quero muito.

Anterior Seguinte Página 5 de 7

5º ano: Impressão 3D

0. Como classificas os teus conhecimentos em Impressão 3D? *

- Nulo (não sei nada)
- Básico (sei pouco)
- Médio (sei várias coisas)
- Avançado (sei muitas coisas)

1. Identifica uma vantagem da impressão 3D *

- Custos de manutenção
- Personalização de peças
- Uso de softwares específicos
- Não sei

2. A impressão 3D é uma tecnologia de *

- Produção formativa
- Produção aditiva
- Produção subtrativa
- Não sei

3. Um dos materiais utilizados na impressão 3D é *

- metal
- plástico PLA
- resina epóxi
- Não sei

4. A calibração da impressora *

- só se aplica a alguns modelos de impressora
- evita que o objeto modelado tenha irregularidades
- não é importante
- Não sei

5. O nozzle deve estar *

- muito junto à plataforma
- muito distante da plataforma
- perto da plataforma mas sem raspar nela
- Não sei

6. Para exportar um gráfico de um software de modulação devo escolher um ficheiro *

- ◯ .STL
- ◯ .jpg
- ◯ .pdf
- ◯ Não sei

Anterior | Seguinte | Página 4 de 7

Avaliação do conteúdo

Avalia as afirmações de 1 a 5, sendo que:
(1) Discordas totalmente
(2) Discordas
(3) Não concordas nem discordas
(4) Concordas
(5) Concordas totalmente

Os materiais apresentados são adequados para a aprendizagem da modelação e impressão 3D *

	1	2	3	4	5	
Discordo totalmente	◯	◯	◯	◯	◯	Concordo totalmente

Os materiais são compreensíveis e lógicos *

	1	2	3	4	5	
Discordo totalmente	◯	◯	◯	◯	◯	Concordo totalmente

Os materiais apresentados são relevantes para mim *

	1	2	3	4	5	
Discordo totalmente	◯	◯	◯	◯	◯	Concordo totalmente

Os materiais apresentados estão relacionados com ambientes reais *

	1	2	3	4	5	
Discordo totalmente	○	○	○	○	○	Concordo totalmente

O material apresentado pode ajudar-me a resolver problemas do meu dia a dia *

	1	2	3	4	5	
Discordo totalmente	○	○	○	○	○	Concordo totalmente

O material apresentado ajuda-me a recordar os conhecimentos anteriores que aprendi *

	1	2	3	4	5	
Discordo totalmente	○	○	○	○	○	Concordo totalmente

O material apresentado ajuda-me a interligar novos conceitos com experiências anteriores *

	1	2	3	4	5	
Discordo totalmente	○	○	○	○	○	Concordo totalmente

Comentário final

Faz uma apreciação geral sobre as atividades desenvolvidas.

Qual é a tua opinião sobre as atividades desenvolvidas? Conseguiste aprender coisas novas? O que gostaste mais e o que gostaste menos? *

A sua resposta

Se estiveres disponível para te fazer uma entrevista sobre as atividades desenvolvidas, deixa abaixo o teu e-mail.

A sua resposta

Anterior   Submeter   Página 7 de 7

9. Annex C: Individual Exploration Guide

Roteiro de exploração individual: Impressão 3D

Para que possas tirar o maior proveito desta atividade, é fundamental começares por ler o seguinte texto com atenção.

Introdução à Impressão 3D

A Impressão 3D é uma tecnologia de **produção aditiva** onde um modelo tridimensional é criado a partir de um modelo digital por sucessivas camadas de material. O material que vais usar para imprimir, chama-se **PLA**. Este material não emite gases nocivos e há uma grande variedade de cores (fluorescente, transparente, semitransparente ...), além disso pode ser impresso com todos os tipos de impressoras. Existem, no entanto, outros materiais para imprimir em 3D, como por exemplo ABS e Nylon.

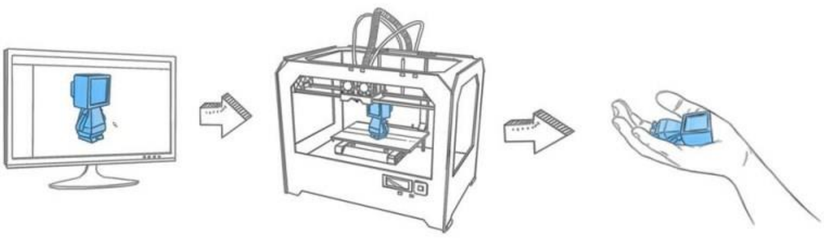


Figura 1. Processo de impressão 3D

Para evitar que o teu modelo tenha irregularidades, deves certificar-te que a impressora está calibrada e que o **Nozzle** não está demasiado próximo ou demasiado longe da **cama**, assim como mostra a figura abaixo.

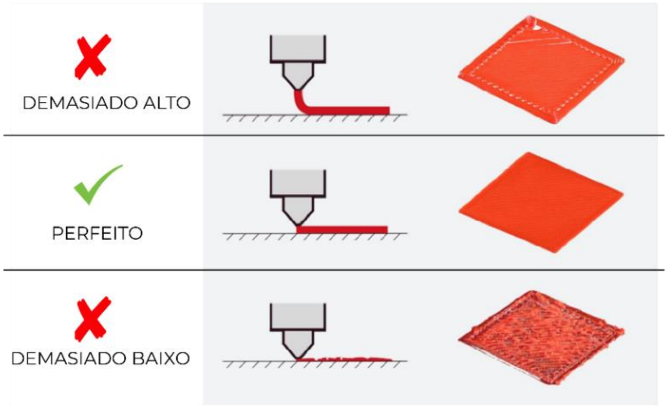


Figura 2. Distância do nozzle à plataforma

Relativamente ao acabamento do objeto, existem técnicas de pós produção como lixar, colar e pintar.

Orientações para a atividade:

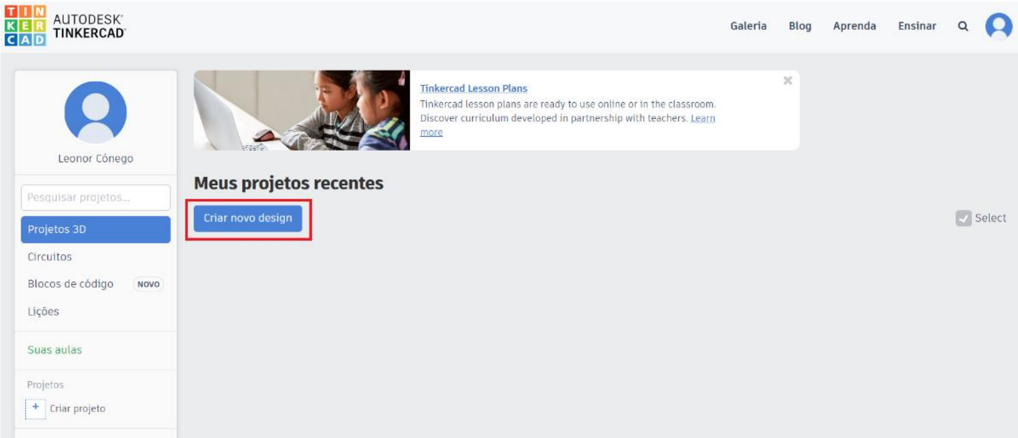
<u>Gerais</u>

1. Este guião está segmentado em duas partes. A primeira parte é sobre modelação e é para ser usado no dia 16 de abril. A segunda parte foca-se na impressão e é para ser usado no dia 23 de abril.
2. Deves fazer esta atividade de forma individual, sem conversar com os colegas. Para tal podes editar diretamente este documento no Word.
3. É recomendável que tomes notas. A última página deste documento destina-se exclusivamente a registos livres que queiras fazer ao longo da atividade.

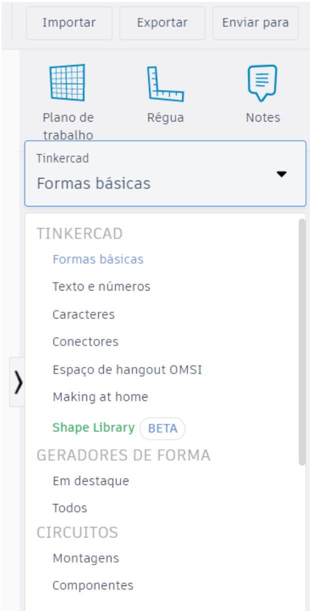
<u>Específicas</u>

PARTE 1: modelação 3D (16 de março)

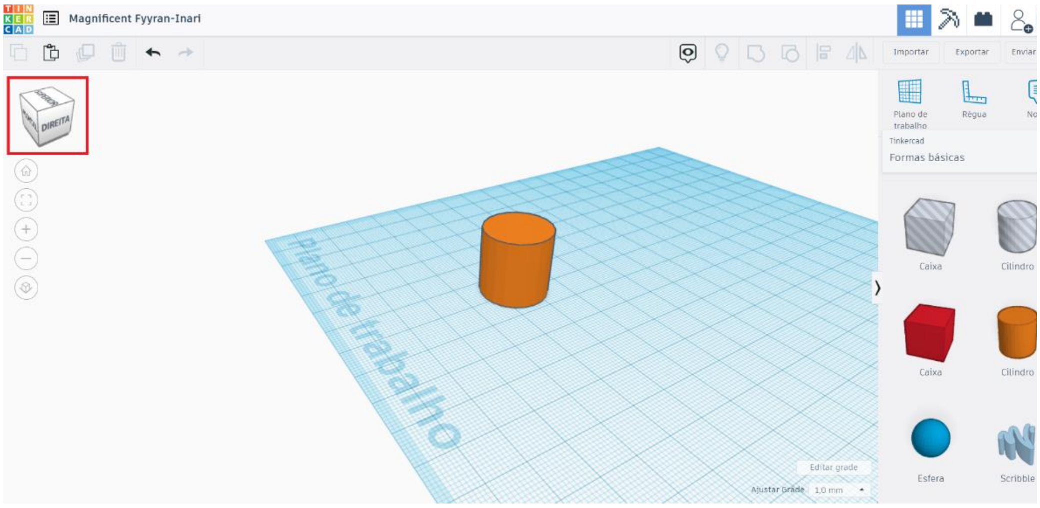
1. Para iniciar esta atividade, acede ao seguinte link: https://www.tinkercad.com/ e, depois de criares uma conta, carrega em “Criar novo design”.



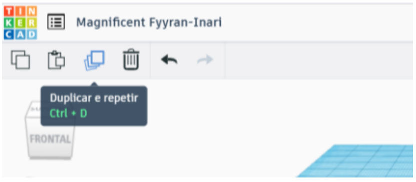
2. Sobre o lado direito do ecrã, como podes verificar, podes escolher trabalhar formas básicas, texto e números e uma série de outras possibilidades.



