Does digital fabrication foster students' creativity? A systematic literature review

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Does digital fabrication foster students' creativity?
A systematic literature review

Master's degree in Learning and Teaching Technologies

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RÉSUMÉ

This research addresses the impact of digital fabrication on creativity in educational settings. A renewed attention to integrating creativity into educational programs has surfaced in the last two decades and creativity is nowadays considered one of the most important skills of the 21st century. Scholars have yet to agree on a single definition of creativity. However, many acknowledge that it can be taught, learned and fostered. Literature has shown that environments that support students' creativity are those where learning activities involve the making of artefacts. Although digital fabrication in education has become very popular in recent years, little is known about its effects on students' creativity. This systematic literature review synthesised empirical research on digital fabrication as a means to foster creativity in educational settings. A survey of published research in the last 10 years identified 15 empirical studies that met the inclusion criteria. The corpus was analysed with the goal of investigating whether digital fabrication fosters students' creativity and in which contexts the interventions were performed. The findings reveal that most of the research has been quantitative and conducted in the Engineering domain, prominently on STEAM or STEM education. Creative process, person, and product have been the primary focus of research and none of the studies focused on the influence of the environment on students' creativity. Researchers have addressed creativity mainly through the prism of three definitions: as implying novelty and usefulness of the outcome, as a form of divergent thinking, or as a form of problem-solving. Digital fabrication has helped stimulate one or more creativity characteristics related to these definitions. The most significant results were the stimulation of participants' originality, their willingness to explore, and the opportunity they were given to generate ideas, experiment, and create. None of the studies, however, thoroughly investigated how digital fabrication and makerspaces activities had contributed to this result.

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Déclaration sur l'honneur

Je déclare que les conditions de réalisation de ce travail de mémoire respectent la charte d'éthique et de déontologie de l'Université de Genève. Je suis bien l'auteur-e de ce texte et atteste que toute affirmation qu'il contient et qui n'est pas le fruit de ma réflexion personnelle est attribuée à sa source ; tout passage recopié d'une autre source est en outre placé entre guillemets.

Genève, le 27/01/2023

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1. Introduction

As educators, we should constantly be knowledgeable of and attentive to current research and trends in the field. A renewed attention to integrating creativity into educational programs has surfaced in the last two decades (Partnership for 21st Century Skills, 2009). Creativity is now considered one of the most important skills for future generations (Azzam, 2009; Dawes & Wegerif, 2004; Glăveanu et al., 2020; Mishra & Henriksen, 2013).

In the last 20 years, digital fabrication and makerspaces activities have been introduced in formal and informal educational settings, mainly to promote Science, technology, engineering, and mathematics (STEM) education (Blikstein, 2013; Chu et al., 2015; Hsu et al., 2017; Lorenzo & Lorenzo, 2018; Martin, 2015; Nemorin, 2017; Schön et al., 2014).
A Makerspace is considered to be a place that allows one to be creative, as people there have the freedom and the motivation to explore, design, and make, thanks to the endless possibilities offered by digital fabrication (Hatch, 2014). However, although the body of research on educational uses and benefits of digital fabrication for STEM education is rapidly expanding, not as much has been done to provide evidence that digital fabrication and makerspaces activities help foster students' creativity. Furthermore, despite the fact that several reviews on educational uses and benefits of 3D printing have been published (Novak et al., 2021), no comprehensive review of the literature on educational uses of digital fabrication to foster creativity in the classroom has been conducted.

This research will document a systematic review of the last decade of empirical research on digital fabrication as a way to nurture and encourage creativity. Its goal is to provide an overview of the results of research on such activities on students' creativity and offer recommendations for future research. The first part of this study will present the context of the emergence of creativity as one of the most important skills students and future generations must possess. In the second part, the theoretical framework, several definitions of creativity will be presented as well as a description of the most common approaches to view and measure creativity. The theoretical framework will then move to a description of the maker movement, its origins and development, as well as its introduction into educational contexts, and it will conclude with an overview of the assertions that seems to support the hypothesis that digital fabrication could be used as a means to foster creativity in the classroom. The detailed steps of the process followed during the research will be documented in the chapters "Methodology" and "Data Analysis". The outcomes of the research will be described in the chapters "Results" and "Discussion".

1.1 The 21st century skills

One of the most recurrent subjects discussed nowadays, especially in Western Countries, are the so-called 21st century skills. Over the past two decades, educators, governmental agencies, academics and business leaders, have all underlined the need for modern students, educators, and all citizens to possess these 21st century skills. What makes these skills of contemporary

interest is that they are considered absolutely needed in the current society as “changes in our economy and the world mean that collective and individual success depends on having such skills” (Rotherham & Willingham, 2010, p. 17).
Binkley et al. (2012) underline the fact that these skills are transdisciplinary, as they are not related to a specific domain. Regardless of the professional field, every individual must possess the ability to “communicate, share, and use information to solve complex problems … adapt and innovate in response to new demands and changing circumstances, … marshal and expand the power of technology to create new knowledge, and in expanding human capacity and productivity” (p. 17). Ken Robinson pointed out that “the ability to innovate and adapt to change is not a luxury: it is a necessity” (Robinson, 2017b, sec. Only connect: education, business and culture section, para. 8)

A way to ensure that the next generations will possess these “new” transversal skills when entering the job market is by adapting current education curricula so as to reflect this shift towards methods and programs that “will enable students to acquire the sophisticated thinking, flexible problem solving, and collaboration and communication skills they will need to be successful in work and life” (Binkley et al., 2012, p. 18). The challenge lies in being able to define these skills, describe them in a way that could be measurable, define learning approaches that could nurture them and, finally, define assessments that could measure their effectiveness in transferring those skills to students (Griffin & Care, 2015a).

A number of researches and reports have been published. The three most relevant frameworks for this study, issued from these documents, will be discussed in the following paragraphs.

The Partnership for 21st Century Learning or P21 (originally called Partnership for 21st Century Skills), a non-profit organisation that includes policymakers, education leaders and members of the business community, identified four main areas of “skills, knowledge and expertise students must master to succeed in work and life” (Partnership for 21st Century Skills, 2009, p. 1). These areas comprise: *Life & Careers Skills; Information, Media and Technology Skills; Key Subjects and 21st Century Themes; Learning and Innovation Skills - 4C*s. The latter, Learning and Innovation Skills - 4Cs includes four critical learning skills, (also called the 4 Cs of 21st century learning): *Creativity, Collaboration, Communication, and Critical Thinking*.

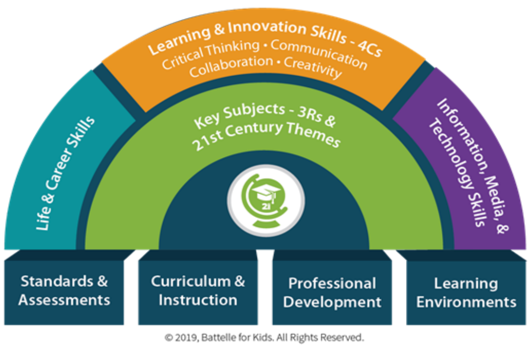

Figure 1. The P21 areas and themes of the Partnership for 21st Century Skills framework.

The ISTE (International Society for Technology in Education) standards are "the standards for learning, teaching and leading in the digital age and are widely recognized and adopted worldwide" (International Society for Technology in Education, 2017, p. n.d.). They were originally developed in 1998 and their main focus was on what students needed in order to learn to use technology tools. The 2007 and 2016 reviews shifted the focus on learning, rather than the tools. Emphasis has also been put on creativity and innovation (International Society for Technology in Education, 2017). The skills and qualities highlighted by the ISTE standards are:

1. Empowered Learner
2. Digital Citizen
3. Knowledge Constructor
4. Innovative Designer
5. Computational Thinker
6. Creative Communicator
7. Global Collaborator

Although these standards focus on K-12 or primary and secondary students (the age range is 4 to 18) "the digital literacies this educational technology organization articulates are more detailed than those in the overall P21 framework" (Dede, 2010, p. 8).

In 2008, three companies - Cisco Systems Inc., Intel Corporation and Microsoft Corp - also realised the need to focus on 21st century skills. They were concerned about transversal workplace requirements that weren't systematically met by new graduates entering the job market (Griffin & Care, 2015b). They decided to fund the Assessment and Teaching of 21st Century Skills (ATC21S™) research project, where 250 researchers from all around the world were brought together to define these 21st century skills; the technological issues schools would have to face; what teaching approaches and methodology of assessment would be most appropriate; and what factors to consider when aiming at bringing these changes into broader educational curricula (*About - Assessment & Teaching of 21st Century Skills*, n.d.; Griffin & Care, 2015b).

The outcomes of this project were several white papers, the first of which had the primary objective of "understanding the nature of these "new" skills and the ways in which they relate to traditional school subjects" (Wilson & Scalise, 2015, p. 58). As part of the first phase of the research project, Binkley et al. (2012) identified ten 21st Century Skills by analysing twelve frameworks applied in a number of countries. These frameworks were analysed under 3 categories (known as the KSAVE model):

1. Knowledge
2. Skills
3. Attitudes, Values and Ethics

The *Knowledge* category embodies all "references to specific knowledge" (Binkley et al., 2012, p. 37) that are related to a given skill. The *Skills* category comprises all the skills, abilities and processes that a curriculum seeks to "develop in students" (Binkley et al., 2012, p. 37). The category *Attitudes, Values, and Ethics* is associated with behavioural aspects of students in

relation to any of these skills (Binkley et al., 2012). The researchers also analysed whether the frameworks provided measurable descriptions of such skills.
These ten skills were subsequently divided into four groups (Binkley et al., 2012, p. 36), as summarised below:

- **Ways of Thinking:**
    - Creativity and innovation
    - Critical thinking, problem solving, decision making
    - Learning to learn, Metacognition
- **Ways of Working:**
    - Communication
    - Collaboration (teamwork)
- **Tools for Working:**
    - Information literacy
    - Information and Communication technology (ICT) literacy
- **Living in the World:**
    - Citizenship – local and global
    - Life and career

The following section will show literature supporting that creativity is considered as one of the most important skills for new generations and it will describe how creativity is included in the current 21st skills frameworks.

1.2 Why is creativity so important?

“CREATIVITY IS FUNDAMENTAL FOR SOCIETY”
(Glăveanu et al., 2020, p. 743)

Thus says the *Socio-Cultural Manifesto for Advancing Creativity Theory and Research* (Glăveanu et al., 2020). The document is a result of a discussion among 20 scholars - Vlad Glăveanu, James C. Kaufman, Robert J. Sternberg, Dean Keith Simonton, Giovanni Emanuele Corazza, to name a few - whose research has contributed to the advancement of creativity studies in the past decades. The reason why creativity appears to be essential for our society does not rely only on the progress led by creative inventions, as much as on the way creativity changes “the way people relate to the world, to others, and to themselves, making them more flexible, more open to the new and, at least in principle, to differences in perspective” (Glăveanu et al., 2020, p. 743). Kerr and Gagliardi (2003) share the belief that creativity is the characteristic that is most “critical to human advancement” (p. 155).
Other scholars, such as Sir Ken Robinson (Azzam, 2009), consider creativity as the most important among the 21st century skills because “the challenges we currently face are without precedent … and we're going to need every ounce of ingenuity, imagination, and creativity to

confront these problems" (s.p.). Dawes and Wegerif (2004) describe creativity as "an important aspect of thinking that can and should be fostered" (p.57).

The P21put a strong focus on the Learning and innovation skills - 4Cs[1]:

> Learning and innovation skills increasingly are being recognized as those that separate students who are prepared for a more and more complex life and work environments in the 21st century, and those who are not. A focus on creativity, critical thinking, communication and collaboration is essential to prepare students for the future. (Partnership for 21st Century Skills, 2009, p. 3)

Mishra and Henriksen (2013) affirm that "the emphasis on creativity has never been as pressing, or as academically discussed, as it is in present day" (p.10).

In the P21 framework, creativity focuses on *thinking creatively*, *working creatively* with others and implementing innovation (Partnership for 21st Century Skills, 2009), as shown in Table 1 below.

Table 1

Creativity and Innovation in the P21 Framework Definitions

THINK CREATIVELY	WORK CREATIVELY WITH OTHERS	IMPLEMENT INNOVATIONS
Use a wide range of idea-creation techniques (such as brainstorming) *Create new and worthwhile ideas (both incremental and radical concepts)* *Elaborate, refine, analyze, and evaluate their own ideas in order to improve and maximize creative efforts*	*Develop, implement, and communicate new ideas to others effectively* *Be open and responsive to new and diverse perspectives; incorporate group input and feedback into the work* *Demonstrate originality and inventiveness in work and understand the real-world limits to adopting new ideas* *View failure as an opportunity to learn; understand that creativity and innovation is a long-term, cyclical process of small successes and frequent mistakes*	*Act on creative ideas to make a tangible and useful contribution to the field in which the innovation will occur*

Note. Adapted from *P21 framework definitions* from Partnership for 21st Century Skills, 2009 Copyright © 2015, The Partnership for 21st Century Learning.

Within the KSAVE model, Creativity and Innovation belong to the *Ways of thinking* group, as described in Table 1 in the previous section. Similarly to the P21 framework, creativity and

[1] 4Cs: Creativity, Critical Thinking, Collaboration, and Communication.

innovation skills are subdivided into thinking creatively, working creatively with others, and implementing innovation.
The ISTE standards propose a set of creativity indicators to guide educators so as to plan their lessons, align their curricula with the standards, and prepare appropriate assessments. These indicators are summarised in the Table 2 below.

Table 2
Creativity indicators according to the ISTE standards

Innovative Designer	**Creative Communicator**
Identify and define authentic problems and significant questions for investigation.	Evaluate and select information sources and digital tools based on the appropriateness to specific tasks.
Apply existing knowledge to generate new ideas, products, or processes	
Use multiple processes and diverse perspectives to explore alternative solutions.	Create original works as a means of personal or group expression
Plan and manage activities to develop a solution or complete a project.	Use models and simulations to explore complex systems and issues
	Interact, collaborate and publish with peers, experts or others employing a variety of digital environments and media
	Communicate information and ideas effectively to multiple audiences using a variety of media and formats
	Evaluate and select information sources and digital tools based on the appropriateness to specific tasks

Note. Adapted from *ISTE standards for students: A practical guide for learning with technology* by International Society for Technology in Education. (2017)

Along the same lines of the P21, The European Commission's Joint Research Centre (JRC) produced the The Digital Competence Framework for Citizens, also known as DigComp. First published in 2013, it has been updated in 2016 and took the name of DigComp 2.0, so as to include the 21 competency descriptors and the "the conceptual reference model" (European Commission. Joint Research Centre., 2016, p. 5). Although the DigiComp 2.0 focuses on digital competencies and skills, creativity is seen as closely related to a number of skills: express *creatively* through digital media and technologies; innovating and *creatively* using technology; *creatively* using digital technologies; *creative* expression. For instance, in the competence area n°5 of the Conceptual Reference Model - that of "Problem solving" - the

DigComp 2.0 affirms that the competences associated with it relates to “Creatively using digital technologies”, as the capability

> to use digital tools and technologies to create knowledge and to innovate processes and products. To engage individually and collectively in cognitive processing to understand and resolve conceptual problems and problem situations in digital environments. (European Commission. Joint Research Centre., 2016, p. 9)

The frameworks and models that were presented in this section provided some insights on how creativity should be integrated in the classroom. Despite the fact that many countries have focused on incorporating in their education programs 21st century skills such as critical thinking, problem solving, or collaboration, less efforts were made to incorporate and cultivate creativity or innovation on a national curricula level (Griffin & Care, 2015a). The following section will discuss the challenges of incorporating creativity in training programs.

1.3 The challenge of incorporating creativity in training programs

As said in the previous sections, if our society aims at having a workforce equipped with 21st century skills in general, and creativity in particular, the focus should be put on education and intentional instruction (Miller & Dumford, 2016).

If we start from the premise that creativity can be taught, learned, and fostered (Amabile, 1983; Beghetto & Kaufman, 2014; Davies et al., 2013; Scott et al., 2004; Torrance, 1972)**,** we should investigate how it can be done, what promotes or supports creativity in the classroom, and whether there are means and learning approaches that could help promote students’ creative potential and creative skills.

The issue of how teachers can help students develop their creative potential is, in fact, long-standing (Barron, 1955; Beghetto & Kaufman, 2014; Guilford, 1950; Torrance, 1972) and creativity has sometimes been met with indifference or “negligence” in schools (Beghetto & Kaufman, 2014). One reason could be related to the difficulty to create instructional design aimed at having “creativity” as the outcome. “The product, or outcome, of a "creative event" is, virtually by definition, not specifiable in advance, except that it should be different, both from one occurrence to the next and from one person to another” (Gehlbach, 1987, p. 36).
Torrance (1972) for example, recommended approaches that “involve both cognitive and emotional functioning, provide adequate structure and motivation, and give opportunities for involvement, practice, and interaction … differences seem to be greatest and most predictable when deliberate teaching is involved” (pp. 132-133).

Beghetto and Kaufman (2014), as well as Davies et al. (2013) argue that one of the main important factors that will determine if creativity is supported or hindered, is the learning environment in which students are immersed. Beghetto and Kaufman (2014) suggest that all students have the potential to be creative in some way and that there is no doubt that creativity has its place in the classroom, “but rather when and how creativity can be best supported and encouraged” (Beghetto & Kaufman, 2014, p. 57).

The development of students’ creative potential depends on both individual characteristics and social factors (Amabile, 1983; Beghetto & Kaufman, 2014; Sternberg, 2006). The teachers should therefore build a learning environment that provides for “creativity-supportive practices” such as “(a) explicitly teaching for creative thinking, (b) providing opportunities for choice and discovery, (c) encouraging students’ intrinsic motivation, (d) establishing a creativity-supportive learning environment, and (e) providing opportunities for students to use their imagination while learning” (Beghetto & Kaufman, 2014, p. 58).

A literature review of creativity in education conducted by Davies et al. (2013) revealed that learning environments that support students’ creativity are those where:

1. a *critical event* takes place, where a critical event is “a project or experience which is in some way ‘special’ or different from everyday practice” (p. 84);
2. learning activities involve “the making of artefacts” (p. 84);
3. students are given access to “new or different media and technologies” (p.84);
4. the tasks are authentic and “set within as real a context as possible and be self-evidently worthwhile” (p. 85);
5. students “are given some control over their learning and supported to take risks with the right balance between structure and freedom” (p. 85)
6. students are encouraged to pursue “exploring and imagining” (p. 85).

A way to make a learning environment support students’ creativity could be by using different tools and materials, both physical and technological, or involve students in unique, engaging and realistics projects (Davies et al., 2013).
Nickerson (2019) suggests some techniques through which creativity can be enhanced in the classroom. Among those:

- “stimulating and rewarding curiosity and exploration” (p. 410)
- “providing opportunities for choice and discovery” (p. 416)
- “brainstorming and creative problem solving” (p. 401)

Gehlbach (1987) speaks about the *Open Process-Open Product* (OP-OP) task as the most recommended type for creativity education. In these tasks students will have to specify their “problems, processes, and products” (p. 42) and will be free to choose what to learn, and what tools to use. He argues, however, that the issue with these types of tasks is that learning happens “accidentally” instead of “intentionally”. This “accidental” learning goes against the purpose of instruction, which is “a goal-directed activity … a deliberate attempt to structure a learning environment so that students will acquire specified knowledge or skill” (Merrill, 2012, p. 6). In other words, learning should be “planned and predictable” (Gehlbach, 1987, p. 35).

The issue of designing instructions for creativity education is, then, to find a balance between freedom and constraints, as limitations would reduce “the opportunities for novel thought”

(Gehlbach, 1987, p. 43). The approach proposed by Gehlbach (1987) is to modify the instructions so as to apply some *functional constraints* to the creative outcome, "not in terms of the details of what it should be, but in terms of what it should do" (Gehlbach, 1987, p. 43). He argues that this increase of constraints stimulates the creative intellect (1987) as the possible solutions are now multiple, if not infinite. By applying functional constraints (i.e., what the product should *do*), the outcome of the process will be both novel and effective, corresponding to a broad definition of creativity that will be discussed in the following chapter. The approaches highlighted by Davies et al. (2013) on the learning environments and discussed earlier in this section could also support this solution, provided that these environments are able to help students focus on their intrinsic motivation to learn, while taking "control of their creativity" (Beghetto & Kaufman, 2014, p. 62). Also, as pointed out by Miller & Dumford (2016) "flexible, open-ended assignments" could favour the expression of students' creativity.

Scott et al. (2004) agree that learning activities that call for idea generation, problem finding, divergent thinking, and conceptual combination, also prove effective in creativity training. The problem is then, for teachers, instructors, and educators in general, to shape such environments, and define such activities. There is, of course, no unique, magic solution.

2. Theoretical framework

2.1 Defining creativity

Creativity is a difficult subject to define and study, as it is considered a complex and multifaceted phenomenon “that involves cognitive, personality and environmental components” (Said-Metwaly et al., 2017b, p. 243). As Harrington (1990) asserted, “creativity does not “reside” in any single cognitive or personality process, does not occur at any single point in time, does not “happen” at any particular place, and is not the product of any single individual” (p.150).

The reader should therefore be warned that there is no single definition universally recognised as “the” definition of creativity (Mishra & Henriksen, 2013). This lack of consensus is therefore problematic since, as Runco and Jaeger (2012) underlined, we should aim at providing a standard definition of creativity if we seek to develop instruments to measure it and assess it. Glăveanu et al. (2020) also underline the importance of defining the framework of reference and state the paradigm (or facet) from which creativity is identified and studied. The following sections will present the most commonly utilised definitions of creativity.

2.1.1 Creativity as originality and usefulness

A commonly accepted - however broad - definition of creativity or of a creative product (Beghetto & Kaufman, 2014; Runco & Jaeger, 2012; Simonton, 2000, 2012; Westberg, 1996) is that it “requires both originality and effectiveness” (Runco & Jaeger, 2012, p. 92); or that “involves the production of novel, useful products" (Mumford, 2003, p. 110). This definition means that creativity implies novelty of ideas - i.e. something that didn’t exist before - but that these ideas must also be of use for someone. The first well defined, not ambiguous definition of creativity that took into account both these aspects (Runco & Jaeger, 2012), was provided by Stein (1953):

> The creative work is a novel work that is accepted as tenable or useful or satisfying by a group in some point in time .... By ‘‘novel’’ I mean that the creative product did not exist previously in precisely the same form. It arises from a reintegration of already existing materials or knowledge, but when it is completed it contains elements that are new. This may well depend on the nature of the problem that is attacked, the fund of knowledge or experience that exists in the field at the time, and the characteristics of the creative individual and those of the individuals with whom he is communicating. (p. 311)

At around the same time Barron (1955) provided another definition close to the previous one, although the author was actually defining originality:

> The first criterion of an original response is that it should have a certain stated uncommonness in the particular group being studied. A familiar example of this in

psychological practice is the definition of an original response to the Rorschach inkblots, the requirement there being that the response should, in the examiner's experience, occur no more often than once in 100 examinations .… A second criterion that must be met if a response is to be called original is that it must be to some extent adaptive to reality. The intent of this requirement is to exclude uncommon responses which are merely random, or which proceed from ignorance or delusion. (pp. 478–479)

2.1.2 Creativity as a form of divergent thinking

Joy Paul Guilford, Frank Barron, and E. Paul Torrance are considered to be the "founding fathers" of the field of creativity and creativity research (Barlow, 2000; Glăveanu & Kaufman, 2019; Sternberg & Grigorenko, 2001). Two of the main contributions Guilford gave to the field (Runco & Jaeger, 2012; Sternberg & Grigorenko, 2001) were his understanding that creativity can be studied scientifically, by means of empirical testing of theories (Sternberg & Grigorenko, 2001), and the development of a number of psychometrics tests for creativity (Barlow, 2000; Sternberg & Grigorenko, 2001).

In his Structure of Intellect theory (SOI), Guilford first theorised that all intellectual factors can be divided into two groups: *memory* and *thinking factors* (Guilford, 1956), with the majority of factors falling into the latter group. For Guilford, creativity is associated with *divergent thinking* and *divergent production*, as opposed to *convergent thinking* and *convergent production* (Sternberg & Grigorenko, 2001; Undheim & Horn, 1977). The process of divergent production could be combined with a product (*units, classes, relations, systems, transformations, and implications*) and one of four different content categories (*semantic, symbolic, figural, and behavioural*) in 24 different ways (Sternberg & Grigorenko, 2001): these combinations is what Guilford identifies as *divergent thinking* (Sternberg & Grigorenko, 2001).

What differs, for Guilford, between convergent and divergent thinking lies mainly in the number of solutions a given problem has. In Guilford's words (1973): "Convergent thinking … is aimed toward a single correct answer. Divergent thinking is inquiring, searching around, often leading to unconventional and unexpected answers" (p. 1). In divergent thinking (Guilford, 1956) "there is much searching or going off in various directions. This is most clearly seen when there is no unique conclusion" (p. 274).

A similar definition of the creative problem (as opposed to the analytical problem) was given by Arnold (1956). In the 1950s Arnold taught the course "Creative Engineering" at the Massachusetts Institute of Technology (MIT) and launched the Creative Engineering seminars at Stanford University. In his paper Creativity in Engineering (1956) he wrote:

> The creative problem … usually has a very broad and general problem statement. There are a great many different approaches that can be used in arriving at a solution. Finally, there is no one right solution. The many different approaches used lead to many different answers, and these answers usually form a complete spectrum from bad to good. I believe that the number of answers arrived at is the best way of distinguishing

> between the analytical and the creative problem. The analytical problem has only one right answer. The creative problem has many, many adequate answers. (p.17)

Arnold (1956), who was influenced by Guilford's model (von Thienen et al., 2018), expanded on the topic and definition of some of Guilford's creativity factors. *Fluency* (as in fluency of ideation) for Arnold (1956) means that a creative person has a larger number of ideas per unit time (with respect to a non-creative person), is able to "rule judgement out during the idea-forming stage" (p. 19); and has "no blocks to prevent the associations made in the subconscious to permeate up into the conscious, and he has no inhibitions or difficulties in communicating them to others" (p. 19).
Flexibility is defined as the ability "to go beyond tradition, habits, and the obvious. To turn ideas and materials to new, different, and unusual uses" (Guilford, 1973, p. 2).
Another attribute Arnold gives to the creative person is their *originality* as another factor "peculiar to creative person" (Arnold, 1956, p. 19). *Originality* is the ability to "penetrate into divergent areas and find remote relationships … always on the lookout for unusual combinations" (Arnold, 1956, p. 19) and the ability to make "more novel and original combinations than the less creative" (Arnold, 1959/2016, p. 86).

Divergent thinking as defined by Runco (2008) "refers to fluency, flexibility, and originality, for example, and evaluative processes include critical thinking as well as valuative and appreciative consideration" (p. 94).

2.1.3 Creativity as a form of problem solving

In Guildford's model, creativity and creative thinking overlap in some cases with problem solving (Guilford, 1956) or can be seen as a form of problem solving (Sternberg & Grigorenko, 2001). In his model, creativity involves three main problem-solving abilities (Sternberg & Grigorenko, 2001): *sensitivity to problems, fluency*, and *flexibility*.
Torrance (Torrance & Shaughnessy, 1998) viewed creativity as a process and in his own words, he defined it as follows:

> I chose a definition process of creativity of research purposes. I thought that if I chose process as a focus, I could then ask what kind of person one must be to engage in the process successfully, what kinds of environments will facilitate it, and what kinds of products will result from successful operation of the process. I tried to describe creative thinking as the process of sensing difficulties, problems, gaps in information, missing elements, something askew; making guesses and formulating hypotheses about these deficiencies, evaluating and testing these guesses and hypotheses; possibly revising and retesting them; and finally communicating the results. (1998, p. 444)

It's worth noting that Torrance's definition of creativity is then related to problem-solving abilities (Wallach & Torrance, 1968).

2.1.4 4Ps of creativity: person, product, process, press

The 4 Ps of creativity were first introduced by Rhodes (1961). In his paper he analysed over 40 definitions of creativity and 16 definitions of imagination and realised that these definitions overlapped and intertwined. He gave creativity the following definition (Rhodes, 1961):

> The word creativity is a noun naming the phenomenon in which a person communicates a new concept (which is the product). Mental activity (or mental process) is implicit in the definition, and of course no one could conceive of a person living or operating in a vacuum, so the term press is also implicit. (p.305)

It was never Rhodes' intention to drastically separate these four Ps into four distinct aspects of creativity. He stated that "each strand has unique identity academically, but only in unity do the four strands operate functionally" (Rhodes, 1961, p. 307). Nonetheless, mostly all traditional creativity theories, models and psychometric measurement's methods have focused on one of 4 perspectives (Glăveanu & Kaufman, 2019; Plucker et al., 2019) :

1. the cognitive aspects related to creativity, the so-called creative **process**;
2. the peculiar characteristics of the creative **person**, such as personality or behavioural traits;
3. the creative **products**;
4. the relationship between the creative person and their "creativity-fostering" (Plucker et al., 2019) environment, the so-called **press**, on the perspective of social psychology, or external circumstances that might be related to creative behaviour (Woodman & Schoenfeldt, 1990).

As a result, research on creativity has focused on a single element at a time.

2.1.5 Modern views on creativity

Whilst the above discussed views on creativity, "in the psychology of creativity (psychometric tests and experiments) narrowly target individual creative outcomes" (Glăveanu, 2015, p. 166), modern view of research on creativity has shifted towards a sociocultural approach where the individuals cannot be distanced from their social context and their culture.

This modern "view" of creativity is reflected, for example, in Glăveanu's Five A's framework (Glăveanu, 2013). The author argues against the cognitive psychology "individualistic, static, and oftentimes disjointed vision of creativity" (Glăveanu, 2013, p. 69) such as proposed in Rhode's Four P's of creativity (Rhodes, 1961) or in Guilford theory of creativity (Guilford, 1950, 1973). Glăveanu (Glăveanu, 2013, 2015) changes the epistemological position of creativity research, as he approaches creativity from a sociocultural and ecological point of view. The author argues that

> this is particularly relevant for understanding a phenomenon like creativity in which the person [the actor] is embedded in/acts from within a system of social relations and the activity of creation produces meaning by integrating and transforming types of knowledge that, although individual in expression, are social in origin". (Glăveanu, 2013, p. 70).

Creativity is seen an action where an individual (the actor), confronted with other individuals, performs actions that result in artefacts that are influenced by affordances provided by the environment (Glăveanu, 2013, 2015). It is important to understand that every action cannot happen or every artefact cannot be considered outside the social, cultural and material context where the actor performs or creates them (Glăveanu, 2013). From an ecological standpoint "creativity ultimately represents the act of engaging with existing artifacts to create new artefacts most often through the combined physical and mental labor of the creator" (Glăveanu, 2013, p. 71).