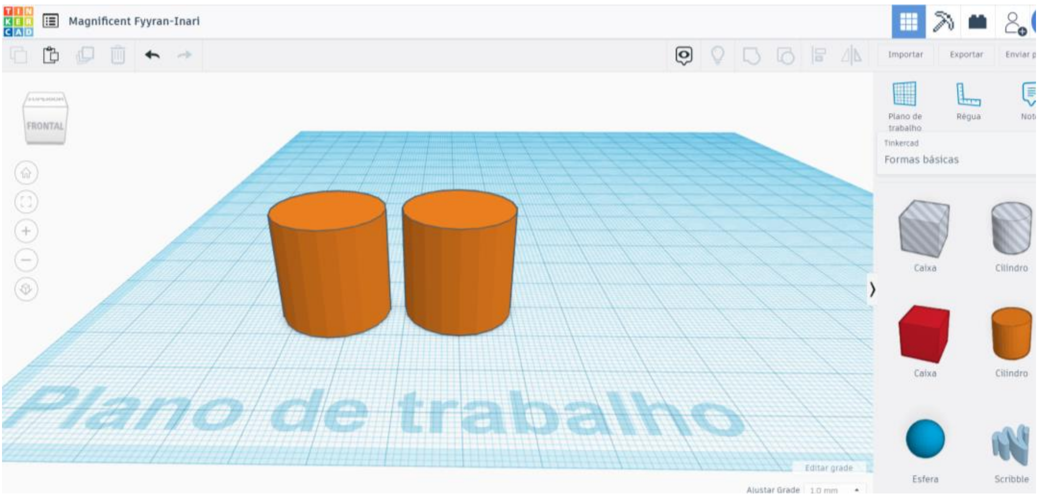
3. Pega por exemplo num cilindro e arrasta-o para o plano de trabalho (esse quadriculado azul no centro do ecrã), explorando as suas diferentes perspetivas. Para tal, utiliza o cubo que se encontra sobre o lado superior esquerdo do ecrã. Se preferires, poderás mudar as perspetivas utilizando o rato: experimenta **a)** premir o botão direito do rato e movê-lo em simultâneo e **b)** carregar no *scroll* do rato e movê-lo também em simultâneo. Para fazer *Zoom In* ou *Zoom Out*, desliza o *scroll* do rato.



4. Agora que dominas as perspetivas, clica no cilindro e faz uma cópia. Para isso deves carregar no objeto e depois clicar em “Duplicar e repetir”.

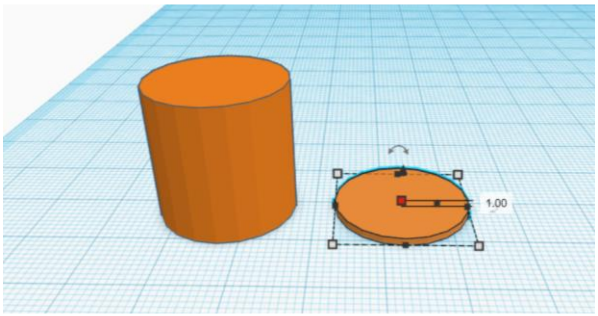


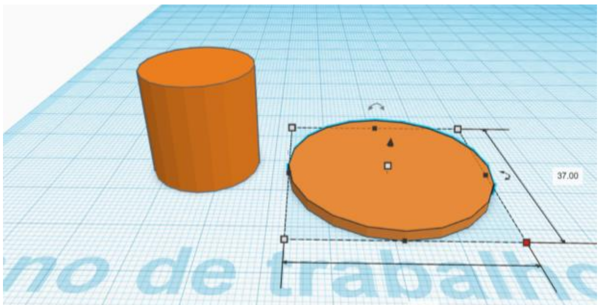
5. Agora os dois objetos estão sobrepostos. Clica nele e desliza para o lado!



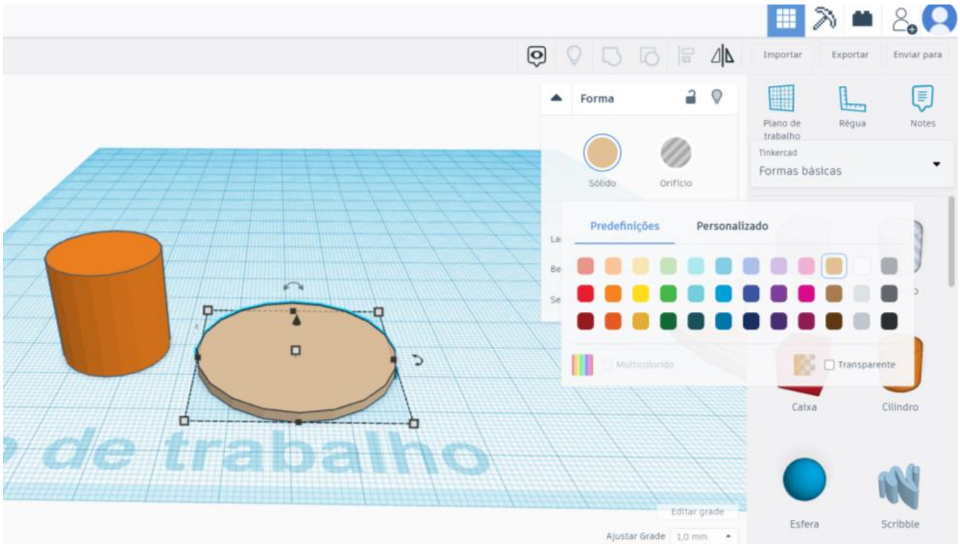
6. Clica num dos cilindros e **a)** reduz a sua altura e **b)** aumenta a sua escala interagindo com os quadrados que aparecem ao carregar no objeto. Ao fazeres a escala (premindo o quadradinho de uma ponta), se carregares na tecla *shift* em simultâneo, o cilindro vai crescer proporcionalmente. Se não o fizeres vai crescer

mais para um dos lados, o que poderá ser necessário dependendo do que estás a modelar. Para uma pizza, que é o desafio que se põe a seguir, quanto mais redonda, melhor. Por isso vamos lá premir o *shift*!

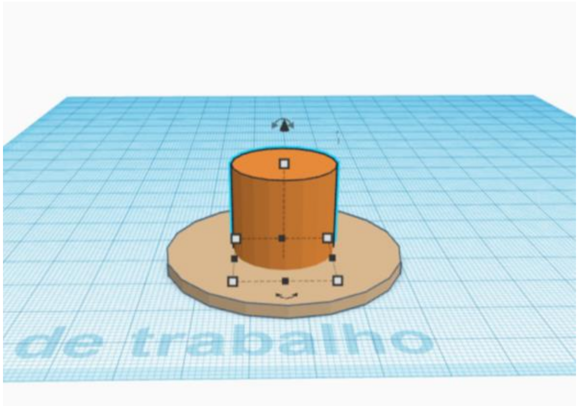
a) 

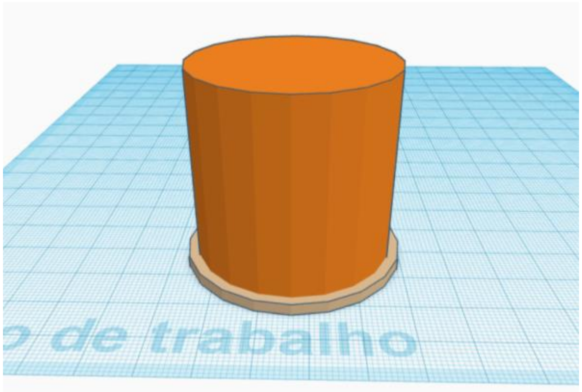
b) 

7. Podes mudar a cor do sólido, carregando no objeto e depois em “Sólido” (junto do “Orifício”) e mudando a sua cor predefinida para se aproximar de uma verdadeira pizza!

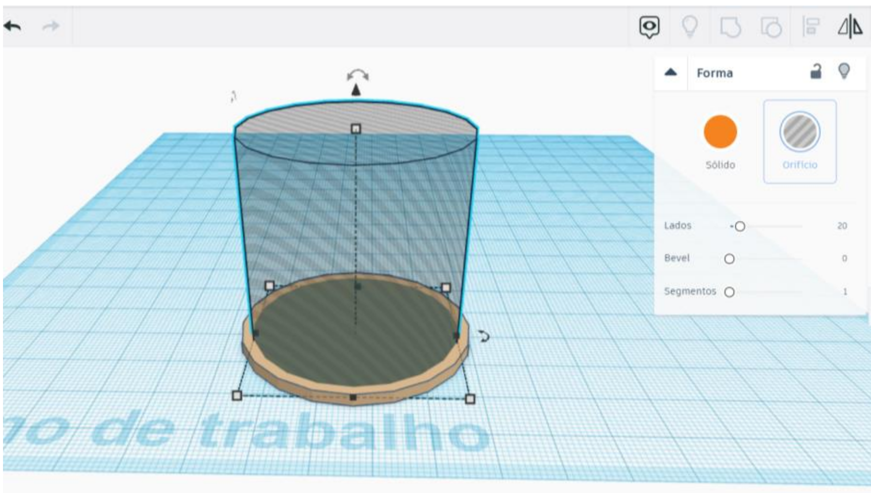


8. Agora carrega no cilindro do lado e arrasta para cima do cilindro mais baixo (e de maior dimensão) e aumenta a sua escala proporcionalmente, como fizeste no passo **6.b)**. Poderá ser preciso reajustares a posição de forma a ficar centrado.

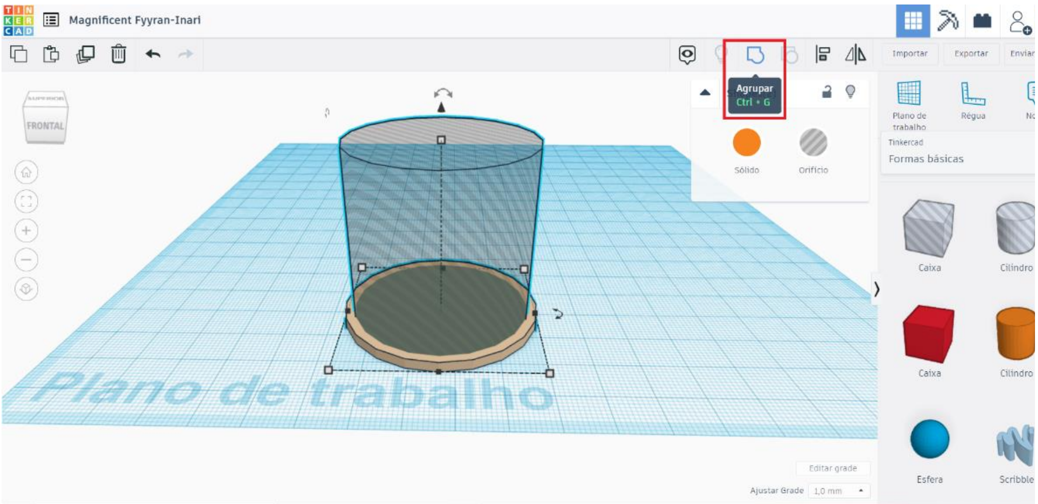




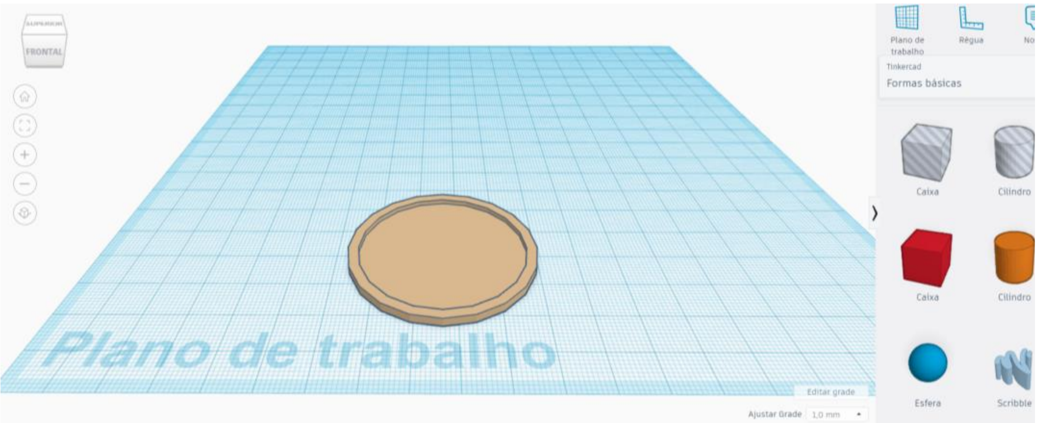
9. Agora carrega no cilindro mais alto e carrega em “Orifício” de forma a ficar transparente e sobe ligeiramente esse sólido, carregando na seta preta que aponta para cima (só um bocadinho, de forma a ficar intersetada no sólido mais baixo).



10. Para selecionares os dois objetos ao mesmo tempo, clica num deles primeiro, depois pressiona a tecla *shift* e sem largar, carrega no outro cilindro. Agora que ambos estão selecionados podes largar a tecla *Shift* e carregar em “Agrupar”.

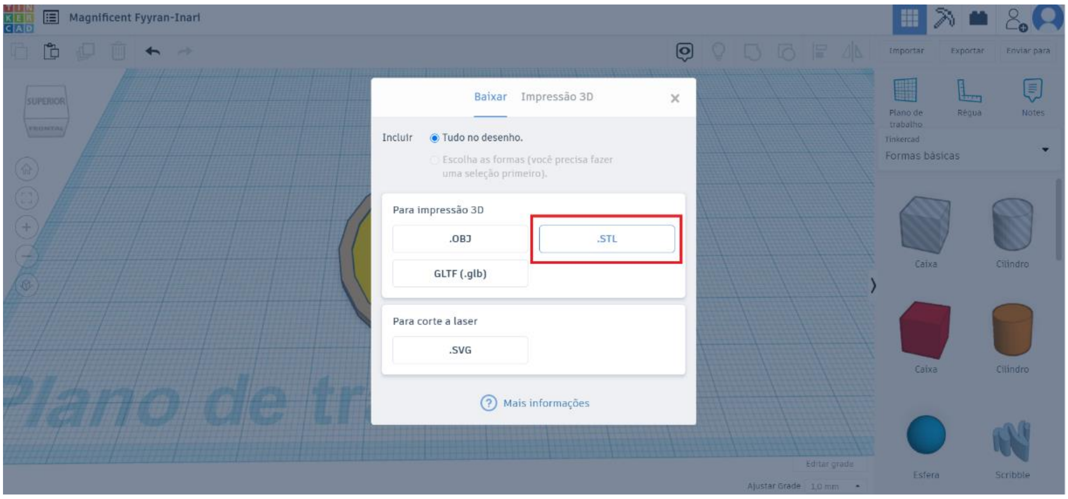


11. O resultado deverá ser este. Parece-se com o pão de pizza! Agora poderás explorar um pouco as outras formas e criar ingredientes para a pizza.

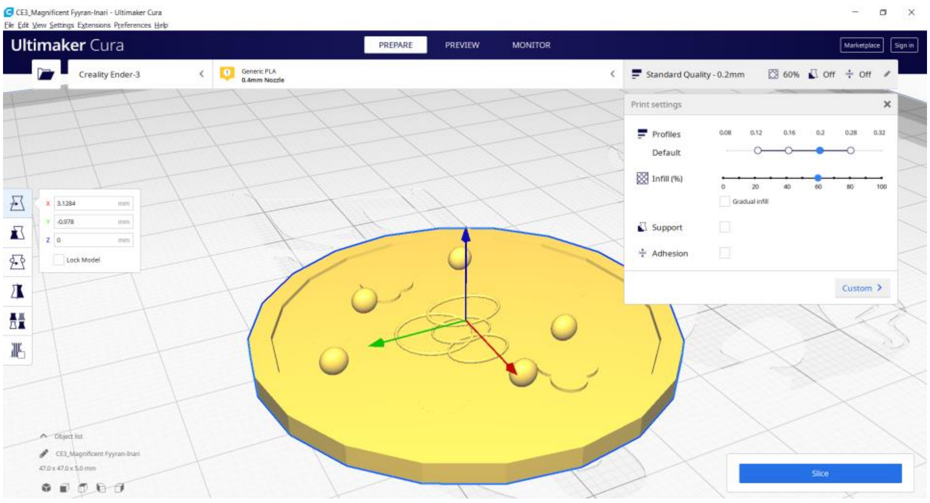


12. Infelizmente não temos tempo nem recursos para imprimir as pizzas de todos os alunos mas já que aprendeste a modelar, agora vamos aprender como poderias exportar este modelo para depois imprimir. Carrega em “exportar” e escolhe o

ficheiro .STL, uma vez que é um formato universal. Desta forma a impressora da tua escola conseguirá reconhecer o objeto modelado. Será descarregado um ficheiro que, se quisesses imprimir deverias importar para um *software* como o *Cura*.



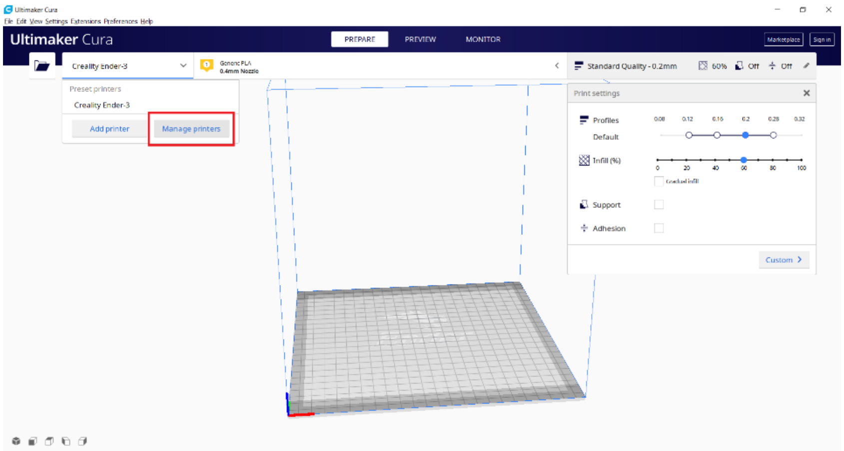
No *Cura* o aspeto seria este e seria necessário definir alguns parâmetros de impressão que vais aprender na próxima sessão do *Teaching Factories 4 Kids* (dia 26 de abril).



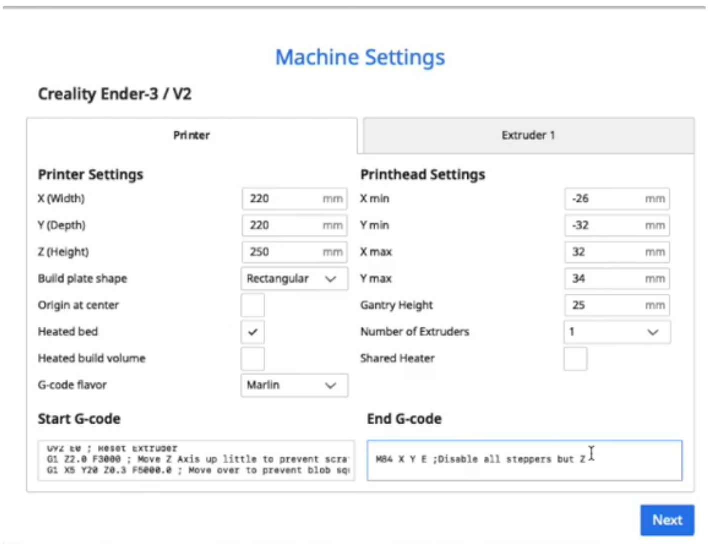
Se acabaste esta atividade antes do tempo terminar, podes fazer outras modelações livremente, explorando outras formas.

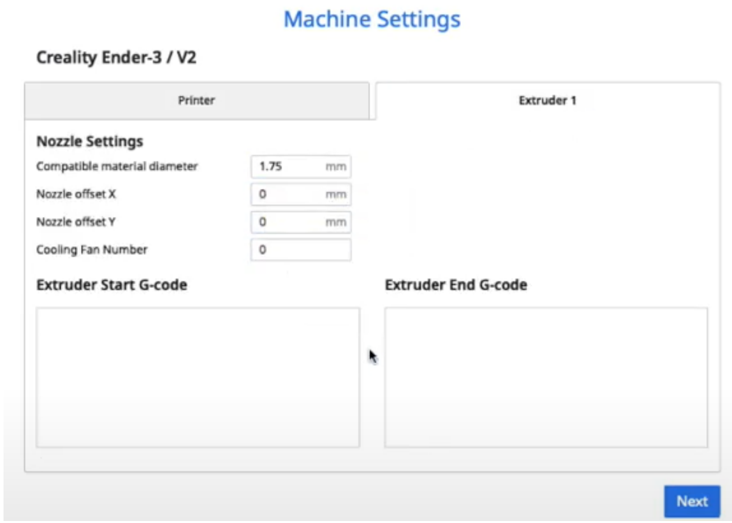
PARTE 2: impressão 3D (23 de março)

1. Para iniciar esta atividade, vais precisar de ouvir com atenção as instruções do Professor relativas à configuração da impressora no programa *Cura*. Como só existem 2 impressoras 3D e o processo de impressão é demorado, nem todos terão oportunidade de imprimir o seu próprio ingrediente de pizza. Mas presta atenção às instruções do Professor. Primeiro temos de nos certificar que a impressora “Creality Ender-3/V2” está configurada no Cura, para isso, carrega em “Manage printers”, este botão encontra-se do lado esquerdo superior:

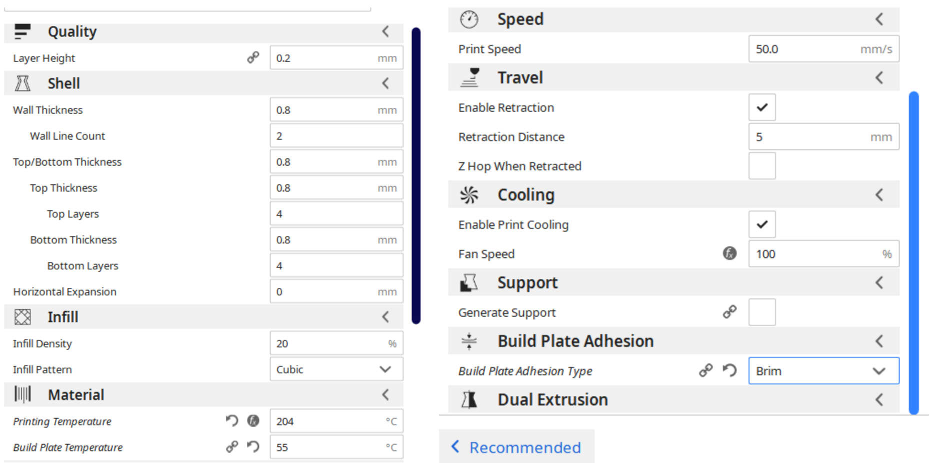


As definições devem ser estas para que o programa reconheça a impressora da tua escola:



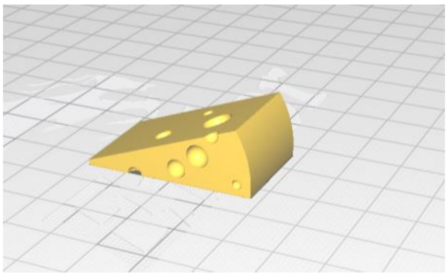


2. Depois de termos a impressora configurada, temos de definir alguns parâmetros como a qualidade, o "infill" (enchimento), "Shell" (casco), "speed" (velocidade), "cooling" (refrigeração) e o "build plate adhesion" (aderência à plataforma), que depende do modelo que queremos imprimir. Para o queijo que vamos imprimir, as definições poderão ser estas:



01. Faz uma pesquisa dos 3 diferentes tipos de adesão à plataforma existentes, adicionando na tabela uma imagem de cada uma delas com o seu nome. Depois justifica qual deles te parece mais adequado para este formato de queijo e para a finalidade que vai ter (ser agarrado por um manipulador robótico e colocado em cima da massa da pizza).

(Imagens)		
(Nomes)		



02. Para este formato de queijo e para a sua finalidade, o tipo de adesão que me parece mais adequado é o________________ porque________ ____ ____ ____.

Para ajudar ainda mais nesta adesão, por vezes utiliza-se fita cola azul ou fixador de cabelo diretamente na plataforma.

Além disso, antes ainda de começar a impressão, tem de se **introduzir o filamento** e tratar da **calibração da impressora**.

03. Faz uma pesquisa para descobrires por que é se deve calibrar a impressora 3D e aponta aqui o que descobriste: ____

____

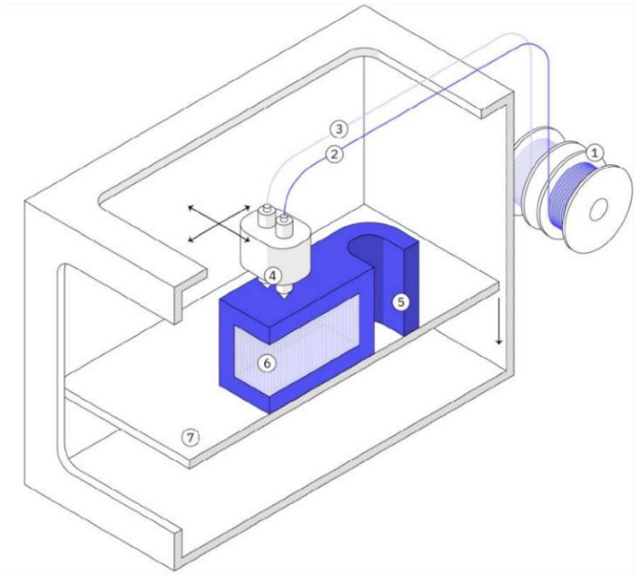
____

____

____

____.

04. Enquanto aguardas a impressão poderás ainda fazer uma pesquisa que te ajude a decifrar os nomes para completar a legenda da figura abaixo:



Indica os nomes abaixo:

1- ________________________________

2- ________________________________

3- ________________________________

4- ________________________________

5- ________________________________

6- ________________________________

7- ________________________________

05. Como última tarefa, desenvolve um pequeno resumo das atividades realizadas hoje e no dia 16 de abril.

PEQUENO RESUMO ____
____
____
____
____.

Envia este documento por e-mail para: leonor.conego@gmail.com e de seguida responde a este **questionário final**: https://forms.gle/A5tdxQDZqVH26yPn6.

Zona de registos livres

10. Annex D: Collaborative Exploration Guide

Roteiro de exploração colaborativo: Impressão 3D

Para que possam tirar o maior proveito desta atividade, é fundamental começarem por ler o seguinte texto com atenção.

Introdução à Impressão 3D

A Impressão 3D é uma tecnologia de **produção aditiva** onde um modelo tridimensional é criado a partir de um modelo digital por sucessivas camadas de material. O material que vão usar para imprimir, chama-se **PLA**. Este material não emite gases nocivos e há uma grande variedade de cores (fluorescente, transparente, semitransparente ...), além disso pode ser impresso com todos os tipos de impressoras. Existem, no entanto, outros materiais para imprimir em 3D, como por exemplo ABS e Nylon.

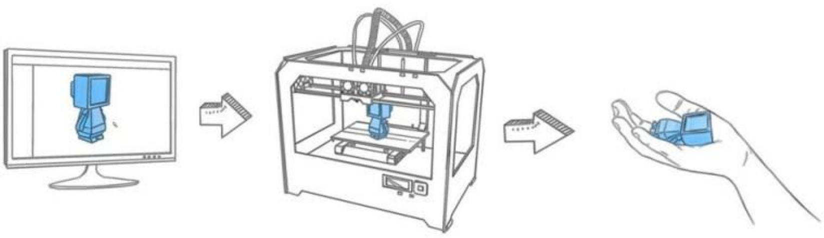


Figura 3. Processo de impressão 3D

Para evitar que o vosso modelo tenha irregularidades, devem certificar-se que a impressora está calibrada e que o **Nozzle** não está demasiado próximo ou demasiado longe da **cama**, assim como mostra a figura abaixo.

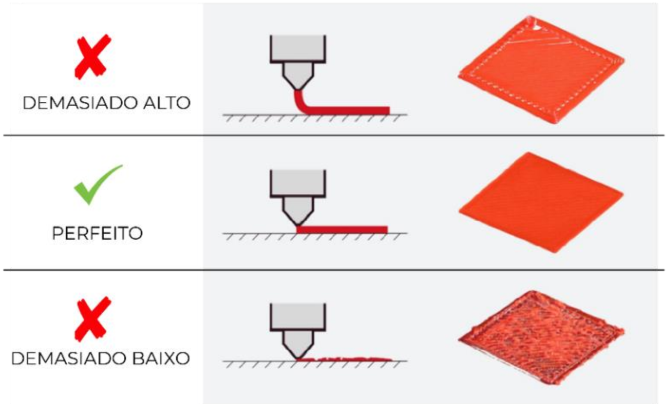


Figura 4. Distância do nozzle à plataforma

Relativamente ao acabamento do objeto, existem técnicas de pós produção como lixar, colar e pintar.

Orientações para a atividade:

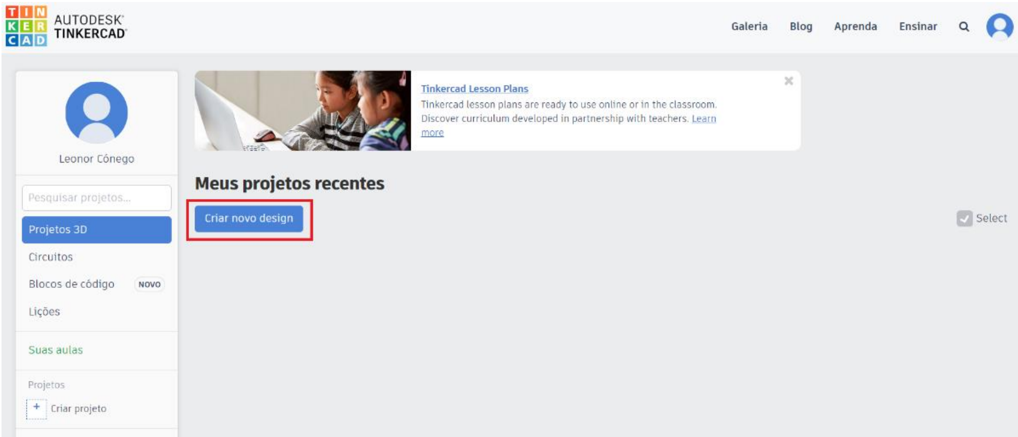
Gerais

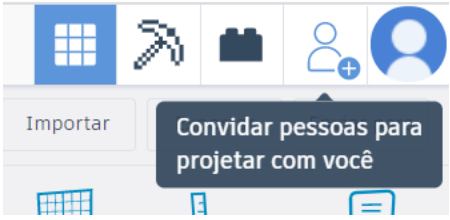
4. Este guião está segmentado em duas partes. A primeira parte é sobre modelação e é para ser usado no dia 16 de abril. A segunda parte foca-se na impressão e é para ser usado no dia 23 de abril.
5. Esta atividade será feita de grupo e como tal devem desde já definir quem será o porta-voz do grupo. Notem que não precisarão de conversar diretamente com os vossos colegas. O porta-voz deve partilhar este documento no *Google drive* para que possam trabalhar colaborativamente.
6. É recomendável que tomem notas. A última página deste documento destina-se exclusivamente a registos livres que queiram fazer ao longo da atividade.

Específicas

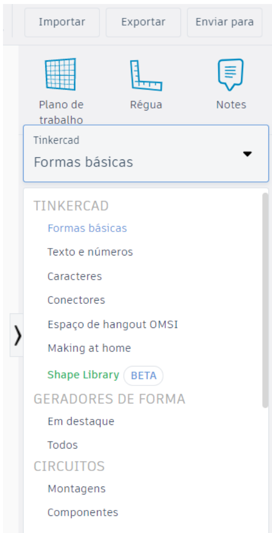
PARTE 1: modelação 3D (16 de março)

13. Para iniciar esta atividade, acedam ao seguinte link: https://www.tinkercad.com/ e, depois de criarem uma conta, um membro do grupo (o porta voz, por exemplo) carrega em "Criar novo design" e convida os colegas de forma a poderem trabalhar no mesmo projeto, de forma colaborativa.



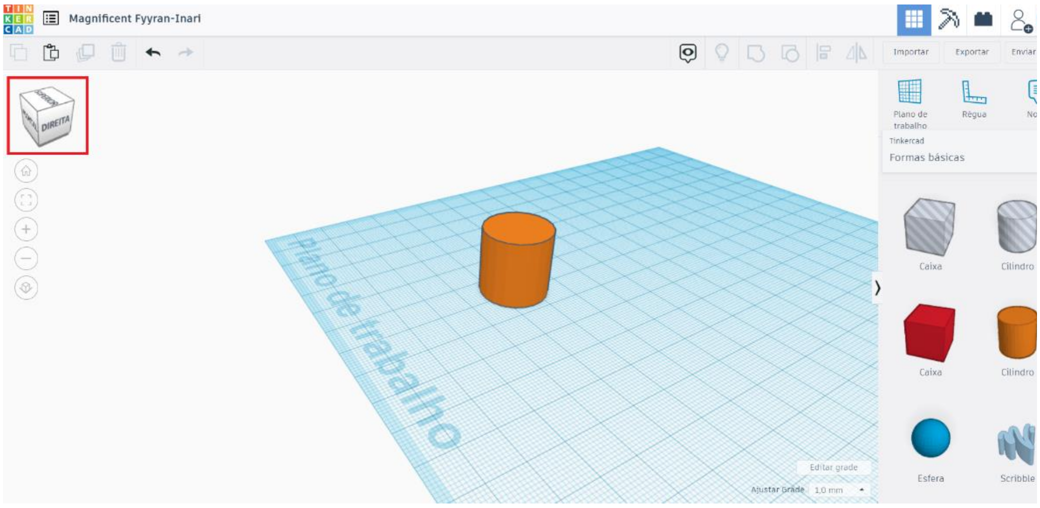


14. Sobre o lado direito do ecrã, como podem verificar, é possível trabalhar formas básicas, texto e números e uma série de outras possibilidades.