According to Gibson, who coined the word "affordance" (Gibson, 1977), affordances are what the environment offers, provides, or furnishes to the animal. For substances having the physical property of being solid, for example, affordances could relate to manufacture: "what can be done with it, what it is good for, its utility; and the hands are involved" (Gibson, 1977, p. 123). Objects (or artefacts) are, thus, the result of a manipulation and manufacture - by the observer (the actor) - of natural substances that are endowed with different affordances (Gibson, 1977).

It was long thought that creative products were some sort of straightforward result of the creative ideas produced by our brain, that they were a mere consequence of the ideas ; that we should read the process backward, from product to idea, to understand it (Pohjoisen kulttuuri-instituutti – Institute for Northern Culture, 2013). This "traditional" approach justifies the use of creativity assessment instruments such the TTCT or Amabile's CAT: evaluators look at the end result (a product or a score in the test) and formulate a "judgement" on the creative aspect (product or process). This vision is what Ingold (2013) calls "hylomorphism": "practitioners impose forms internal to the mind upon a material world 'out there'" (p.21). The term refers to the Aristotelian doctrine, according to which "physical objects result from the combination of matter and form" (*HYLOMORPHISM | Meaning & Definition for UK English | Lexico.Com*, n.d.)

More recent views reverse this paradigm affirming that the creative process is also outside the mind of the creator. People think through making (Ingold, 2013), and the environment - social, cultural, and material - shapes the end results, the creative artefact (Glăveanu, 2013, 2015).

> Because action is not preplanned but continuously unfolds over time, creativity is to be found in the process of making. Indeed, creativity can be conceived of as the discovery and creation of unconventional affordances (action possibilities) of objects and materials. (Withagen & van der Kamp, 2018, p. 1)

Ingold (2013) sees making as *growth,* and the maker

> as a participant in amongst a world of active materials. These materials are what he has to work with, and in the process of making he 'joins forces' with them, bringing them together or splitting them apart, synthesising and distilling, in anticipation of what might emerge. (p.21)

With this, the author argues that creativity has an improvisational aspect, and things come along as the maker goes about making (Ingold, 2013). In other words, "creativity does not so much exist in the head but in the unfolding of action" (Withagen & van der Kamp, 2018, p. 1).

This section has described the most commonly utilised definitions of creativity and has shown the complexity of this phenomenon. The following section will describe how research has approached the measurement and assessment of creativity despite the lack of general consensus for its definition.

2.2. Measuring creativity

The most common creativity assessments can be classified into psychometric instruments (process), self-report scales or questionnaires (person), third-party rating of creative achievement (product), and behavioural research (press) (Said-Metwaly et al., 2017b).
A review of the literature by Said-Metwaly et al. (2017b) on quantitative instruments used in research on creativity, showed that the process approach was the most common one, followed by person, product, and press. The authors also identified 18 different instruments used in quantitative studies (Said-Metwaly et al., 2017b).

Another review by Katz-Buonincontro et Anderson (2020) that analysed research using quantitative or qualitative observation methods to study creativity in education, so as to "capture the creative process as it unfolds in real time" (p.1) revealed that observation is rarely used in creativity research in education: the authors only found 37 articles in the timespan of 38 years, most of which were qualitative studies.

2.2.1 Measuring the creative process: Psychometric tests

The most known psychometric test is the Torrance Test of Creative Thinking (TTCT), developed in 1966. The test has been renormed four times since (Kim, 2006b) and is "by far the most used test for measuring creativity" (Almeida et al., 2008, p. 5). The test has two subtests: verbal and figural, so as "to look at how creativity may be different in different domains" (J. C. Kaufman & Baer, 2006, p. 100). Both subtests aim at assessing 5 cognitive processes of creativity: fluency, originality, elaboration, resistance to premature closure, and abstractness of titles (Almeida et al., 2008). Fluency, flexibility, originality, and elaboration, were derived from Guilford's SOI's divergent thinking's factors (Kim, 2006b).

To these 5 sub-scales, Torrance later added 13 criterion-referenced measures called "creative strengths":

1. emotional expressiveness,
2. storytelling,
3. movement or action,
4. expressiveness of titles,
5. synthesis of incomplete figures,

6. synthesis of lines or circles,
7. unusual visualisation,
8. internal visualisation,
9. extending or breaking boundaries,
10. humour,
11. richness of imagery,
12. colourfulness of imagery,
13. articulateness,
14. fantasy (Kim, 2006a).

Being the most used test for measuring creativity implies that a lot of research and analysis has been conducted to prove its validity. However, some studies are currently questioning its validity (Almeida et al., 2008) showing, for example, the "inconsistency of the cognitive processes (fluency, flexibility, originality and elaboration)". It has been suggested by Torrance and Cropley (Kim, 2006a) that a creativity assessment should be based on measures produced by several tests, meaning that the TTCT test alone should not be used to measure creativity.

2.2.2 Measuring the creative product: independent raters' assessments

The most regarded assessment tool for measuring product creativity is Amabile's Consensual Assessment Technique (J. C. Kaufman et al., 2008). Amabile developed the CAT in "reaction" to psychometric assessments (meant to be objective, but that were actually subjective) "that were expressly designed to reveal consistent individual differences" (Amabile, 1982, p. 999). Amabile operational definition of creativity is the following:

> A product or response is creative to the extent that appropriate observers independently agree it is creative. Appropriate observers are those familiar with the domain in which the product was created or the response articulated. Thus, creativity can be regarded as the quality of products or responses judged to be creative by appropriate observers, and it can also be regarded as the process by which something so judged is produced. (Amabile, 1982, p. 1001)

The assessment is openly based on subjective criteria (the experts' ratings) but assumes it is possible to obtain reliable judgments (from appropriate judges) and that "there are degrees of creativity (...) some products are more or less creative than others" (Amabile, 1982, p. 1001).
Taking into account that Amabile definition also calls for a domain specific creativity, the most important aspect of this assessment is the experts "qualification" as experts, as they must know the domain very well. Over the years, several studies have provided satisfactory interrater reliability among experts' ratings (Amabile, 1982, 1983; J. C. Kaufman et al., 2008). The challenge with this assessment is, however, to gather a panel of expert judges for each domain in which a product needs to be rated. Also "the validity of the ratings (...) cannot be assured merely by high interrater reliability alone" (J. C. Kaufman et al., 2008, p. 175).

2.2.3 Measuring the creative person: self-reports

Personality and motivational traits (in relation to creativity) are predominantly measured with self-reporting or rating scales, in which individuals are asked to auto-evaluate themselves on creativity characteristics. The main advantages of this approach are that questionnaires and scales are easy to administer, and the scoring procedures are standardised (Said-Metwaly et al., 2017a). However, the problems of self-reports and scales are several. Firstly, "the unverifiable, subjective nature of people's reported creative accomplishments or self-description" (Barbot et al., 2011, p. 61) and the potential for (intentional or unintentional) biases, distortion of the answers for social desirability or mood state (Barbot et al., 2011, Said-Metwaly et al., 2017b). Also, these instruments assume that creativity can only be associated to personality traits, ignoring the complexity and multidimensional nature of creativity (Said-Metwaly et al., 2017a) and that "even if persons have such traits, they may not produce creative accomplishments due to their lack of abilities, attitudes, motivation or supporting environment" (Said-Metwaly et al., 2017a, p. 251).

This section has presented how instruments for assessing creativity are at least as abundant as the number of creativity definitions. This could be due to the complexity of the phenomenon, the lack of a unique definition for creativity, the unsolved issue of what characteristics or aspects should be measured and which approach to use to do so (Said-Metwaly et al., 2017b). Each instrument depends therefore on the definition of creativity used by the developers, the aspect they chose to study and its focus (person, product, process, or press), the characteristics of creativity (related to its definition).

The following sections will present a description of the maker movement and why digital fabrication was introduced into educational contexts, among other reasons, as a way to foster students' creativity.

2.3. Digital Fabrication

"Making experiences can create opportunities for all young people to develop confidence, creativity, and interest in science, technology, engineering, math, arts, and learning as a whole" (Regalla, 2016, p. 257)

The *Maker Movement* was born in 2005 when the *Make:* magazine was founded by Dale Dougherty and published by the O'Reilly publishing house (Blikstein, 2018; Martin, 2015; Schön et al., 2014). The *Maker movement* refers to people "who are engaged in the creative production of artefacts … share their processes and products with others" (Halverson & Sheridan, 2014, p. 496). The first *Maker Faire* - now a registered trademark - was held in San Mateo, California, in 2006 (Martin, 2015; Schön et al., 2014).

The *Maker Movement* follows the 21st century skills trend as "there have been widespread demands from the business world for workers who are more creative and flexible" (Blikstein, 2018, p. 422) and an effort is being made by “governments, science academies, and international organizations in the form of new national curricula and international tests” (Blikstein, 2018, p. 422). Thus, subjects such as creativity, problem solving or creative thinking are not anymore seen just “as “nice to haves,” but as necessities for modern societies to thrive" (Blikstein, 2018, p. 422).

As is the case for creativity, there exist several definitions for the term *making* and *maker.* Based on concepts previously elaborated by other scholars, Martin (2015) came up with the following working definition for *making* as

> a class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends, oriented toward making a ‘‘product’’ of some sort that can be used, interacted with, or demonstrated. Making often involves traditional craft and hobby techniques (e.g., sewing, woodworking, etc.), and it often involves the use of digital technologies, either for manufacture (e.g., laser cutters, CNC machines, 3D printers) or within the design (e.g., microcontrollers, LEDs). (p. 31)

The definition of the term *maker* was drawn from Martin’s researches in the San Francisco Bay Area : “Being a maker means building things, being creative, having fun, solving problems, doing social good, collaborating, and learning” (2015, p. 31).
When *makers make* using digital tools, either Physical (3D printers, vinyl or laser cutters, digital embroidery machines, etc.) or Logic (microcontrollers or electronic boards, for instance) we generally talk about *digital fabrication* (Martin, 2015).
Digital fabrication made its first appearance in the classroom in 2002 (Blikstein, 2013) when the first *FabLab* was opened at the MIT Media Lab (Blikstein, 2018), after a course previously established by Neil Gershenfeld in the 2000s. The course was called “How to make almost anything” and was opened to students with different backgrounds such as arts, programming, education, engineering, and interaction design. Since then, *FabLabs* have opened all around the world (Schön et al., 2014) and more than a thousand exist worldwide (Blikstein, 2018). A *FabLab* is a space where standard equipment must be used and strict rules are applied, following the *Fab Charter*[2]. Each FabLab must have at least a member of the staff having followed a training at the *Fab Academy,* approved by the global *FabLab community* (Blikstein, 2018). These criteria are meant to “allow collaboration and cross-pollination of ideas among participating labs and the creation of a worldwide network of very similar small scale fabrication facilities” (Blikstein, 2018, p. 430). After the MIT FabLab, one of the first digital fabrication spaces within the premises of a school was opened in 2011 in the San Francisco Bay Area (Blikstein, 2018). Thanks to his pioneering 2008 FabLab @School project, Blikstein was able to establish digital fabrication labs in schools around the world.

[2] https://fab.cba.mit.edu/about/charter/

2.3.1 Digital Fabrication in the 21st century classroom

In the last decade researchers have been studying and educators have been using digital fabrication in education (Blikstein, 2013). The theoretical foundations behind the use of digital fabrication in education contexts have their roots in Piaget's theories that led to constructivism (Blikstein et al., 2017; Hsu et al., 2017; Martin, 2015), Montessori's approach of *learning by playing and building* (Hsu et al., 2017; Martin, 2015), Dewey's experiential education *learning by doing* (Blikstein, 2018; Blikstein et al., 2017; Corsini & Moultrie, 2018; Hsu et al., 2017; Schön et al., 2014), Freire's critical pedagogy (Blikstein, 2013), project-based science (Schneider, Krajcik, Marx, & Soloway, 2002, as cited in Halverson & Sheridan, 2014), problem-based learning (Schwartz, Mennin, & Webb, 2001, as cited in Halverson & Sheridan, 2014), and Papert's constructionism or *learning by making* (Blikstein, 2013; Chu et al., 2015; Hsu et al., 2017; O'Brien et al., 2016; Suero Montero et al., 2018).

One of the characteristics of making is indeed the fact that "it requires a tacit integration of prior knowledge and skills with any new skill or knowledge that is being introduced or acquired for the project at hand" (Chu et al., 2015, p. 13), which relates to Papert's constructionism and are "at the very core of what "making" and digital fabrication mean for education" (Blikstein, 2013, p. 5). Digital fabrication offers students the possibility of empowerment, which is related to Freire's vision of education (Blikstein, 2013).
The beneficial aspects of digital fabrication in education have been discussed in several papers and research. Blikstein (2018) observed a number of benefits related to the use of digital fabrication activities in the classroom, such as providing students with a place where they could "make, build, and share their creation [and accelerate] the process of ideation and invention" (Blikstein, 2013, p. 209).

Digital fabrication is mainly studied as a way of promoting Science, technology, engineering, and mathematics (STEM) education. It is in fact increasingly used in the classroom with this purpose (Blikstein, 2013; Chu et al., 2015; Hsu et al., 2017; Lorenzo & Lorenzo, 2018; Martin, 2015; Nemorin, 2017; Schön et al., 2014) for its capacity to "engage children in complex uses of technology, that those same children could actively construct with technology rather than just consume technological products" (Blikstein, 2013, p. 6). Digital fabrication also allows students to test the scientific theoretical knowledge acquired in the classroom through hands-on activities (Lorenzo & Lorenzo, 2018) and it is strictly linked to engineering practices such as defining problems and finding solutions (Martin, 2015).

Another reason to use digital fabrication for STEM education is proposed by Chu et al. (2015) who refer to Vygotsky's concept of *everyday knowledge* and *scientific knowledge.* What happens in "traditional" education is that students receive scientific knowledge that is not necessarily learned until that same knowledge is applied in the students' daily life. Everyday knowledge lays "the foundations for learning scientific (or academic or schooled) concepts" (Fleer & Ridgway, 2007, p. 25) and the two concepts are strictly related to one another and they mutually reinforce each other.

Another benefit is that learning happens on different levels: students not only learn the *scientific knowledge* planned in the standard, formal educational curriculum, they also learn about to use software and tools, the process of designing their artefact, and “the engineering that goes into invention and innovation” (Lorenzo & Lorenzo, 2018, p. 7836). In Blikstein’s words (2018) these “technological tools would … enable students to design, engineer, and construct complex artifacts, also enabling a variety of new forms of work and expression” (p. 421).

2.3.2 Digital fabrication for creativity

“The maker movement refers broadly to the growing number of people who are engaged in the creative production of artifacts” (Halverson & Sheridan, 2014, p. 496)

Makers seem to be considered as “intrinsically” creative (Hatch, 2014; Martin, 2015; Sheridan & Konopasky, 2016). The whole idea of the maker movement turns around the assumption that makerspaces allow people to be “creative”, to make “creative products”, because they have the freedom and the motivation to explore, design, thinker, and make thanks to the endless possibilities offered by digital fabrication (Hatch, 2014). The practice of making is, almost by definition, to be considered as “creative, innovative, and interdisciplinary” (Fields & Lee, 2016, p. 121) and makerspaces as places where “creative endeavors take place” (Regalla, 2016, p. 257).