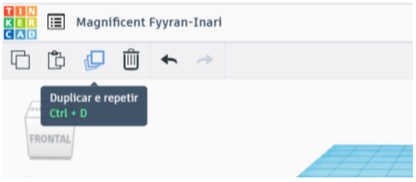


15. Peguem por exemplo num cilindro e arrastem-no para o plano de trabalho (esse quadriculado azul no centro do ecrã), explorando as suas diferentes perspetivas. Para tal, utilizem o cubo que se encontra sobre o lado superior esquerdo do ecrã. Se preferirem, poderão mudar as perspetivas utilizando o rato: experimentem **a)** premir o botão direito do rato e movê-lo em simultâneo e **b)** carregar no *scroll* do

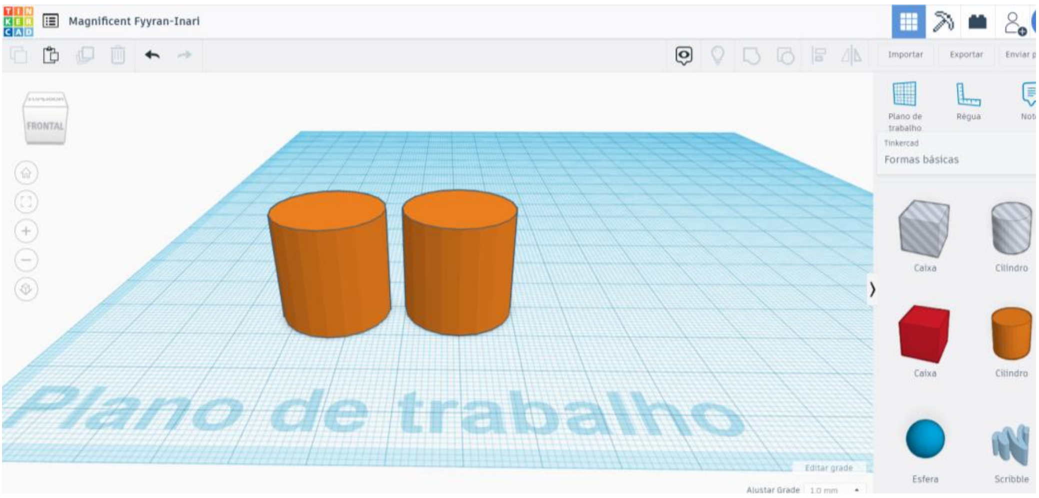
rato e movê-lo também em simultâneo. Para fazer *Zoom In* ou *Zoom Out*, deslizem o *scroll* do rato.



16. Agora que dominam as perspetivas, cliquem no cilindro e façam uma cópia. Para isso devem carregar no objeto e depois clicar em “Duplicar e repetir”.

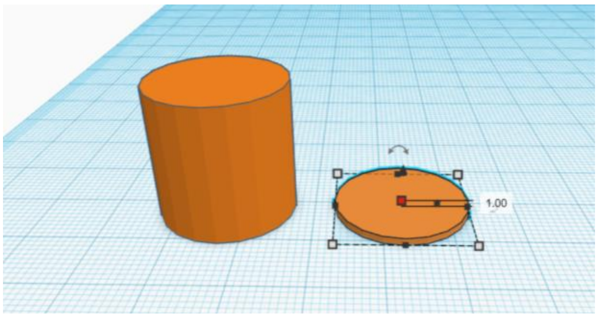


17. Agora os dois objetos estão sobrepostos. Cliquem nele e deslizem para o lado!

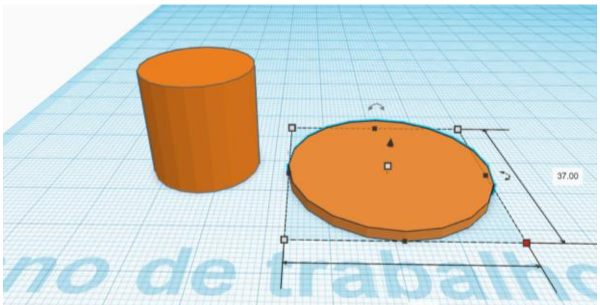


18. Cliquem num dos cilindros e **a)** reduzam a sua altura e **b)** aumentem a sua escala interagindo com os quadrados que aparecem ao carregar no objeto. Ao fazerem a

escala (premindo o quadradinho de uma ponta), se carregarem na tecla *shift* em simultâneo, o cilindro vai crescer proporcionalmente. Se não o fizerem vai crescer mais para um dos lados, o que poderá ser necessário dependendo do que estão a modelar. Para uma pizza, que é o desafio que se põe nesta atividade, quanto mais redonda, melhor. Por isso vamos lá premir o *shift*!

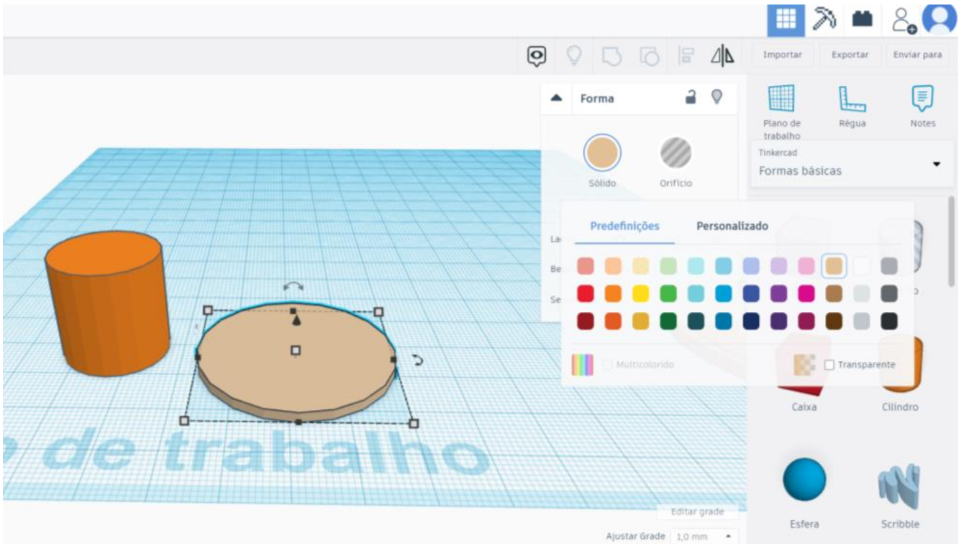


b)

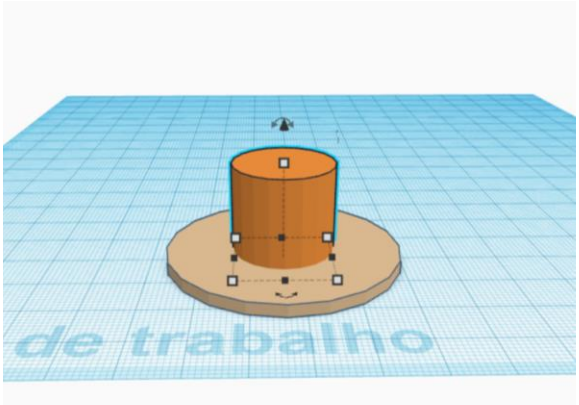


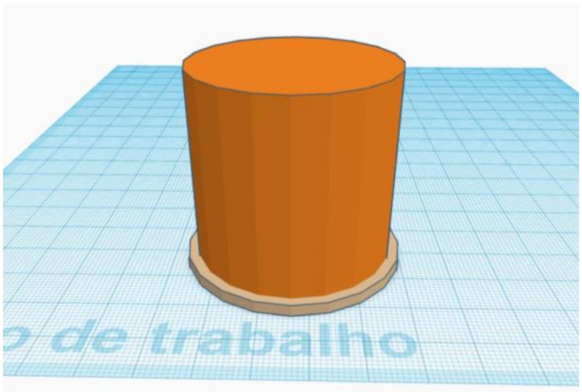
b)

19. Podem mudar a cor do sólido, carregando no objeto e depois em “Sólido” (junto do “Orifício”) e mudando a sua cor predefinida para se aproximar de uma verdadeira pizza!

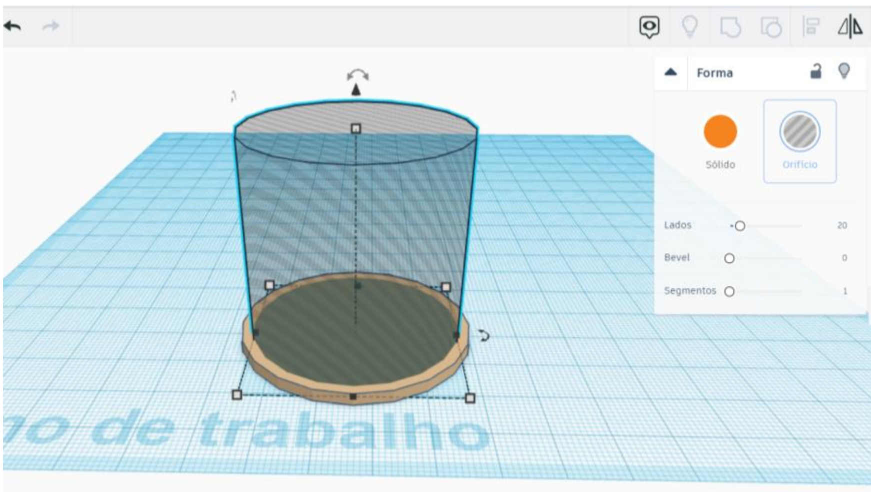


20. Agora carreguem no cilindro do lado e arrastem-no para cima do cilindro mais baixo (e de maior dimensão) e aumentem a sua escala proporcionalmente, como fizeram no passo **6.b)**. Poderá ser preciso reajustar a posição de forma a ficar centrado.

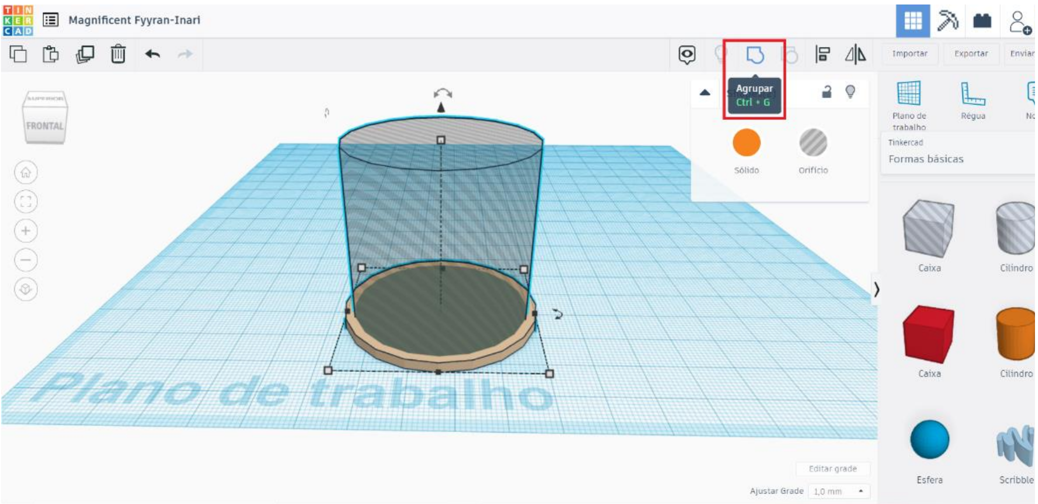




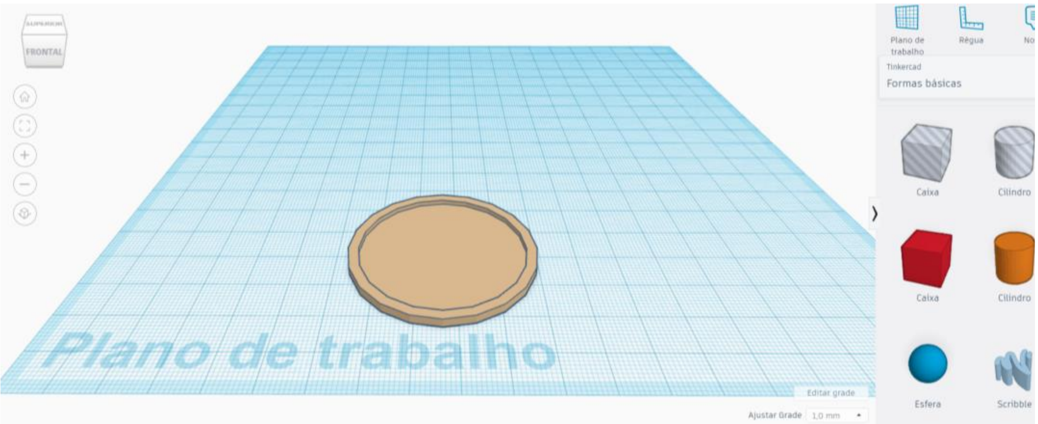
21. Agora carreguem no cilindro mais alto e depois cliquem em “Orifício” de forma a ficar transparente e subam ligeiramente esse sólido, carregando na seta preta que aponta para cima (só um bocadinho, de forma a ficar intersetada no sólido mais baixo).



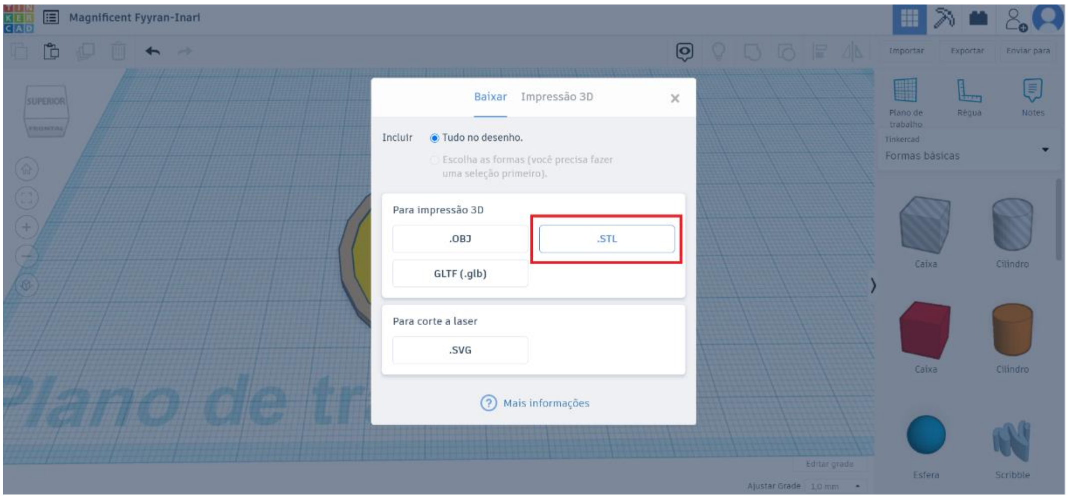
22. Para selecionarem os dois objetos ao mesmo tempo, cliquem num deles primeiro, depois pressionem a tecla *shift* e sem largar, carreguem no outro cilindro. Agora que ambos estão selecionados podem largar a tecla *Shift* e carregar em “Agrupar”.



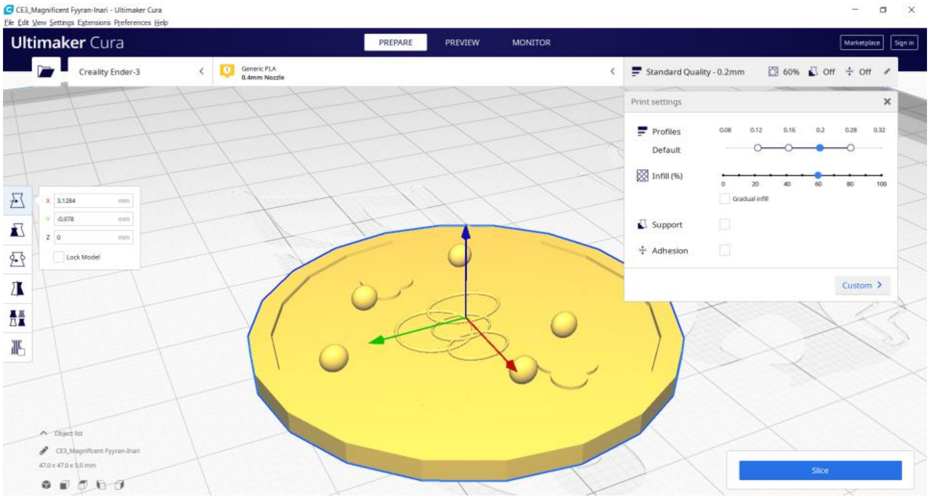
23. O resultado deverá ser este. Parece-se com o pão de pizza! Agora poderão explorar um pouco as outras formas e criar ingredientes para a pizza.



24. Infelizmente não temos tempo nem recursos para imprimir as pizzas de todos os alunos mas já que aprendeste a modelar, agora vamos aprender como poderiam exportar este modelo para depois imprimir. Carreguem em “exportar” e escolham o ficheiro **.STL**, uma vez que é um formato universal. Desta forma a impressora da vossa escola conseguirá reconhecer o objeto modelado. Será descarregado um ficheiro que, se quisessem imprimir deveriam importar para um *software* como o *Cura*.



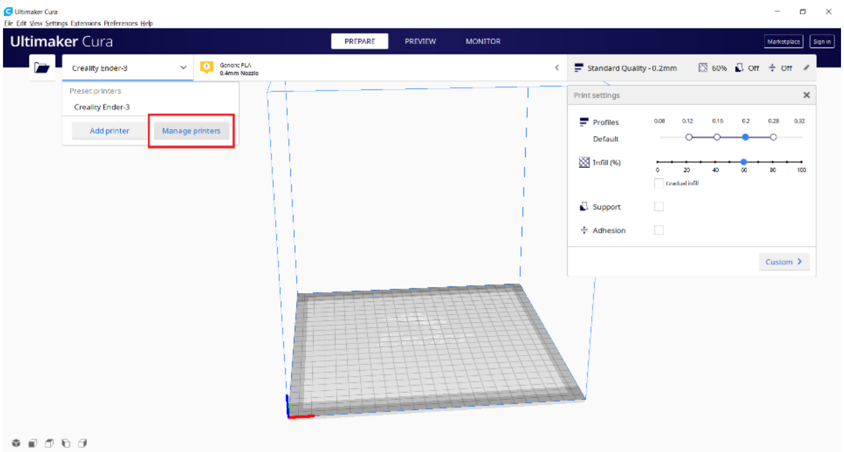
No *Cura* o aspeto seria este e seria necessário definir alguns parâmetros de impressão que vão aprender na próxima sessão do *Teaching Factories 4 Kids* (dia 26 de abril).



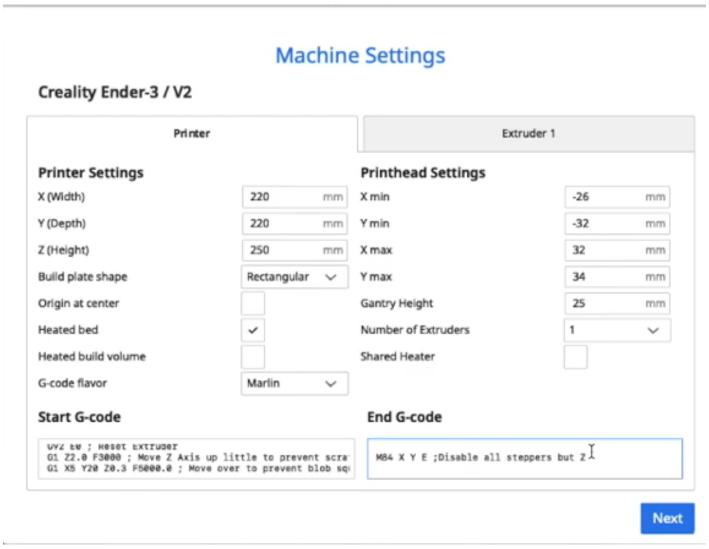
Se acabaram esta atividade antes do tempo terminar, podem fazer outras modelações livremente, explorando outras formas.