The success of Makerspaces and FabLabs in fostering creativity led to questioning their use in educational settings. Many in the Maker movement praised such approach (Blikstein, 2013; Blikstein et al., 2017; Halverson & Sheridan, 2014; Martin, 2015; Peppler et al., 2016; Schön et al., 2014; Suero Montero et al., 2018). For example:

> maker tools and maker movement will challenge and develop [students’] ability to construct something, and potentially to construct something new, creative and innovative .... The skills of creating and innovating can have a broad impact on students’ lifelong learning and ultimately for education and society. (Schön et al., 2014, p. 8)

According to Blikstein (2013), who associates creativity with innovation, digital fabrication has the advantage of accelerating invention and innovation since students “can focus their attention on improving the design rather than taking care of mundane issues with the materials” (p.7). Peppler et al. (2016) argue that through making “students can discover creativity in themselves” (p. x). Another advantage offered by digital fabrication that can foster students’ creativity are the - potentially endless- opportunities that open up in front of them to explore, discover, shape and create (Suero Montero et al., 2018).

As discussed in the previous chapter, Ingold's improvisational view of the “process of making” is consistent with the hypothesis that digital fabrication can foster student’s creativity. Any design “does not develop along a single predetermined trajectory” (Corsini & Moultrie, 2018,

p. 1023) and the student-makers, while interacting and engaging with the tools, the materials, and the environment, have the opportunity to make their initial idea evolve and take shape (Corsini & Moultrie, 2018; Nemorin, 2017), so as to "respond to situated factors" (Corsini & Moultrie, 2018, p. 1023). Students can, for example, "play" with the digital tools, explore and change different parameters, and new and unforeseen designs can take shape.

This improvisational aspect is also associated, in design, to the concept of "emergences" proposed by Gero (Corsini & Moultrie, 2018) or the "affordances" proposed by Glăveanu (2013, 2015). Emergence "is the process of making features explicit that were previously only implicit" (Corsini & Moultrie, 2018, p. 1024) as this "facilitates the development of creative design" (Corsini & Moultrie, 2018, p. 1024). The concept of emergence is also related with novelty "in the sense that novelty expands design possibilities" (Corsini & Moultrie, 2018, p. 1024), which is one of the main characteristics associated with creativity, as seen in the previous chapters.

Some authors also argue that digital fabrication fosters creativity as a (creative) problem-solving (Blikstein, 2018; Blikstein et al., 2017; Hsu et al., 2017; Lorenzo & Lorenzo, 2018; Peppler et al., 2016) or associate it with the acceleration of innovation (Blikstein, 2018).

As seen in Chapter 1.3, when discussing Davies et al. (2013) literature review of creativity in education, learning environments that support students' creativity are those where learning activities involve "the making of artefacts" (p.84), where students are given access to "new or different media and technologies" (p.84) and where they are encouraged to pursue "exploring and imagining" (p. 85). All these characteristics apply to makerspaces activities, and as such, support the arguments that digital fabrication can foster students' creativity.

Nonetheless, the issue with all the above arguments is that they seem to be coming from a direct transposition to the educational context, of what defines the maker movement, making, and makers in contexts that are - habitually - outside a classroom. An educational setting is, however, different to a makerspace. Also, education in schools is - generally - constrained to strict requirements, standards, programmes, curricula, evaluations and examination (Halverson & Sheridan, 2014; Lorenzo & Lorenzo, 2018; Nemorin, 2017) that might do just the opposite. In fact, other authors are doubtful or - at least less optimistic - and argue that school settings put limitations on students' creative potential and argue that digital fabrication could actually hinder students' freedom of action (Corsini & Moultrie, 2018; Nemorin, 2017). Creativity could, for example, be "constrained by a computer application" (Nemorin, 2017, p. 533) as students might feel discouraged by the software complexity, or even detached from their artefact as they are less involved "manually" in its fabrication (Nemorin, 2017).

As pointed out by Corsini and Moultrie (2018), there has not been much research on how digital fabrication influences creativity and creative design and whether this influence is positive or negative. As the authors point out, digital fabrication might have a positive effect on creativity as "digital tools may enable designs that were not previously possible" (p.1021). However, it might also have a negative effect, as it could hinder design and reduce “the potential for improvisation” (p. 1021), as well as encourage “the production of replicas” (p. 1021) or even the “trivialisation” of the design (Blikstein, 2013). This last phenomenon is also described by Blikstein (2013) as the *keychain syndrome*. The author illustrates the results of a workshop he held in 2009, where - in the first part - students had to learn to engrave using a laser cutter to make simple keychains before moving on to more complex subjects. His project was so successful that it backfired: students would keep making and making keychains and very reluctantly move on to more complex concepts, such as robotics and electronics (Blikstein, 2013). As a result, Blikstein (2013) noted that students “were using the lab as a fabrication facility, rather than a place for invention” (p. 9).

As seen in this chapter, while there is a lot of interest around making as a school activity in general, and digital fabrication as a way to foster creativity in education in particular, empirical research on its effectiveness - which could provide an explanation on how digital fabrication affects students’ creativity - seems scarce (Corsini & Moultrie, 2018; Hsu et al., 2017; Nemorin, 2017; Suero Montero et al., 2018).

3.Research objective

3.1 Summary of the problem

The previous chapters highlighted the importance of the so-called 21st century skills in modern society in general, and in education in particular. In order to prepare the future of our workforce, there is a need to incorporate these skills in educational programs or curricula. One level of difficulty is related to the complexity of these skills and their transversality.
Among these skills, Chapter 1 drew attention to creativity, as it is considered one the most important among the 21st century skills (Azzam, 2009; Dawes & Wegerif, 2004; Glăveanu et al., 2020; Mishra & Henriksen, 2013). Creativity was also shown through the lense of three frameworks: the P21, the ISTE Standards, and the KSAVE model.

The chapter also highlighted some difficulties related to the teaching of creativity. One is that a creative product (or idea), by its own definition, cannot be specified beforehand (Gehlbach, 1987), showing the difficulties of designing instruction and assessment aimed at creativity as the outcome. Also, intentional teaching should be involved, so that the learning will happen incidentally rather than accidentally (Gehlbach, 1987; Torrance, 1972). Activities meant to foster creativity should involve idea generation, problem finding, divergent thinking, and conceptual combination (Scott et al., 2004)

The problem of the creative-supportive environment was also discussed, highlighting the importance of environments that provide opportunity for discovery and use of imagination (Beghetto & Kaufman, 2014; Nickerson, 2019); that involve the making of artefacts and give students access to new tools and technologies (Davies et al., 2013) ; where the tasks are authentics (Davies et al., 2013) and framed within the boundaries of functional constraints (Gehlbach, 1987).

The assumption that was made based on literature, is that creativity can be taught, learned and fostered (Amabile, 1983; Beghetto & Kaufman, 2014; Davies et al., 2013; Scott et al., 2004; Torrance, 1972). The question is, therefore, not whether it is possible to teach, learn, or foster creativity, but rather how. What disciplines, activities, learning processes or approaches, and environment that correspond to the criteria discussed above can foster students' creative abilities? And then, how can we measure the "success" of any given strategy? How can we assess a creative teaching program? In other words, how do we measure creativity in the classroom?

In Chapter 2, a first, broad definition of creativity was given as a skill that implies the production of novel and useful ideas (Beghetto & Kaufman, 2014; Mumford, 2003; Runco & Jaeger, 2012; Simonton, 2000, 2012; Westberg, 1996). Other definitions relate creativity with problem-solving and divergent thinking (Guilford, 1956; Sternberg & Grigorenko, 2001; Undheim & Horn, 1977; Wallach & Torrance, 1968).

As discussed at the end of Chapter 2, there is some evidence that digital fabrication might indeed provide the tools and the types of activities that would stimulate and promote students' creativity, as it gives participants opportunities to create something new and useful while making, thereby experiencing creativity (Corsini & Moultrie, 2018; Fields & Lee, 2016; Hatch, 2014; Regalla, 2016).

In view of what is known about the context and what emerged from the review of the literature, the problem can now be classified, and a research question can be formulated.

3.2 Research questions

To define a researchable question, the S.PI.D.E.R. tool was used, as it is "more suited to qualitative research questions" (Cooke et al., 2012, p. 1439). The letters of the acronym stand for:

1. S as in Sample
2. PI as in Phenomenon of Interest
3. D as in Design
4. E as in Evaluation
5. R as in Research Type

Table 3 below summarises the definition of a researchable question using the S.PI.D.E.R. tool.

Table 3

Defining a researchable question using the S.PI.D.E.R. tool

Sample	**Phenomenon of Interest**	**Design**	**Evaluation**	**Research Type**
Studies studying digital fabrication activities in educational settings	Fostering creativity through digital fabrication	Systematic literature review	Effect on digital fabrication on students' creativity	Qualitative

The S.PI.D.E.R. strategy allowed to formulate a general research question as follows:
In what ways have researchers addressed digital fabrication as a means to foster students' creativity in educational settings?

This general research question was then broken down into the following research questions:

1. Do studies show that digital fabrication fosters students' creativity in an educational setting?

    a. If so, which creativity traits were enhanced?
2. How has creativity been measured?
3. What educational interventions involving digital fabrication activities were successful in fostering students' creativity?
    a. In which context and or which education level (primary school, secondary school, university, post-education/professional, etc.) were they performed?
    b. In which domain (STEM, arts, design, etc.)?

The S.PI.D.E.R. was also utilised to define search criteria for the literature review. The search criteria are summarised in Table 4 below.

Table 4

Defining search criteria using the S.PI.D.E.R. tool

Sample	**Phenomenon of Interest**	**Design**	**Evaluation**	**Research Type**
Students performing digital fabrication activities in educational settings	Creativity	Descriptive, explanatory, exploratory, experimental designs	Evidence of creativity	Experimental (qualitative, mixed method, quantitative studies)

4. Methodology

To ensure that the review was systematic, and conducted so as to be structured, transparent, and comprehensible, the researcher used the PRISMA guidelines and carried out the following steps:

1. Scoping the review
2. Searching for studies
3. Screening studies

The first step has been developing explicit criteria for specifying studies that would be included in the review (see below "Inclusion criteria"), listing the search keywords and the most appropriate databases. The S.PI.D.E.R. strategy was also utilised to define inclusion criteria.

1. Article mentioning creativity and digital fabrication in educational contexts, both formal and informal
2. Empirical, peer reviewed, and rigorous (explicitly mentioning process of data collection and analysis), studies using qualitative, quantitative or mixed methods
3. Studies mentioning the creativity definition that was applied, the creativity model or framework that was used, or the assessment instrument used to measure creativity
4. Descriptive, Explanatory, Exploratory or Experimental studies

Additional criteria were:

1. The studies were published in the last ten years
2. The studies were written in English, French or Italian

4.1 Selection criteria

4.1.1 Article mentioning creativity and digital fabrication in learning environments

Educators are being called upon to include creativity in their classroom, curricula, and programmes. Therefore, although digital fabrication activities could be performed in other environments than the classroom, such in *FabLabs*, makerspaces or techshops, this study aims at investigating the fostering of creativity in the classroom. Classroom social dynamics, instructional designs, assignments/structured activities, and assessments make these environments quite specific and add constraints that do not reflect in, for example, a *FabLab* or a makerspace. As mentioned in Chapter 1.3 "creativity is a particularly difficult skill to subject to instructional designs" (Gehlbach, 1987, p. 36) and it is "situated", that is, it depends on the context (Mishra, & Henriksen, 2013). Therefore, it is important to understand what happens at this level if we wish to create instructional programs and shape learning environments that promote and foster this 21st century skill.

4.1.2 Empirical, peer reviewed, and rigorous studies using quantitative, qualitative or mixed methods

Only articles reporting on empirical or evidence-based research were selected since they are ‘‘a systematic attempt to collect information about an identified problem or question, the analysis of that information, and the application of the evidence to confirm or refute some prior statement(s) about the problem or question under study’’ (Callahan & Moon, 2007, p. 307).

The objective of this systematic review is to investigate whether digital fabrication is effective in fostering students' creative skills and only empirical studies could provide this answer. Additionally, if literature shows the effectiveness of digital fabrication, research design that presents positive findings could help shed light on "best practices" to apply when designing learning programs that could foster creativity. For the same reason, an additional criterion that was used was to only include rigorous studies, explicitly mentioning the process of data collection and analysis.

4.1.3 Studies explicitly mentioning the creativity model or framework

Since the evaluation of the "results" will depend on the model or framework used by the researcher to capture a particular aspect or characteristic of creativity, only studies explicitly mentioning the focus of the study will be included, as was also stated by (Treffinger et al., 2002): "The definition of creativity that a researcher adopts will greatly influence the selection of the aspects of this construct that are to be studied and, in turn, the instrument chosen to measure them" (p.8).

Table 5

List of search terms guided by S.PI.D.E.R. tool

S.PI.D.E.R. TOOL	**Search terms/inclusion criteria**
Sample	classroom OR class* OR school OR education OR learning
Phenomenon of interest	Creativ* AND Digital Fabrication OR mak*
Design	Descriptive, Explanatory, Exploratory, Experimental studies; qualitative interview, content analysis, ethnographic research, phenomenological research, semantic analysis interview, case study, grounded theory, observation, phenomenological study, rubric*, questionnaires
Evaluation	Creativity assessment instrument, creativity definition, framework/model for creativity
Research type	Empirical, quantitative, qualitative analysis, mixed-methods

5. Data collection

At the end of three research iterations using the keywords defined in Table 5, a total of 1075 references were found in several databases (the complete list is included in Annex 3); 1025 of them were excluded through a screening of the title and the abstract as they didn't meet the selection criteria defined through the S.PI.D.E.R. tool (Table 5). At the end of the screening process, 50 of them were further analysed against the inclusion criteria. A total of 35 references were further discarded: 15 were excluded because they were not research articles, 7 didn't explicitly investigate or define creativity and 6 didn't use digital fabrication. For the remaining reference, the full text was not available. At the end of this process, 15 articles were retained. After a more careful reading, 4 additional articles were discarded because the inclusion criteria were not completely fulfilled. Four additional references were added analysing the references cited in the retained articles.

A total of 15 articles were retained for data analysis.