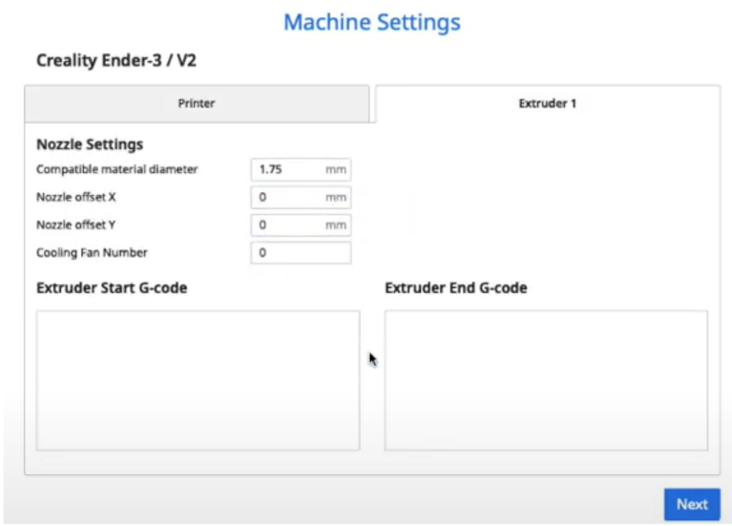
PARTE 2: impressão 3D (23 de março)

3. Para iniciar esta atividade, vão precisar de ouvir com atenção as instruções do Professor relativas à configuração da impressora no programa *Cura*. Como só existem 2 impressoras 3D e o processo de impressão é demorado, nem todos terão oportunidade de imprimir o seu próprio ingrediente de pizza. Mas presta atenção às instruções do Professor. Primeiro temos de nos certificar que a impressora "Creality Ender-3/V2" está configurada no Cura, para isso, devem carregar em "Manage printers", este botão encontra-se do lado esquerdo superior:

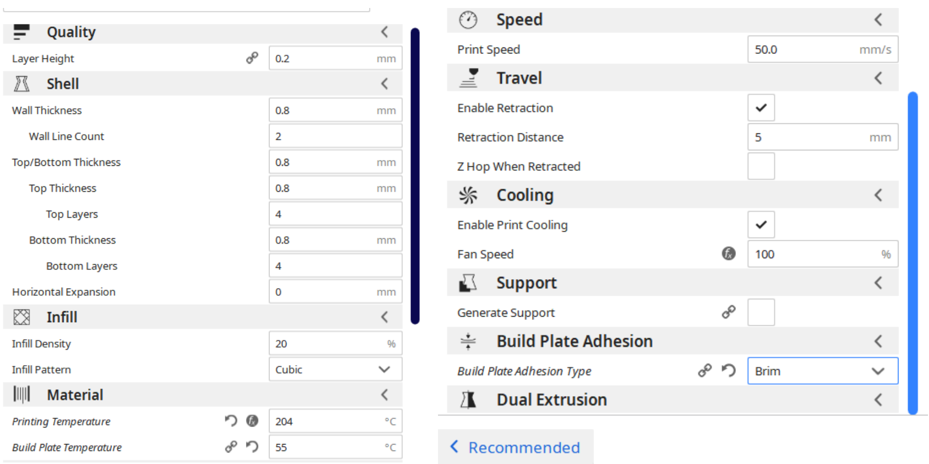


As definições devem ser estas para que o programa reconheça a impressora da vossa escola:



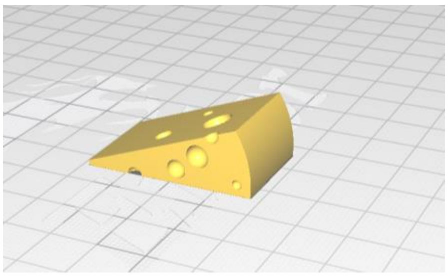


4. Depois de termos a impressora configurada, temos de definir alguns parâmetros como a qualidade, o "infill" (enchimento), "Shell" (casco), "speed" (velocidade), "cooling" (refrigeração) e o "build plate adhesion" (aderência à plataforma), que depende do modelo que queremos imprimir. Para o queijo que vamos imprimir, as definições poderão ser estas:



01. Façam uma pesquisa dos 3 diferentes tipos de adesão à plataforma existentes, adicionando na tabela uma imagem de cada uma delas com o seu nome. Depois justifiquem qual deles vos parece mais adequado para este formato de queijo e para a finalidade que vai ter (ser agarrado por um manipulador robótico e colocado em cima da massa da pizza).

(Imagens)		
(Nomes)		



02. Para este formato de queijo e para a sua finalidade, o tipo de adesão que nos parece mais adequado é o________________ porque________

____

____

____.

Para ajudar ainda mais nesta adesão, por vezes utiliza-se fita cola azul ou fixador de cabelo diretamente na plataforma.

Além disso, antes ainda de começar a impressão, tem de se **introduzir o filamento** e tratar da **calibração da impressora**.

03. Façam uma pesquisa para descobrir por que é se deve calibrar a impressora 3D e apontem aqui o que descobriram:

____

____

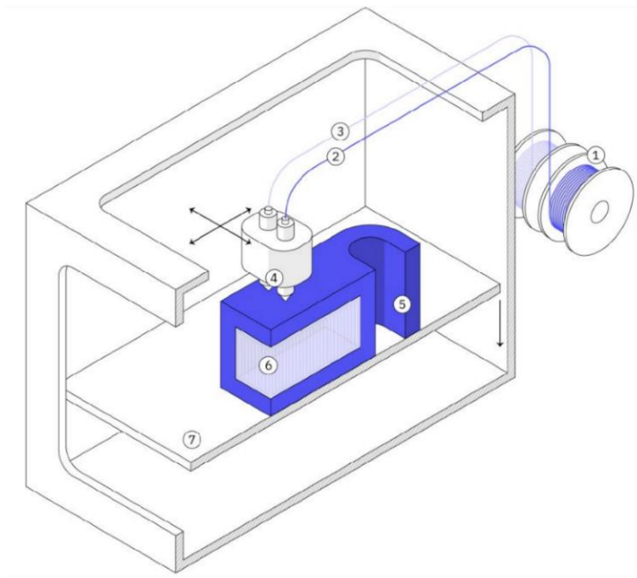
____

____

____

____.

04. Enquanto aguardam a impressão poderão ainda fazer uma pesquisa que vos ajude a decifrar os nomes para completar a legenda da figura abaixo:



Indiquem os nomes abaixo:

8- ______________________________

9- ______________________________

10- ______________________________

11- ______________________________

12- ______________________________

13- ______________________________

14- ______________________________

05. Como última tarefa, desenvolvam um pequeno resumo das atividades realizadas hoje e no dia 16 de abril.

PEQUENO RESUMO

____

____

____

____

____.

O porta voz do grupo deverá enviar este documento por e-mail para: leonor.conego@gmail.com e todos os membros do grupo devem responder ao **questionário final**: https://forms.gle/A5tdxQDZqVH26yPn6.

Zona de registos livres

11. Annex E: Informed Consent Protocol

Protocolo de consentimento informado: Entrevista

Eu, ____ encarregado de educação do aluno(a) ____.

autorizo a sua participação no estudo da autoria de Leonor Cónego (aluna da Faculdade de Engenharia da Universidade do Porto), orientado pelo Professor Doutor Gil Gonçalves (Professor Auxiliar na FEUP) e coorientado pelo Professor Doutor António Baía Reis (Professor Auxiliar Convidado na FEUP) e Professor Rui Pinto (Assistente Convidado na FEUP) no âmbito da dissertação de Mestrado em Multimédia, com especialização em Educação.

Foram-me explicados e compreendo os objetivos principais deste estudo que foram referidos previamente à entrevista. Entendi e aceito que o meu educando(a) responda a uma entrevista, que será gravada (imagem e áudio) e explora questões sobre as atividades desenvolvidas presencialmente na “escolaglobal”.

Compreendo que a participação neste estudo é voluntária, podendo o meu educando(a) desistir a qualquer momento, sem que essa decisão se reflita em qualquer prejuízo.

Ao participar neste trabalho, o meu educando(a) está a colaborar para o desenvolvimento da investigação na área da educação, não sendo, contudo, acordado qualquer benefício direto ou indireto pela sua colaboração. Entendo, ainda, que toda a informação obtida neste estudo será estritamente confidencial e que a identidade do meu educando(a) nunca será revelada em qualquer relatório ou publicação, ou a qualquer pessoa não relacionada diretamente com este estudo, a menos que eu o autorize por escrito.

____

(Assinatura do Encarregado de Educação)

_____ /_____ / 2021

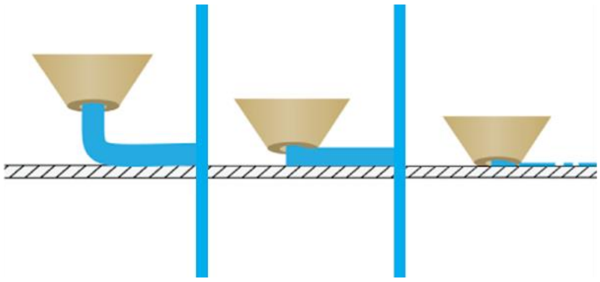
12. Annex F: Students' Interview

Questões de conhecimento

1. Identifica uma vantagem da impressão 3D
   a) Custos de manutenção
   b) Personalização de peças
   c) Uso de softwares específicos
   d) Não sei
2. A impressão 3D é uma tecnologia de
   e) Produção formativa
   f) Produção aditiva
   g) Produção subtrativa
   h) Não sei
3. Um dos materiais utilizados na impressão 3D é…
   i) metal
   j) plástico PLA
   k) resina epóxi
   l) Não sei

4. A calibração da impressora…
   m) só se aplica a alguns modelos de impressora
   n) evita que o objeto modelado tenha irregularidades
   o) não é importante
   p) Não sei

5. O nozzle deve estar…
   q) muito junto à plataforma
   r) muito distante da plataforma
   s) perto da plataforma, mas sem raspar nela
   t) Não sei



6. Para exportar um gráfico de um software de modulação devo escolher um ficheiro
   u) .STL
   v) .jpg

w) .pdf

x) Não sei

Questões Individual *versus* Colaborativo

Fizeste a atividade sozinho ou em grupo?

SOZINHO

1. No geral gostaste de fazer as atividades de forma individual? (ou preferias ter feito em grupo? Porquê?)
2. Que vantagens vês em fazer a atividade sozinho? (Sentiste-te mais focado, com menos distrações?)
3. O que é que achaste mais desafiante ou menos positivo em fazer a atividade sozinho(a)?
4. Achas que foi mais vantajoso fazer a atividade sozinho(a) na aula de modelação ou na aula de impressão 3D? E porquê?

GRUPO

1. No geral gostaste de fazer as atividades em grupo? (ou preferias ter feito sozinho(a)? Porquê?)
2. Que vantagens vês em fazer a atividade em grupo? (Partilhar ideias com colegas ou distribuir tarefas?)
3. O que é que achaste mais desafiante ou menos positivo em fazer a atividade em grupo?
4. Achas que foi mais vantajoso fazer a atividade em grupo na aula de modelação ou na aula de impressão 3D? E porquê?

Questões Engenharia

1. No final do questionário, perguntávamos se já tinhas pensado em seguir uma carreira na área da engenharia… Tens ideia que tipo de profissão pode ter um engenheiro?
2. Entendes a ligação que tem as atividades que fizemos e os conceitos abordados com a engenharia?