The figure below presents the different steps of the research selection based on the PRISMA guidelines:

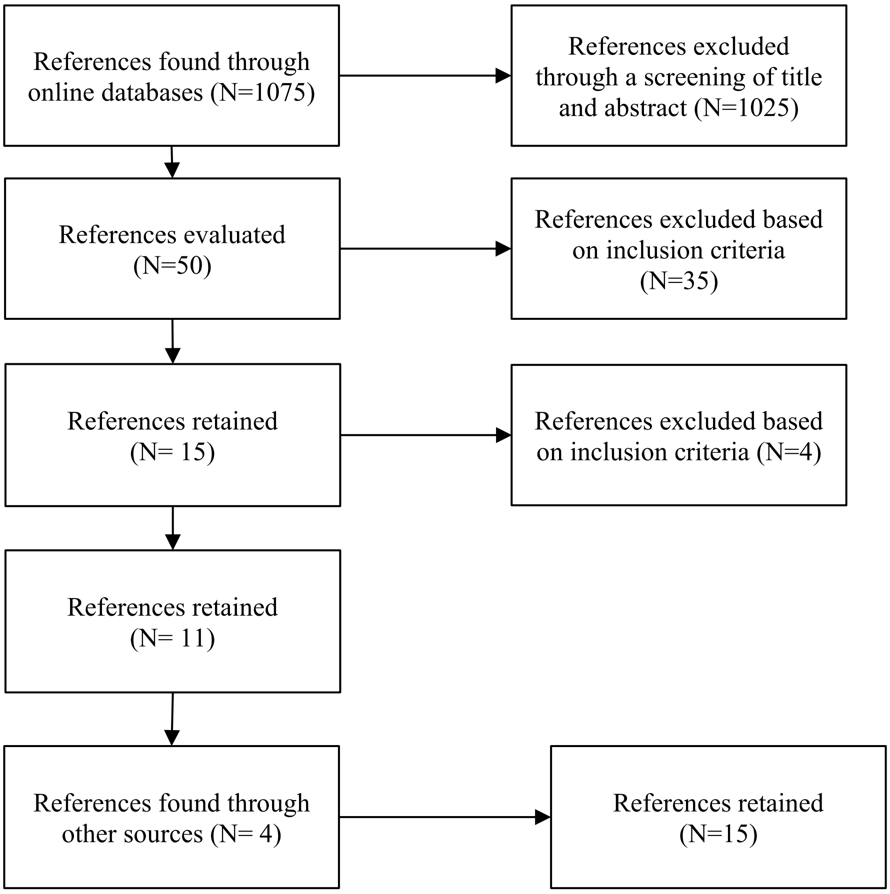

Figure 2. PRISMA guidelines and research iterations

5.1 Corpus

Austin, J. B. (2017). *Making it Matters: Makerspaces' Impact on Creativity in an Elementary School Media Center*. Gardner-Webb University.

Carbonell-Carrera, C., Saorin, J. L., Melian, D., & de la Torre Cantero, J. (2017). 3D Creative Teaching Learning Strategy in Surveying Engineering Education. *EURASIA Journal of Mathematics, Science and Technology Education*, *13*(11), 7489–7502. https://doi.org/10.12973/ejmste/78757

Carbonell-Carrera, C., Saorin, J., Melian-Diaz, D., & de la Torre-Cantero, J. (2019). Enhancing Creative Thinking in STEM with 3D CAD Modelling. *Sustainability*, *11*(21), 6036. https://doi.org/10.3390/su11216036

Chien, Y.-H. (2017). Developing a Pre-engineering Curriculum for 3D Printing Skills for High School Technology Education. *EURASIA Journal of Mathematics, Science and Technology Education*, *13*(7). https://doi.org/10.12973/eurasia.2017.00729a

Chien, Y.-H., & Chu, P.-Y. (2018). The Different Learning Outcomes of High School and College Students on a 3D-Printing STEAM Engineering Design Curriculum. *International Journal of Science and Mathematics Education*, *16*(6), 1047–1064.

García, G., Presentación Caballero, & Fernandez, T. G. (2018). Makerspaces and scientific creativity level of middle school students. *Global Journal of Arts Education*, *8*(2), 75–83. https://doi.org/10.18844/gjae.v8i2.3767

Lille, B., & Romero, M. (2017). Creativity Assessment in the Context of Maker-based Projects. *Design and Technology Education: An International Journal*, *22*(3), 32–47.

Lin, K.-Y., Lu, S.-C., Hsiao, H.-H., Kao, C.-P., & Williams, P. J. (2021). Developing student imagination and career interest through a STEM project using 3D printing with repetitive modeling. *Interactive Learning Environments*, 1–15. https://doi.org/10.1080/10494820.2021.1913607

Melián Díaz, D., Saorín Perez, J. L., De La Torre Cantero, J., & López Chao, V. (2020). Analysis of the factorial structure of graphic creativity of engineering students through digital manufacturing techniques. *International Journal of Engineering Education*, *36*(4), 1151–1160.

Prabhu, R., Bracken, J., Armstrong, C. B., Jablokow, K., Simpson, T. W., & Meisel, N. A. (2020). Additive creativity: Investigating the use of design for additive manufacturing to encourage creativity in the engineering design industry. *International Journal of Design Creativity and Innovation*, *8*(4), 198–222.

Saorín, J. L., Melian-Díaz, D., Bonnet, A., Carbonell Carrera, C., Meier, C., & De La Torre Cantero, J. (2017). Makerspace teaching-learning environment to enhance creative competence in engineering students. *Thinking Skills and Creativity*, *23*, 188–198.

Stansberry, S., Thompson, P., & Kymes, A. (2015). Teaching Creativity in a Master's Level Educational Technology Course. *Journal of Technology and Teacher Education*, *23*(3), 433–453.

Unterfrauner, E., Voigt, C., & Hofer, M. (2021). The effect of maker and entrepreneurial education on self-efficacy and creativity. *Entrepreneurship Education*, *4*(4), 403–424.

Walan, S. (2021). The dream performance – a case study of young girls' development of interest in STEM and 21st century skills, when activities in a makerspace were combined with drama. *Research in Science & Technological Education*, *39*(1), 23–43. https://doi.org/10.1080/02635143.2019.1647157

Weng, X., Cui, Z., Ng, O.-L., Jong, M. S. Y., & Chiu, T. K. F. (2022). Characterizing Students' 4C Skills Development During Problem-based Digital Making. *Journal of Science Education and Technology*, *31*(3), 372–385.

6. Data analysis

The heuristic applied during the data analysis process followed a "general inductive approach" (Thomas, 2006), so as to "explore and infer … from the particular to the general" (Saldaña, 2011, p. 93). Inductive analysis "refers to approaches that primarily use detailed readings of raw data to derive concepts, themes, or a model through interpretations made from the raw data by an evaluator or researcher" (Thomas, 2006, p. 238).

The analytic strategy was adapted from Thomas (2006):

- Multiple readings and interpretation of the raw data, guided by the evaluation objectives in order to "identify domains and topics to be investigated" (p. 239)
- Categories are developed from the raw data, and the evaluator must decide "what is more important and less important in the data" (p.239). There are two levels for the categories:
    a. Upper-level categories: more general, derived by the evaluation objectives
    b. Lower-level categories: specific, "derived from multiple readings of the raw data" (p. 241)
- Categories are combined "or linked under a superdordinate category when the meanings are similar" (p. 242).

This process aims at establishing a limited number of summary categories (Thomas (2006) suggests between three and eight categories) that "capture key aspects of the themes identified in the raw data" (p. 242).

Specifically, the researcher followed the following steps:

1. Development of the code book
2. First round of coding, in order to "patterning classifying, and later reorganizing each datum into emergent categories for further analysis" (Saldaña, 2011, p. 95)
3. Post-coding transition, so as to classify codes "into similar clusters" (Saldaña, 2011, p. 95)
4. Second round of coding

The process of data analysis is described in the following sections.

6.1 Code book development

The researcher analysed the list of categories derived from the inclusion criteria and did a first reading of the articles in the corpus in order to create the code book shown in Table 6 below.

The first code book was developed with an exploratory coding approach (Saldaña, 2013) using attribute coding and containing descriptive codes (i.e. nouns that describe and summarise the data), so as to encapsulate the subjects of the data, as described by Miles and Huberman (1994). Descriptive codes also help "index the data corpus' basic contents for further analytic work"

(Saldaña, 2011, p. 104). As described by Saldaña (2013), attribute coding methods are used as a "management techniques" (p. 64) and as a "coding grammar" (p.71), as they allow the researcher to gather essential information in the data, such as participants, sample size, contexts, etc.

Table 6
First Code book

CODE	CATEGORY	DESCRIPTION
ATT:Participants	Attribute	Study participants, the grade (middle school, high school, university), level of expertise with DF
ATT:Sample size	Attribute	How many participants in the study
ATT:DF technology	Attribute	Digital Fabrication tool used and studied
ATT:data collection	Attribute	The way data were collected
ATT: Methodology, methods and Research design	Attribute	Methodology (qualitative, quantitative, mixed-study), Methods (observations, interviews, surveys or questionnaires, experiments...) and research design (case study, ethnographic, experimental, quasi-experimental, …)
ATT:Rationale	Attribute	Rationale and motivation for the research (for example pedagogical principle, industry need, national policy implementation)
ATT:data analysis	Attribute	The way data were analysed
ATT:research question	Attribute	The research question of the study
ATT:research subject	Attribute	The subject and the objective of the study, the problem on which the research is focused
ATT: Limitations	Attribute	The limitation of the study, either explicitly mentioned by the author(s) of the study or noted by the reviewer
ATT:Results	Attribute	Results of the study on digital fabrication as a means to foster students's creativity in an educational setting
ATT:Digital Fabrication contribution	Attribute	Explicit characteristic of digital fabrication that stimulates or hinders creativity

ATT: Intervention	Attribute	Type of intervention (experiment, workshop, seminar, lecture, course, e-learning, etc) and how it was implemented.
ATT:context	Attribute	The context (domain, formal VS informal learning setting, school, university, library…) where DF and creativity were studied
ATT:Creativity definition	Attribute	The theoretical approach used to study creativity, i.e. the creativity model, framework or definition on which the research was based
ATT:Creativity characteristic	Attribute	The creativity characteristic, aspect, or metric that is measured
ATT:Creativity assessment instrument	Attribute	The instrument used to assess students' creativity: test, survey, questionnaire, interview, etc.

6.2 Post coding transition and second round of coding

After a first round of coding using the code book described in Table 6, an analysis of the coded items was performed by the researcher through post coding transitions (Saldaña, 2013). The goal of the transition is to

> [select] new coding methods for a reanalysis of [the] data; [construct] categories from the classification of [the] codes; [draw] preliminary models of the primary actions at work in [the] data; and [reorganise] and [reassemble] the transformed data to better focus the direction of [the] study. (Saldaña, 2013, p. 187)

This analysis allowed the researcher to identify broader categories that could be generalised into group codes, in order to answer the research questions.

The first step of the transition was Code Mapping as a way to organise and assemble the codes developed in the first coding process (Saldaña, 2013). The researcher analysed the individual coded segments (for each code defined in the code book) and was able to define the following 6 categories:

1. Level of education of the participants
2. Domain of the study
3. Setting of the study
4. Intervention
5. Instrument used to measure creativity
6. Creativity characteristics - either measured by the instrument chosen or implied in the creativity definition/framework utilised in the study.

All the items in the above categories were listed and further analysed by the researcher. They were then grouped when similarities emerged. For example, all the instruments used to measure creativity were grouped by type: psychometric tests, questionnaires, scales, etc.

The 51 creativity characteristics that were studied and measured in the 15 articles of corpus - listed by the researcher in this phase of the study and detailed in Annex 2 - were thoroughly analysed through a scrutiny of their definitions[3], "abstracted or conceptualized further to discern semantic, logical, or theoretical links and connections between and across the categories" (Given, 2008, p. 72). This thematic analysis, also referred to as pattern coding (Miles & Huberman, 1994), allowed the researcher to interpret and make sense of the data (Maguire & Delahunt, 2017) and, done at a semantic level, allowed to further group the 51 characteristics into 10 subcategories, based on similarities in their definitions (Annex 1). Table 7 below illustrates two examples of how multiple definitions for creativity characteristics were grouped into subcategories.

[3] If a definition for a characteristic was not provided in a study but referenced to in the text of the article, the researcher located the source mentioned in the study and utilised the original definition.

Table 7

Examples of categorization and theming of creativity characteristics

Characteristic	**Definition**	**Sub-category**	**Definition**
Originality/ Original thinking/Original ideas	*"Measures the ability to make different responses to the rest of the group (unusual and unconventional responses)" (Carbonell-Carrera et al., 2017, p. 7494).*	**Originality**	*"The subject's ability to produce ideas well beyond the obvious, commonplace, banal, or established" (Torrance, 2008, p. 9)*
Novelty	*"The novelty dimension includes 3 variables: form (overall originality of the form design), materiality (originality in the selection of materials), Structure (originality in the design parts)" (Chien & Chu, 2018, p. 1054).*		
Fantasy/ Willingness to fantasise	*"The representation of something that does not exist" (Carbonell-Carrera et al., 2017)*		
Uniqueness	*"Evaluates the originality of the design in comparison to other designs generated in the sample." (Prabhu et al., 2020, p.207)*		
Unusual visualisation	*"This measure points out an individual who sees things in new ways as well as old ways and who can return repeatedly to a commonplace object or situation and perceive it in different ways." (Torrance, 2008, p. 4)*		
Initiating imagination	*"Initiating imagination can be defined as the capability to explore the unknown and productively originate novel ideas." (Liang & Chia, 2014, p. 111)*		

Boldness	*"The confidence to push boundaries beyond accepted conventions … also the ability to eliminate fear of what others think of you." (StanSberry et al., 2015, p.445)*	**Exploration**	The ability to make something different from what is usual or from the way most people do things, go beyond conventions, explore
Extending or breaking boundaries	*"Extend the lines, up, down or out ; split the imaginary rectangle" (Torrance, 2008, p. 4)*		
Curiosity	*"The desire to change or improve things that everyone else accepts as the norm" (StanSberry et al., 2015, p.445)*		
Figurative expansion	*"It measures the space occupied by the drawing … This factor responds to an attitude or tendency to face risks and to exceed limits given" (Carbonell-Carrera et al., 2017, p. 7494)*		
Internal visualisation	*"This measure indicates that a subject is able to visualize beyond exteriors and pay attention to the internal, dynamic workings of things." (Torrance, 2008, p. 4)*		
Synthesis of lines or circles	*"The combination of two or more lines or circles is quite rare and points out an individual whose thinking departs from the commonplace and established, who is able to see relationships among rather diverse and unrelated elements, and who, under restrictive conditions, utilizes whatever freedom is allowed" (Torrance, 2008, p. 4)*		

This further grouping allowed to limit the number of codes and simplified the coding process so that the researcher could focus on variables relevant to the research questions and understand if and how digital fabrication had an impact on the creativity of the participants of the research at study. The 6 categories of codes and the items included in each category are summarised in Table 8 below.

Table 8
Categories for coding

Category	Description	Items in the Category
Creativity Characteristics[4]	The creativity characteristics measured in the studies.	Subcategories: Perseverance, Exploration, Originality, Synthesis, Expressive communication, Imagery abilities, Usefulness, Self-efficacy, Fluency, Flexibility
Level of Education	Level of education of the participants of the studies	Primary education, Secondary education, Tertiary education, Professional development
Domain	The educational domain in which the intervention took place	Engineering, Computer science, STEM, STEAM, Education technology, Design, General education, Science
Setting	The context/place where the study took place	School/Class, Company, Outside school, School media centre
Intervention	The type of intervention used in the research	Workshop, Lecture(s), Programme, Course, Online course, Curriculum, makerspace activities, Sponsored programme, Classroom activities, Design Challenge, Problem-solving activities
Instrument[5]	The instrument used to assess students' creativity	Scale, Questionnaire, Psychometric Test, Rating, Survey

Before the second round of coding, the documents were also grouped by:

- Type of research
- Type of intervention
- Type of population (education level)
- Type of instrument
- Type of domain

[4] The complete list of grouped categories and characteristics included in each category is available in Annex 1

[5] "*Instrument" for qualitative research was analysed with code "data analysis" when a specific instrument was not specified*

All the articles in the corpus were coded again applying codes derived from the categories described in Table 8. The results of the data analysis are presented in the following chapter.

7. Results

7.1 General description of the results

The first observation to be made is that only a limited amount of research (n=15) has studied, in the last ten years, the role of digital fabrication in fostering creativity in educational contexts, either formal or informal. All the studies found were written in English and published between the years 2015 and 2021.

Secondly, more than a half of the studies were focused on STEAM or STEM (n=8, three and five, respectively) and almost a half (n=7) were conducted specifically in the Engineering domain. Two interventions addressed future teachers in the Education Technology domain, one was interested in Science. In one study the context was not specified as the research was conducted in several different countries as part of a European project.

One third of the studies (n=10) used 3D modelling and printing as the digital fabrication tool. Only three studies were qualitative and one used mixed methods. The majority of the studies were quantitative (n=11). The researcher counted 51 creativity traits measured across the 15 studies. These characteristics were determined by the creativity definition, framework, or model that was applied, which in turn, determined the instruments used to assess creativity. In the course of the analysis process, as specified in the Data analysis section of this study, the researcher grouped into ten categories those traits whose definitions - when provided - were equivalent or similar, so as to limit the number of codes and make it easier to spot recurrent elements and emerging themes.

Of the 15 studies, four were conducted with university students, two with university and high school students, two with primary and secondary school students, three in secondary schools only, and one in primary schools only; two were conducted in a professional setting and one in an informal learning setting.

The 15 studies in the corpus employed "traditional" definitions of creativity, such as involving novel and useful ideas, divergent thinking, or problem-solving. For example, Lille and Romero (2017) acknowledge "creativity as an individual or collaborative reflective iterative process … valued by a group of references in a context-specific situation" (p.2). However, the authors still view creativity as "defined by the balance residing between divergent, convergent and associative thinking" (Lille & Romero, 2017, p. 2) and cite Guilford for his studies on divergent thinking. García and Fernandez (2018) make explicit reference to Guilford Structure of the Intellect (SI) model, Carbonell-Carrera et al. (2019) also reference Guilford studies on divergent thinking in creativity.

The majority of the studies (n=10) applied the general/standard definition of creativity as involving ideas or products that are both novel and useful. In 5 studies (Chien, 2017; Chien & Chu, 2018; Lin et al., 2021; Prabhu et al., 2020; Walan, 2021), this definition was the only applied, while in three studies (Austin 2017, Carbonell-Carrera et al, 2019, Lille & Romero, 2017) this definition was also linked to divergent thinking and problem-solving. One study (Carbonell-Carrera et al, 2017) was focused on creativity as involving novel and useful ideas and as a form of divergent thinking; while one study (StanSberry et al., 2015) coupled the definition of novelty and usefulness with problem-solving. Three studies (García & Fernandez, 2018; Melián Díaz et al., 2020; Unterfraune, Voigt & Hofer, 2021) focused on creativity solely as a form of divergent thinking. Two studies (Saorín et al., 2017; Weng et al., 2022) linked creativity solely to problem-solving. Eleven different creativity assessment instruments were utilised, classified into 5 types: psychometric tests (n=6), scales (n=6), ratings (n=2), questionnaires/surveys (n=4), qualitative data analysis (n=3). Some studies utilised more than one instrument.

In eleven studies the researchers studied the creative process, in four the creative person, and in three the creative product. Some studies focused on more than one aspect at the time. None of the studies focused on the creative press.

The description of the sample is summarised in Table 9 below.

Table 9

Characteristics of the sample and their frequency of use

Sample description		Frequency of use
Research type	Qualitative	3
	Quantitative	11
	Mixed Methods	1
Context/setting	Tertiary education	4
	Tertiary education + secondary education	2
	Primary + secondary education	2
	Secondary education	3
	Primary education	1
	Professional setting	2
	Informal setting	1
Domain[6]	STEAM/STEM	8
	Engineering	7
	Computer Science	2

[6] In some research more than one domain was studied

	Educational Technology	1
	Design	2
	General Education	1
	Science	1
Digital Fabrication Tool[7]	3D printers/modelling	10
	Laser cutting	2
	Scratch	1
	Auto-CAD software	1
	Computer-controlled cutting machine	1
	Lego WeDo Robotics and software	1
	LittleBits circuits	1
	Not specified	3
Definition of creativity	Novelty and usefulness of ideas/products	5
	Divergent thinking	3
	Problem-solving	2
	Novelty and usefulness of ideas/products + Divergent Thinking	1

[7] In some studies more than one tool was used

	Novelty and usefulness of ideas/products + Problem-solving	1
	Novelty and usefulness of ideas/products + Divergent Thinking + Problem-solving	3
Focus	Person	1
	Process	9
	Product	3
	Person + Process	2
	Person + Product	1
Instrument used to measure creativity[8]	Psychometric test	6
	Scale	6
	Ratings	2
	Questionnaire/Survey	4
	Qualitative data analysis	3
Creativity characteristics enhanced	Originality	12
	Exploration	7
	Synthesis	7

[8] In some studies more than one instrument was used.

	Creative self-efficacy	5
	Expressive communication	4
	Imagery abilities	4
	Usefulness	4
	Connectivity	3
	Collaboration, collaborative creativity	2
	Elaboration	2
	Imaginative scope	2
	Figurative expansion	2
	Perseverance	2
	Fluency	1
	Flexibility	1
	Fantasy	1
	Scientific creativity	1

A detailed summary of the results is presented in Annex 5.

7.2 Results for creativity as "novel and useful ideas"

Table 10 below summarises the results of the studies that used the definition of creativity as implying originality and usefulness.

Table 10

Results of the studies using the definition of creativity as implying novelties and usefulness

Reference	Definition	Characteristics[9]	
		Originality	**Usefulness**
Austin, 2017	*"Cropley posed a working definition of creativity as an interaction between aptitude and process in an environment where a product is produced that is considered both novel and useful"(p.27)*	Y	Y
Carbonell-Carrera et al., 2017	*"Creativity is defined as the generation of ideas in a novel and useful (or appropriate) way" (p. 7493)*	Y	N
Carbonell-Carrera et al, 2019	*""creativity in engineering" is understood as a way of thinking that brings new ideas which are original and easy to apply in a functional and practical way" (p.1)*	Y	N
Chien, 2017	*"A revised version of the Creative Product Semantic Scale (CPSS) developed by Besemer and Treffinger (1981) was adopted as a rubric to evaluate seven variables in three dimensions of the students' work (Chang, 2003). The three dimensions were novelty, functionality, and sophistication." (p. 2950)*	Y	Y
Chien & Chu, 2018	*"A revised version of the Creative Product Semantic Scale (CPSS) (Besemer & Treffinger, 1981) was adopted as a rubric for evaluating seven factors related to the students' work along three dimensions (Chang, 2002). The three dimensions were novelty, functionality, and sophistication" (1054)*	N	N
Lille & Romero, 2017	*"We consider creativity as an individual or collaborative reflective iterative process (Runco, 2014) that aims to design a new, innovative and pertinent way to respond to a potentially problematic situation, which is valued by a group of references in a context-specific situation" (p.2)*	N	Y
Lin et al., 2021	*"Characteristics of imaginative capability into three types: (i) "Initiating imagination" encompasses exploration,*	Y	N

[9] (Y=enhanced, N=not enhanced)

	novelty, and making; (ii) "Conceiving imagination" includes effectiveness, diagnosis, feeling, intuition, and concentration; (iii) "Transforming imagination" includes figurativeness and adaptiveness." (p. 3)		
Prabhu et al., 2020	*"Creative products must be novel, relevant (useful), workable (feasible), and specific (elaborate), and the overall creativity of an idea can be obtained by taking an average of the ratings for these four components" (p. 203)*	Y	N
StanSberry, Thompson & Kymes, 2015	*"Authors of this paper adhere to Plucker, Beghetto, and Dow's definition: ''Creativity is the interaction among aptitude, process and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context'' (2004, p. 90)" (p.436).*	Y	Y
Walan, 2021	*"The concept of creativity (...) as a process over time, resulting in products that are novel (...) these can emerge from elements that already exist, but are combined in new ways" p.26*	Y	N

7.3 Results for creativity as "divergent thinking"

Table 11 below summarises the results of the studies that used a definition of creativity as divergent thinking, as they were presented in the articles of the corpus, as well as the the results of the analysis of the studies of the corpus through codes established using the operational definition of divergent thinking provided by Runco (2008) and discussed in Section 2.1.2 : "Divergent thinking actually refers to fluency, flexibility, and originality, for example, and evaluative processes include critical thinking as well as valuative and appreciative consideration" (p. 94).

Table 11

Results for creativity as divergent thinking

Reference	Definition of creativity in the study	Results for divergent thinking as presented in the studies		Results for divergent thinking analysed according to indicators defined by Runco (2008)			
		Results	Instrument used	Originality	Fluency	Flexibility	Elaboration
Austin, 2017	*"For the purposes of education, creativity is a skill students should cultivate to address the challenges of problem finding, problem solving, divergent thinking, and the creation of new ideas and products" (p.25)*	*"The researcher completed a paired sample t test for the group … the two-tail analysis resulted in a P value of .03 which would qualify the difference as significant because the value is less than the alpha value of .05" (p. 81)*	TTCT	Y	Y	Y	Y
Carbonell-Carrera et al., 2017	*"bring different solutions to the same problem, in a creative and novel way" (p. 7493)*	*"In the treatment group, there is a statistically significant difference (p-value<0.01) between the*	Abreaction Test for Creativity	Y	Y	N	Y

		pre-test (84.0) and the post-test (122.0) of 36.00 points in the Creativity Test Score. Students exercise their creativity by adopting different solutions around the same problem" (p. 7500)					
Carbonell-Carrera et al, 2019	*"A creativity workshop was proposed in order to find multiple solutions to the problem posed, according to divergent thinking, in which there were open-ended activities, problem finding, and a variety of solutions together in an original way" (p.2)*	*"The results of the ANOVA revealed a major effect of the test type, such that the post-test performance was higher than pre-test performance, F (1,70) = 18.02, p < 0.001" (p. 9)* *"The Stella 3D workshop, which was designed to foster students' ability to find multiple solutions to the same geometrical problem, improved the creativity of the participants in the treatment group" (p. 11)*	Abreaction Test for Creativity	Y	N	N	N
García & Fernandez, 2018	*"According to Guilford, creativity is mostly associated with 'divergent production' leading to a*	*"The experimental group experiences a variation in the post-test as a result of the intervention made*	Scientific Creativity Test	Y	Y	Y	N

	number of solutions of a particular problem" (p.76)	*through maker-centred learning, resulting in a greater standard deviation for almost every item"(p. 79)*					
Lille & Romero, 2017	*"creativity in educational contexts is defined by the balance residing between divergent, convergent and associative thinking" (p.2)*	*"Grade from 0 to 1.7 points .... The average grade for all 198 students was 1.5345 (sd=0.29)" (p. 9)*	Rubric-based assessment tool	N	N	Y	N
Melián Díaz et al., 2020	*"The activity, based on one of the definitions of creativity, consists of generating different solutions based on the same proposal" (p. 1154)*	*"at least 0.502 of variance in each variable" (p. 1159)*	Abreaction Test for Creativity	Y	N	N	Y
Unterfraune, Voigt & Hofer, 2021	*"Creativity is perceived as the ability to find different solutions for the same problem in the sense of divergent thinking and to turn these possible solutions into new opportunities (Baer, 2014)" (p. 408)*	*"The creativity score increased from the pre-test to the post-test by 1.59 points in the TCT-DP Test" (p. 413)*	Test for Creative Thinking-Drawing Production (TCT- DP)	N	N	N	N

7.4 Results for creativity as "creative problem-solving"

Table 12 below summarises the results of the studies that used a definition of creativity as problem-solving, as they were presented in the articles of the corpus, as well as the results of the analysis of the studies of the corpus through codes developed using an operational definition of problem-solving as provided in Treffinger et al. (2008): (1) understanding the Challenge, (2) generating Ideas (includes fluent, flexible, original, and elaborative thinking), (3) focusing phase, in order to "examine, review, cluster, and select promising ideas" (p. 392); (4) developing solutions. This definition was used as the authors "review and update models for understanding CPS [Creative Problem Solving] and problem-solving style" (p. 390), allowing the researcher to code and analyse the data with indicators supported by recent research.

Table 12

Results for creativity as problem-solving

Reference	**Definition of creativity in the study**	**Results for problem-solving as presented in the studies**	**Results for problem-solving analysed according to indicators defined by Treffinger et al. (2008)[10]**			
			Problem framing	**Divergent Thinking [11]**	**Synthesis**	**Developing solutions**
Austin, 2017	*"For the purposes of education, creativity is a skill students should cultivate to address the challenges of problem finding, problem solving, divergent thinking, and*	/	Y	Y	N	Y

[10] (Y=enhanced, N=not enhanced, /=details of the results not provided in the study)

[11] Divergent thinking was coded with: Originality, Fluency, Flexibility, Elaboration

	the creation of new ideas and products" (p.25)					
Carbonell-Carrera et al, 2019	*"Creativity is an important tool in the search for a more sustainable future, directly linked to innovation and creative problem solving" (p. 1)*	/	N	N	N	Y
Lille & Romero, 2017	*"a research project that aims to develop learners' 21st-century competencies, such as creative problem-solving" (p.4)*	*"In our maker-based activity, we induced students' need to acquire knowledge about educational technologies by engaging them in an inquiry about authentic educational issues in which they had to propose a creative and original way of addressing their selected educational issue" (p.12)*	Y	N	Y	Y
Saorín et al., 2017	*"the ability to engage in a creative process so as to define or solve a problem, or to design a product, is essential to engineering as a profession" (p. 188)*	/	N	N	N	N
StanSberry, Thompson & Kymes, 2015	*"one of the goals of the creativity course was to prompt participants to extend themselves beyond creative thinking and also become excellent problem solvers who*	*"Teachers learning creative problem solving in a manner that allows them to see themselves as creative individuals and realize that creative processes can be learned, practiced, and taught" (p. 443)*	Y	N	Y	Y

	discover novel solutions" (p.439)					
Weng et al., 2022	*"Creativity suggests using innovative approaches to finish a task, find a solution…" (p. 374).*	*"As the nature of the camp was focused on problem-based DM, we observed that the students did propose various creative solutions for certain problems presented during the camp" (p. 379)*	N	N	Y	Y

None of the studies in the corpus was able to develop all the characteristics associated with problem-solving.

8. Discussion

Our broad research objective was to study and analyse the ways researchers have addressed digital fabrication as a means to foster students's creativity in educational settings in the past ten years.

The research objective was broken down into the following research questions:

1. Do studies show that digital fabrication fosters students' creativity in an educational setting?
    a. If so, which creativity traits were enhanced?
2. How has creativity been measured?
3. What educational interventions involving digital fabrication activities were successful in fostering students' creativity?
    a. In which context and or which education level (primary school, secondary school, university, post-education/professional, etc.) were they performed?
    b. In which domain (STEM, arts, design, etc.)?

In the following sections, the researcher will first discuss these results by answering the research questions. This will make it possible to analyse the results in light of traditional VS modern creativity research and explain the strengths and limitations the author of this research has found in the different articles of the corpus.

Secondly, the results will be analysed through themes that have emerged during the analysis. These themes will help address possible future research in the field of creativity in education through the use of digital fabrication.

8.1 RQ1: Does digital fabrication enhance students' creativity?

As shown in the Results sections, all of the studies in the corpus adopted one of (or a combination of) three main definitions of creativity:

1. **Creativity as involving novel and useful ideas** (Austin, 2017; Carbonell-Carrera et al., 2017; Carbonell-Carrera et al, 2019; Chien, 2017; Chien & Chu, 2018; Lille & Romero, 2017; Lin et al., 2021; Prabhu et al., 2020; StanSberry, Thompson & Kymes, 2015; Walan, 2021)
2. **Creativity as a form of divergent thinking** (Austin, 2017; Carbonell-Carrera et al., 2017; Carbonell-Carrera et al, 2019; García & Fernandez, 2018; Lille & Romero, 2017; Melián Díaz et al., 2020; Saorín et al., 2017; Unterfrauner, Voigt & Hofer, 2021; Weng et al., 2022)
3. **Creativity as a form of problem solving** (Austin, 2017; Carbonell-Carrera et al, 2019; Lille & Romero, 2017; Saorín et al., 2017; StanSberry, Thompson & Kymes, 2015)

The instruments used in these studies were therefore meant to measure characteristics related to these definitions. The following sections will analyse and discuss the characteristics that were enhanced in the studies, in relation to these definitions.