13. Annex G: Industry Profile

Table 18 Industry profile: advanced manufacturing. Extracted and adapted from World Economic Forum (2020)

Emerging skills	
1. Technology use, monitoring and control	
2. Critical thinking and analysis	
3. Active learning and learning strategies	
4. Leadership and social influence	
5. Analytical thinking and innovation	
6. Reasoning, problem-solving and ideation	
7. Complex problem-solving	
8. Service orientation	
9. Resilience, stress tolerance and flexibility	
10. Technology design and programming	
11. Troubleshooting and user experience	
12. Systems analysis and evaluation	
13. Coordination and time management	
14. Quality control and safety awareness	
15. Attention to detail, trustworthiness	
Current skills in focus of existing reskilling/upskilling programs	
1. Technology use, monitoring and control	
2. Analytical thinking and innovation	
3. Complex problem-solving	
4. Technology installation and maintenance	
5. Critical thinking and analysis	
6. Technology design and programming	
7. Quality control and safety awareness	
8. Service orientation	
9. Management of financial, material resources	
10. Leadership and social influence	
Technology adoption in Industry	
Cloud Computing	89%

Internet of things and connected devices	87%
Robots, non-humanoid (industrial automation, drones, etc.)	85%
E-commerce and digital trade	83%
Big data analytics	76%
Encryption and cyber security	74%
3D and 4D printing and modeling	74%
Artificial intelligence (e.g. machine learning, neural networks, NLP)	68%
Text, image and voice processing	62%
Power storage and generation	58%

Barriers to adoption of new technologies

Skills gaps in the local labor market	67.7%
Skills gaps among organization's leadership	54.8%
Inability to attract specialized talent	45.2%
Shortage of investment capital	41.9%
Insufficient understanding of opportunities	38.7%
Lack of flexibility of the regulatory framework	25.8%
Lack of flexibility in hiring and firing	19.4%
Lack of interest among leadership	9.7%
Other	6.5%

Emerging jobs

Role identified as being in high demand

Business Development Professionals
Software and Applications Developers
Sales Representatives, Wholesale and Manufacturing, Technic…
Robotics Engineers
Internet of Things Specialists
Data Analysts and Scientists
Project Managers
Power Production Plant Operators
Assembly and Factory Workers
AI and Machine Learning Specialists

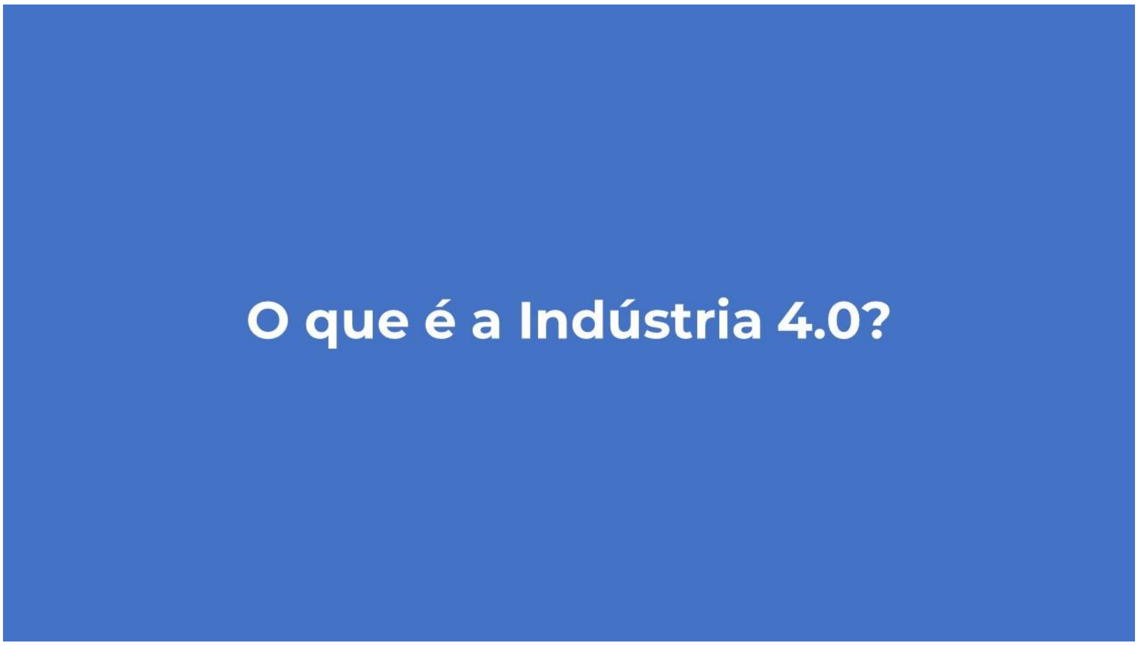
Redundant jobs

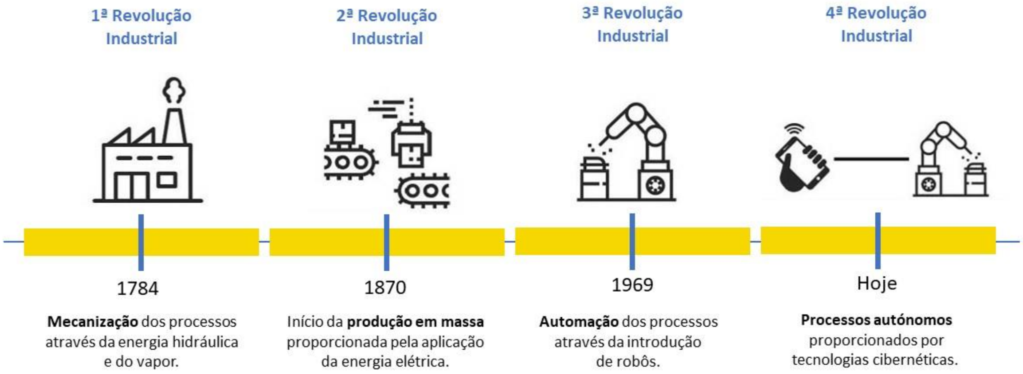
Increasingly redundant within organization

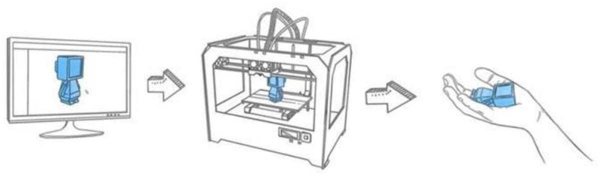
Assembly and Factory Workers
Relationship Managers
Business Services and Administration Managers
Sales Representatives, Wholesale and Manufacturing, Technic…

Administrative and Executive Secretaries
General and Operations Managers
Door-To-Door Sales Workers, News and Street Vendors, and R…
Data Entry Clerks
Accounting, Bookkeeping and Payroll Clerks
Accountants and Auditors

14. Annex H: First Class Presentation







Fabrico de um objeto tridimensional a partir de um modelo digital

Quais as vantagens e desvantagens?

VANTAGENS

- Prototipagem de baixo custo
- Grande variedade de materiais
- Personalização das peças

DESVANTAGENS

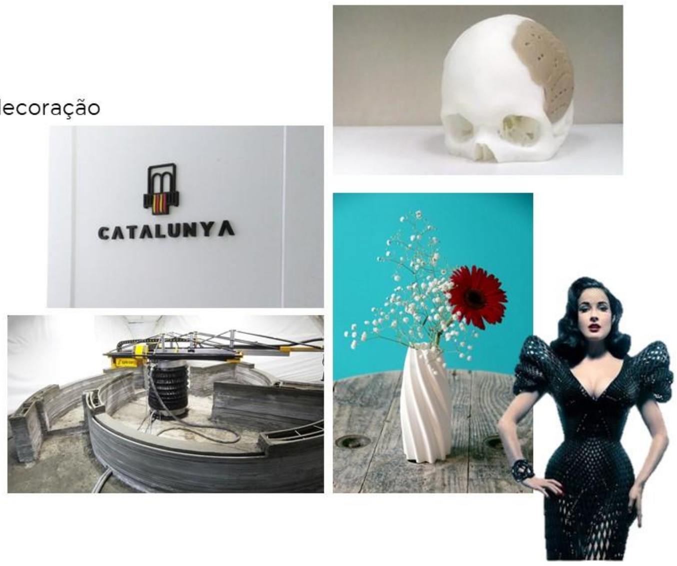
- Custos de manutenção
- Uso de softwares específicos

IMPRESSÃO 3D

Quais as aplicações da impressão 3D?

Aplicações

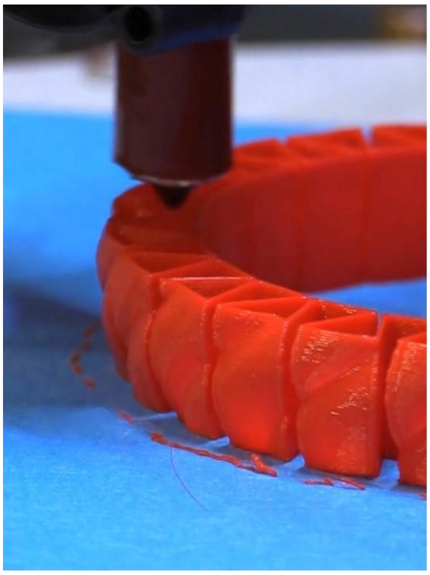
- Peças para uso doméstico e decoração
- Protótipos
- Medicina
- Moda
- Presentes personalizados
- Sinalização
- Educação
- Engenharia



http://tinkercad.com

15. Annex I: Second Class Presentation

O que fazer antes e depois de imprimir?



Processo anterior à impressão

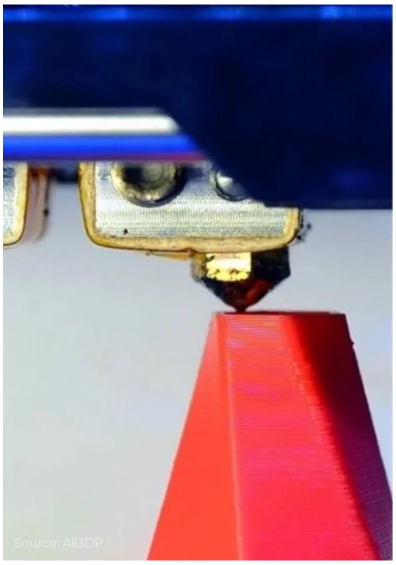
Preparar a 'cama'
Calibrar impressora (quando necessário)
Carregar filamento (se ainda não carregado)
Passar o ficheiro de modulação (.STL) para um Software apropriado (ex. Cura)
Gerar o ficheiro GCODE
Imprimir

Processo posterior à impressão

Fazer o *unload* do filamento
Aplicar técnicas de pós produção ao objeto impresso

ShapiNG II

Calibração



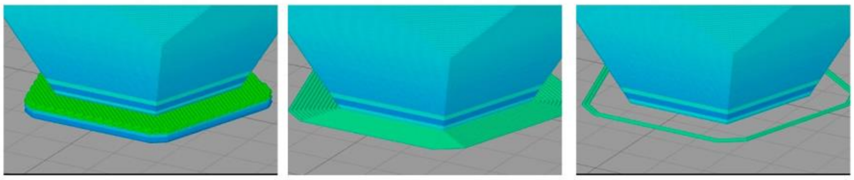
Uma **boa calibração** é indispensável para obter modelos com camadas homogéneas, sem erros e esteticamente coerentes.

A calibração deve ser realizada antes de se fazer *load* do filamento, evitando partículas de plástico no nozzle que podem afetar a qualidade da calibração.

Depois da impressão, é necessário realizar **sempre *unload* do filamento** para evitarmos que os nozzles entupam resultando em manutenções dispendiosas e evitáveis.

Adesão à Plataforma

Adesão à Plataforma



Raft Brim Skirt

Preenchimento

Preenchimento

20% 50% 75%