8.1.1 Originality[12] and Usefulness

"The ability to produce ideas well beyond the obvious, commonplace, banal, or established". (Torrance, 2008, p. 9)

Originality is probably the single characteristic that scholars agree upon as a creativity attribute. Twelve studies out of the fifteen that made up the corpus revealed that participants improved in this aspect.

In Walan (2021) study, drama and making were both used as mediating artefacts and the researcher was not able to draw a conclusion whether it was one of the two (or a combination of both) that had contributed to the originality of the outcome (the ideas and the props created by the participants). The author suppose that creativity was also influenced by the support offered by the "community".

In Lin et al. study (2021) the characteristics coded with originality (initiating imagination) increased significantly in the experimental group (3D printing with repetitive modelling) with respect to the control group (problem-solving based hands-on activities without repetitive modelling where 3D printing was optional). Participants of the experimental group produced more original designs (earthquake-resistant structures) and they could reduce the time spent to solve issues "associated with traditional processing" (p. 11) and focus on the design process. It is not clear whether this improvement was also due to the fact that participants in the experimental group had the possibility to review and optimise their designs through repetitive modelling, as opposed to participants in the control group that "used problem-solving to guide them in the modeling activities, but they did not modify or optimize their designs through repetitive modeling" (p. 5).

Weng et al. (2022) study was more focused on programming for problem-based Digital Making (DM) than on actual fabrication. However, the study demonstrated that the participants (62, 10 to 14 years old, upper elementary and lower secondary school students) showed improved creativity and originality of the solutions to the problems provided in the learning activities. The positive results were attributed, in this qualitative study, to the problem-based learning activities, the openness of the instructions and the "automation" provided by digital making. The authors also noted that "problem-based DM environment provides opportunities for students to explore as many designs as they like effortlessly and effectively" (p. 380).

In Chien (2017) study it does not seem that the novelty component was influenced by the intervention. Only form, structure, consistency and attractiveness (characteristics rather proper to engineering design) were improved in the 3D group.

[12] *Characteristics included in this group were: originality, novelty, fantasy/willingness to fantasise, uniqueness, initiating imagination*

Usefulness[13] was only observed in four studies out of the eight that employed this definition of creativity. In one instance (StanSberry, Thompson & Kymes, 2015), usefulness was measured with a self-assessment commercial instrument - the AULIVE Survey - which was not designed for research purposes. The construct validity of this instrument is therefore in doubt and will be discussed in Section 9.4.2.

In Chien (2017) study, functionality and sophistication were both coded as usefulness. In this study, the participants, 182 high school students divided in two groups (108 that used 3D printers and 74 that didn't) had to make a CO_2 dragster at the end of the teaching experiment. The scores for sophistication for the 3D printing group were significantly higher than those of the handmade group but no significant difference was observed for functionality between the two groups. The higher score for sophistication was explained by Chien (2017) with the use of the 3D modelling software - not available to the students in the handmade group - that allowed the participants to easily alter their design as needed, thus obtaining more complex solutions. The lack of difference in the functionality score between the two groups was not explained by the researcher.

Even though not specifically mentioned in the article, it could be inferred that in the study by Lille and Romero (2017) participants effectively created useful solutions, for example in the instance where a group of students decided to "program a Sphero robot that would circulate around the city model in order to help them understand the concept of angles in mathematics" (p. 10). It would have been interesting to have more concrete examples of the participants' outcomes. This would have helped shed more light on how the intervention had an influence on the creative usefulness of the participants' ideas and productions. The question whether it was digital fabrication that had contributed to this aspect of creativity remains, thus, unanswered.

The studies from Carbonell-Carrera et al. (2017; 2019), although using this definition and measuring an improvement in the originality of the participants in the experimental group (through pre- and post-tests using the Abreaction Test for Creativity), were more focused on creativity as a form of problem-solving or divergent thinking. In Carbonell-Carrera, Saorin, de la Torre Cantero (2017), Melián Díaz et al. (2020), and Carbonell-Carrera et al. (2019) the problem-solving definition of creativity seems to be "related" to the domain at study, in engineering the outcome (product or design) must solve a problem and must solve it efficiently (effectiveness and usefulness of the solution). In addition, the instrument chosen to assess creativity did not have a variable for usefulness, as the Abreaction Test for Creativity is mainly used as a test for graphic creativity (as stated by the authors themselves).

In Austin (2017) study, the increased originality and usefulness components were inferred by the researcher through indirect connections that were not made explicit. The author

[13] *Usefulness, Functionality, Sophistication*

administered a pre- and post- test using the Torrance Test for Creative Thinking (TTCT) but only the overall/total score was discussed in the study.

In summary, out of the ten studies that adopted this definition of creativity, only 3 (Austin, 2017; Chien, 2017; StanSberry, Thompson & Kymes, 2015) seem to have proven their hypothesis that digital fabrication was successful in enhancing the creativity of the participants in both the originality and usefulness component. Of these three, one (StanSberry, Thompson & Kymes, 2015) used a commercial instrument not designed for research, and one (Austin, 2017) did not make explicit connections nor explained these results.

It is worth reflecting on the applicability of this definition in the context of education, especially on primary and secondary education: do ideas and products generated in a pedagogical activity really need to be useful to be creative? A case could be made in favour of certain domains and/or higher levels of education, such Engineering or Design, where - indeed - products should have some sort of "value", or usefulness. Usefulness could therefore be a criterion relevant to some domains (such engineering), but not others. We might exercise some precautions in generalising usefulness as a creativity characteristic to be assessed in lower educational levels such as primary schools.

Also, as Craft (2001) pointed out "how is novelty to be understood in the context of school pupils?" (p. 23). Should it be assessed with respect to other students' originality or "against each individual's past performance" (p. 23)?

8.1.2 Divergent thinking

In this study, divergent thinking was analysed with the codes for originality, fluency, flexibility and elaboration, following the definition of Divergent Thinking provided by Runco (2008).

Several studies (Austin, 2017; Carbonell-Carrera et al., 2017; Carbonell-Carrera et al, 2019; García & Fernandez, 2018; Lille & Romero, 2017; Melián Díaz et al., 2020; Saorín et al., 2017; Unterfrauner, Voigt & Hofer, 2021; Weng et al., 2022) directly associated creativity with divergent thinking even though divergent thinking was not a creativity variable (or combination of variables) directly measured by the assessment instruments that were used. For example, Carbonell-Carrera et al. (2019) proposed a workshop "in order to find multiple solutions to the problem posed, according to divergent thinking, in which there were open-ended activities, problem finding, and a variety of solutions together in an original way (...) The present research is based on divergent thinking" (pp. 2 - 3). But the instrument used, the Abreaction Test for Creativity, does not have indicators for fluency and flexibility.

Only one (Austin, 2017) of the 9 studies that used this definition proved effective in stimulating all the four components of divergent thinking. The increase in the originality component for

this study was discussed in the previous section. As for the three other components, Austin (2017) interpreted the results of the questionnaire administered to the teachers, on their perceptions of students' P21 competences.
Fluency, flexibility, and elaboration (measured by the TTCT) were not explicitly discussed in Austin's (2017) quantitative data analysis. Nonetheless, the author made inference, in the qualitative part of her study, by analysing the teachers' responses to the questionnaire used in the research: "Responses from each of the five teachers on the questionnaire addressed communication in relationship to their students' creativity. For flexibility, a teacher stated: "Students enjoyed problem solving and finding new strategies to answer questions or suggest different strategies from their peers" (p. 88). For elaboration, which was coded with Expressive communication, a teacher reported that "students are more verbal with creative ideas" (p. 96) or "Students are better able to communicate new ideas effectively" (p.86). For fluency, "the researcher noticed teacher comments related to communication and the application of creative practices such as fluency of ideas" (p. 95). For example, a teacher answered: "My class has become very good at brainstorming ideas no matter how far-fetched they are" (p. 87).

Although the connection between creativity and divergent thinking is one of the most common approaches in creativity research (Arnold, 1956; Sternberg & Grigorenko, 2001; Undheim & Horn, 1977; Guilford, 1973), some expert scholars on creativity have reassessed (if not rejected) the link between divergent thinking and creativity (Runco, 2008; Haase et al., 2018). Runco (2008), for example, defines divergent thinking tests as capable of estimating "the potential for creative problem solving (…) emphasizing tests as estimates and potential instead of guaranteed creative behavior" (p. 93) and considers divergent thinking tests rather as "tests of ideation" (Runco, 2019, p. 430). Although divergent thinking tests are still the most utilised creativity assessment, divergent thinking should possibly be considered as "causally related but conceptually distinct from the construct of creativity" (Hocevar & Bachelor, 1989, p. 63). "The mere generation of ideas and the ability to fulfill an actual creative accomplishment may not be equivalent. Several researchers have pointed out that DT is not creativity per se". (Haase et al., 2018, p. 8)

8.2 Other characteristics that were enhanced

8.2.1 Synthesis[14]

The ability to abstract concepts from ideas

The enhancement of this characteristic was more explicitly linked to the interventions than originality. In several studies the researchers provided an interpretation of the results. For

[14] *The attributes included in this group are: abstractness of titles/abstraction, conceiving and transforming imagination, connectivity (creative integration)/connection, perspective, and selecting a solution considering the context.*

example, Melián Díaz et al., 2020 ascribe this result to the practice of 3D digital modelling as "the separation into parts of a 3D model can enhance the connectivity" (p. 1159).

Lin et al. (2021) study has shown that technical knowledge (or lack of) can hinder some aspects of creativity, especially those related to "synthesis" when digital fabrication is applied to a very specific domain (engineering) in a general education context (secondary education).

Lille and Romero (2017) observed that participants were able to select a solution while considering context, that is to say that connections were made between pieces of information that were analysed, organised and synthesised so as to come up with an idea (a solution) that was relevant and adapted to the context. Another example (Lille & Romero, 2017) of participants making connections was provided by an analysis of a participant reflection:

> During the first session, our team decided that western-themed would be our urban norms. One of the difficulties that I encountered during the construction of the building model was the choice of material because the building model had to be detachable. (p. 10)

This also relates to modern views of creativity that imply the interrelation of different factors when it comes to creativity.

> Thus, I chose to use cork planks as well as Velcro. What was particular, though, was the material manipulation; cork being too delicate to manipulate once it is cut. It was therefore decided that exterior facing would be made with wood planks or with bricks. After doing the base of my building model, I painted it and then I used little wooden branches that I sawed. (Lille & Romero, 2017, p. 10)

In this quote it can be inferred that the participants realised that the properties (affordances) of the material that was chosen in the first instance were not adapted to the project. Subsequently, they were able to find new ones whose properties were more adapted.

8.2.2 Exploration

The grouped characteristic identified as Exploration[15] was defined, in the coding process, by the ability to make something different from what is usual or from the way most people do things, go beyond conventions, explore. All the characteristics coded with Exploration were increased in the corresponding research. For example, for figurative expansion, it seems that this characteristic is enhanced by problem solving activities as the participants in these studies were not afraid to take risks (Carbonell Carrera et al, 2019), or to try new things without fearing

[15]*In this grouped definition were included the following characteristics: Boldness, Exploration, Exploring new solution, Curiosity, Figurative expansion, Using inspirational sources to guide creative research*

of being wrong (Austin, 2017). Participants were willing to explore new solutions (Weng et al., 2022, Lille et Romero,2017) or “think beyond what was in front of them” (Austin, 2017, p. 96). In the study by StanSberry, Thompson and Kymes (2015) the participants - teachers - showed a significant improvement in Exploration as they were trying to find solutions for authentic problems they encountered in their workplace. In the qualitative study by Weng et al (2022), participants had to program in Scratch to solve several problems. The researchers observed that a participant explored the possible outcome of the tool by manipulating the different parameters so as to create new digital artefacts.
This characteristic relates with modern socio-cultural view of creativity in the way new affordances (of the environment, the tools, or the materials for example) emerge and influence the creative expression of individuals or groups (Glăveanu, 2013, 2015). In the context of digital fabrication and making, participants are encouraged to explore: explore the technology, the problem, the materials, the solutions. They can “test” and explore in a safe and less energy consuming way as they can immediately visualise (virtually) the outcome of their creative ideas.

8.2.3 Collaborative creativity

Collaborative creativity or collaboration was studied and observed in 2 studies out of 15. In Austin (2017) the researcher reported several responses provided by the teachers showing how this characteristic became apparent in the students involved in the study and it was associated with improved communication skills. A few examples of these responses are the following :
“My class seems to be willing to share ideas for how to solve a problem” (p. 86)
“I hear them asking others, ‘What do you think?’” (p.86)
“They also take turns talking and validating each other’s ideas and thoughts.” (p.86)
In Lille and Romero (2017), participants chose together a problem to solve and worked together to solve it, for example they diverted “the intended use of a Sphero robot in order to address the need of kids with dysphasia” (p. 10). In this study, however, collaboration was not further encouraged through the intervention, as also pointed out by the researcher “it would be relevant to support collaboration by implementing a sharing platform that would give students the opportunity to share the design process of the project as well as possible multiple iterations” (Lille & Romero, p. 12).
Even though this aspect was not extensively explored in the corpus, it could be argued that the participative environment of makerspaces in the school could play an important part in the development of collaborative creativity.

8.3 RQ2: How was creativity measured?

As discussed in section 2.1.5, modern research on creativity is going towards a sociocultural approach, where individuals should be studied in context, because they “often feel that they are creative at some times in some situations, but not at other times in other situations — it often is hard to just sit down and “be creative”” (Sternberg, 2020, p. 21). This section will discuss the results in the light of the creativity instruments that were utilised in the studies in the corpus, according to the focus they had on each of the 4P's of creativity.

8.3.1 Psychometric tests to evaluate a creative process

The psychometric instruments utilised in the studies of the corpus were the Torrance Test for Creative Thinking (Austin, 2017) and the Abreaction Test to Evaluate Creativity (Carbonell-Carrera et al. 2017, 2019; Melián Díaz et al., 2020; Saorín et al., 2017). The construct validity of the Torrance Test for Creative Thinking has been questioned by a study of Almeida et al. (2008) in which fluency, flexibility, originality, and elaboration, were shown to be inconsistent with their definition of being the main factors defining creativity. Additionally, fluency, should not be considered a predictor for creativity, because as stated by Runco (2008) it "is not as important as originality nor flexibility, at least if the intent is to predict creative performance" (p.94) Critiques on the reliability and validity of the TTCT were also addressed in the literature review conducted by Said-Metwaly (2017b).

The author of this research has not been able to find any validation studies (in English, French or Italian) on the Abreaction Test to Evaluate Creativity used in Carbonell-Carrera et al. (2017, 2019), Melián Díaz et al. (2020), and Saorín et al. (2017). No conclusion can be thus made on the validity or reliability of this instrument in measuring creativity. However, the researchers were able to measure, with a pre- and post- test that digital fabrication had enhanced several characteristics in the populations at study: Imagery abilities, Expressive communication, Synthesis, Originality, Exploration (Carbonell-Carrera et al., 2017, Melián Díaz et al., 2020) and Originality, Perseverance, Exploration, Imagery abilities (Carbonell-Carrera et al, 2019).

As seen in Chapter 2.2 - Measuring Creativity - what psychometrics tests do is ask people to sit down and demonstrate their "creativeness" or creative cognitive abilities. The main assumption of psychometric tests "is that there is a unidimensional trait of creativity that can be measured on a single interval scale" (Stenberg, 2020, p.21). However, "an individual's whole creativity cannot be obtained through the simple sum of the scores of its aspects, because of the interrelated forces among these aspects" (Said-Metwaly, et al., 2017, p. 280).

Barbot and Hocevar (2011) and Teffinger et al. (1971), while discussing construct validity of psychometric tests for measuring creativity, underline that

> the measures of most common creativity constructs have been based on simple quantitative rather than qualitative dimensions … a simple numerical count of frequency of responses … could overlook the occurrence of two or three highly significant responses on the part of one examinee that qualitatively would be worth a hundred fairly mundane responses of another examinee. (Barbot et al., 2011, p. 35)

As for reliability of creativity psychometric tests, Barbot and Hocevar (2011) also point out that - these tests being open-ended, their scoring is subject to the examiners' judgement, therefore a high level of agreement among the examiners on what is creative is required, but rarely accomplished.

The debate is therefore still ongoing on the validity of psychometric tests to measure creativity (Almeida et al., 2008; Barbot et al., 2011; Hocevar & Bachelor, 1989; Kim, 2006a; Treffinger et al., 1971).

8.3.2 Self-reports, scale and questionnaires to evaluate a creative person

In her research on makerspaces activities in an elementary school media centre, Austin (2017) used the Renzulli Scales for Rating the Behavioral Characteristics of Superior Students (SRBCSS) designed to obtain "teacher estimates of a student's characteristics" (Renzulli et al., 2021, p. n.d) in several areas, including creativity. The author confronted the results obtained with the TTCT and found a positive correlation between these results and teachers' ratings of students' creativity.

Renzulli, the author of the scale, states that the "items are derived from the research literature dealing with characteristics of gifted and creative individuals" (Renzulli et al., 2021, p. n.d.). The characteristics associated with creativity in the SRBCSS scale are (Renzulli et al, 2021) : humour/sense of humour, imaginative thinking ability, "the ability to come up with unusual, unique, or clever responses, an adventurous spirit or a willingness to take risks" (Renzulli et al., 2021, p. n.d.), fluency, "the ability to adapt, improve, or modify objects or ideas" (n.d.), fantasy and a "nonconforming attitude" (n.d.).

The Scale has no standard scoring system and does not include any norms (Jarosewich et al., 2002) ; the administration manual encourages teachers to generate local norms but does not provide any detail on how to do so (Jarosewich et al., 2002). In terms of reliability of the SRBCSS, internal consistency estimates for the scale are not provided but inter-rater reliability was reported as excellent in the manual (Jarosewich et al., 2002). The SRBCSS was not validated or constructed with quantitative methods, but it rather relied on expert reviews. The manual does not specify "the qualifications of the experts or how the experts were chosen" (Jarosewich et al., 2002, p. 331). Thus, there is no evidence for its validity, nor for criterion-related validity (Jarosewich et al., 2002). In conclusion, the validity of the positive correlation in Austin's (2017) study in relation to creativity must be taken cautiously.
For the qualitative data collection of her research, Austin (2017) developed an open-ended questionnaire based on "the key components of creativity defined and described by the Partnership for 21st Century Learning … communication, collaboration, novelty, and value" (p. 66). The questionnaire was addressed to the teachers and aimed at collecting their perceptions "with regard to the level of creativity they found in their students after their exposure to makerspaces" (p.67). Teachers' perceptions on students having been exposed to 12 weeks of makerspaces activities were coded and 3 major themes emerged from the study: communication, motivation and engagement (Austin, 2017). Austin (2017) also noticed that

“the predetermined themes of collaboration, value, and novelty were not explicitly stated in the raw data, indirect connections can be made to these themes” (p. 86) such as fluency.
Other characteristics that emerged while coding Austin (2017) teachers’ answers to the questionnaire, were: students’ creative perseverance, problem framing, and developing solution abilities. Among the teachers' responses: “They certainly are not afraid to try. Hands on activities seem to be less intimidating for them from when they are given more traditional assignments” (p.87); “Students researched information on certain ideas to make sure information is accurate and more detailed” (p.87);

Prabhu et al. (2020) used the Creative Self-Efficacy (CSE) Scale developed by Tierney and Farmer (2022). This scale was developed to be used in professional settings so as to “examine specified creative efficacy beliefs in direct relation to employee creativity in an ongoing corporate setting” (Tierney, 2022, p. 1145). Creative self-efficacy is defined as “the belief one has the ability to produce creative outcomes” (Tierney, 2022, p. 1138).
In Prabhu study, a Design for additive manufacturing[16] (DfAM) training was administered to employees of an Engineering company. The aim of the study was to understand DfAM’s role on engineers and designers’ creative self-efficacy and whether an increase in their self-efficacy would translate in improved creativity of their design[17]. Three items were used by Prabhu et al. (2020) and they were measured on a 5-point Likert scale (from Strongly disagree to Strongly agree):

- I am good at coming up with new ideas
- I have a lot of good ideas
- I have a great imagination

Creative self-efficacy in this scale seems therefore related to idea generation, fluency (number of ideas) and imagination. In Prabhu et al. study (2020), the participants' creative self-efficacy was measured before and after the training. The results showed that the training had no effect on the creative self-efficacy of the participants. This was attributed to an already high level of creative self-efficacy of the participants, before receiving the training.

StanSberry et al. (2015) were also measuring participants' creative self-efficacy and used a commercial instrument, the AULIVE Survey. Aware about the limitations of the instrument, the authors wrote: “the limitations of the instrument (which was valuable for prompting self-reflection in the students but was not designed for data collection) used in this study, however, call for a more sophisticated measure of self-efficacy” (p. 449).
If the results of StanSberry et al. (2015) study were to be confirmed by a validated instrument, they would show that digital fabrication not only increased participants creative self-efficacy, but potentially other characteristics as well, such as exploration, fluency, flexibility, ability to framing problem and develop solutions, originality, synthesis and usefulness.

[16] Additive manufacturing is “the construction of a three-dimensional object from a CAD model or a digital 3D model” (‘3D Printing’, 2022) and can thus be considered as a synonym of 3D printing.
[17] The assessment of the creative product will be discussed in the following section.

Unterfrauner et al. (2021) measured participants (6 to 16 years old from 10 European Countries) creative self-efficacy with a 15 items scale developed by selecting suitable items from several other creative self-efficacy scales. Their scale was used to measure self-efficacy on three aspects: in relation to peers, on own capabilities and on problem solving. The questions were reformulated and redesigned after having tested the scale with practice partners and children and then translated in the national languages. Pre-test and post-test questionnaires were administered and showed no significant change in self-efficacy among the participants in relation to peers, but an increase in self-concept regarding own capabilities and self-concept regarding problem solving. (Unterfrauner et al., 2021)

A meta-analysis by Haase et al. (2018) revealed that the type of measurement has an influence on the relation between self-efficacy and creativity measures. In particular, in their meta-analysis they found that studies "measuring creativity with questionnaires/scales showed stronger association (...) between creativity and self-efficacy than when verbal tests[18] of creativity (...) were used" (Haase et al., 2018, p. 8). The scale category included both self and external rating but there were not enough studies to define a relation between creative self-efficacy and "other-rated creativity" (Haase et al., 2018, p. 8).
In summary, Haase et al. (2018) meta-analysis showed that the relation between creativity and creative self-efficacy exists when the focus is on the person (and their opinion on their creativity). This relation weakens when the focus is on the creative product or process.

This means that "the creativity measurement involving the creative person demonstrated a high statistical relation to self-efficacy" (Haase et al., 2018, p.8) compared to those measuring creative process or product, such as Amabile's Consensual Assessment Technique that was used in Prabhu study to evaluate the creativity of the participants' final products.

8.3.3 Experts' Ratings to evaluate creative products

One can certainly assume that it is possible to rate various products for levels of creativity. However, such ratings are an oversimplification, because creative products can represent different kinds of creativity. "There are just too many ways of being creative to compress all the information one needs to make an informed judgement about a person's creativity into a single number on a single scale." (Stenberg, 2020, p.34)

Chien (2017) and Chien and Chu (2018) used a revised version of the Creative Product Semantic Scale (CPSS) that was originally developed by Besemer and Treffinger to evaluate the products' creativity in their studies. The dimensions of the scale were product novelty, functionality, and sophistication. It is unclear how this revised version of the scale was

[18] Verbal tests for creativity are tests where the participant performs verbal tasks. Examples are the verbal part of the Torrance Test of Creative Thinking (Kaufman & Baer, 2006) or the Creative Self-Efficacy (CSE) Scale developed by Tierney and Farmer (2022).

validated; therefore, the results are subject to questioning. The only reference made in both articles is to an unpublished doctoral thesis by Chang (2002) and to three teachers that evaluated "36 handmade wooden stationery holders using the scale" (Chien, 2017, p. 2950; Chien & Chu, 2018, p. 1054).

The purpose of Chien and Chu (2018) study was to "examine the differences in competency levels between high school and college students with regard to engineering design" (p. 1058). Firstly, it was not really clear why a comparison between college and high school students was studied and why it was "pertinent" to evaluate the difference in creativity between the products of the two groups. Also, all college students could use 3D tools, while high school students were further divided into 3D and handmade groups. It seems that only in this case (the two groups of high school students) it would have made sense to evaluate the difference in creativity of the product between participants exposed to the intervention and participants that were not. In Prabhu et al. (2020) study the creativity of the products was measured with the CAT. The raters in their study were students (graduate and undergraduate) in mechanical engineering considered to be "quasi-expert" in the DfAM domain and the observed inter-reliability among the raters was deemed strong by the researchers.

A study by Kaufman et al. (2008) focused on investigating whether non-expert raters would reach consensus and provide "accurate judgments of creativity" (p. 172) showed that experts and non-experts showed "differential levels of interrater agreement" (p. 175). The study was conducted in the poetry domain, it is therefore not possible to generalise their results to other domains. However, this raises questions on the reliability of Prabhu's positive results on the increased originality of the products created by the participants, while using "quasi-expert" raters in their study.

If Amabile's CAT is a reliable instrument to measure products' creativity, a question arises about the practicality of the implementation of this assessment in the classroom. Who would be the experts judging students' creative outcome? Are the teachers to be considered as "experts" and "independent judges"? Also, for the CAT to be used in educational settings to evaluate creative products obtained through digital fabrication tools and activities, should the teachers be experts in both the domain (for example STEM) and the tool used? If the answer is no, who should be judging students' products? The logistics involved in having independent raters assessing students' production would be too difficult to put in place in any school setting. The instrument seems to be valid and appropriate for research on creativity, but a different approach should be used in the classroom by the teacher to evaluate the effectiveness of a learning program or intervention focused on fostering student's creativity, for instance through digital fabrication and makerspace activities.

It is an argument for reflection to ask whether, in educational contexts, creativity should be linked to a creative product outcome or simply to "possibility thinking" (Craft, 2001). In fact, Craft (2001) introduces possibility thinking as the idea that "that pupils are encouraged to approach learning across the curriculum with a 'what if?' attitude. In other words, with a questioning approach which wonders about possibilities and is both prepared to follow, and be supported in, seeing the questions through to an outcome" (p. 20).

8.4 RQ3: In which context, education level, and domain were the interventions performed?

As seen in the results section, more than half of the studies (Austin, 2017; Carbonell-Carrera et al., 2019; Chien & Chu, 2018; Lille & Romero, 2017; Lin et al., 2021; Saorín et al., 2017; Walan, 2021; Weng et al., 2022) were focused on STEAM or STEM and almost a half (Carbonell-Carrera et al., 2017, 2019; Chien, 2017; Chien & Chu, 2018; Melián Díaz et al., 2020; Prabhu et al., 2020; Saorín et al., 2017) were conducted in the Engineering domain. One study (García & Fernandez, 2018) focused on Science - or scientific creativity - and one (Stansberry et al., 2015) on Education technology.

These results came as no surprise since, as revealed by a literature review conducted by Noval et al. (2021) on 78 studies on 3D technology in educational settings[19] since 1977, most of the research has been conducted in technology (18 studies) or science classes (8 studies), Engineering (16 studies), and mathematics (3 studies), making up about 58% of the total studies. 3D modelling and printing (the tool used in 10 of the studies) offer "a new approach for engineering design and manufacturing" (Novak et al., 2021, p. 1455) and involve "integrative STEM education that connects technology and engineering design to existing curriculum projects in different disciplines" (Novak et al., 2021, p. 1456).

The general trend identified by Novak et al. (2021) on academic levels, was also confirmed by the present literature review. The majority of studies on digital fabrication were conducted on post-secondary students, which is also no surprise since engineering was the domain of almost half of the studies.

In some studies of the corpus, the relationship between the domain (engineering, for example) and the study of creativity through digital fabrication was made explicit by the authors. For example Melin Diaz et al. (2020) state that "engineers face challenges that require to generate different design proposals (...) Therefore, the development of creativity should be an axis in engineering training" (p. 1151). In Carbonell-Carrera et al. (2019) the authors say: "Creativity is a necessary engineering skill, so engineers have a wide field for the support of creative skill development" (p. 2).

The link between STEAM/STEM and the use of digital fabrication tools is quite common and has been found in the literature in several circumstances (Blikstein, 2013; Chu et al., 2015; Hsu et al., 2017; Lorenzo & Lorenzo, 2018; Martin, 2015; Nemorin, 2017; Schön et al., 2014) as seen in Chapter 2. However, the relationship between STEM or STEAM and creativity was not

[19] Formal and informal, professional development workshops, and other settings

necessarily anchored to literature or previous research. For example, Walan (2021) simply argues that the “act of making the props was supposed to stimulate the girls’ interest in STEM and support their development of twenty-first-century skills” (p. 24). In Lin et al. (2021) study, the interest in STEM and creativity was due to national education policies pushing towards enhancing “students’ imaginative capabilities and interest in STEM careers” (p. 1). Chien et Chu (2018) - whose study was focused on STEAM - state that “Combining art and science fosters creativity, critical thinking, and cooperative learning and helps students to develop problem-solving skills that are beneficial throughout their lives” (p. 1049).

Makerspaces activities used in the studies consisted of “open-ended activities designed to promote higher order thinking” (Austin, 2017, p.63), makings props for a drama performance (Walan, 2021), “creation, design and manufacture of three-dimensional scale models” (Melián Díaz et al., 2020, p. 1151), “the creation and individualization of articulated objects such as dolls (...) the 3D scanning of the pupil’s head (...) and finally proceed to print the creations in 3D” (Saorín et al, 2017, p. 193), model different three-dimensional proposal from a given template (Carbonell-Carrera et al., 2019), making 3D terrain models (Carbonell-Carrera et al., 2017).

Problem-solving/PBL activities or Design challenge/task activities were employed in Austin (2017), Carbonell-Carrera et al. (2017, 2019), Chien (2017), Lille and Romero (2017), Melián Díaz et al. (2020), StanSberry et al. (2015), Weng et al. (2022). These activities aimed at developing problem solving skills in the participants and were often linked to divergent thinking. In these problem-solving/problem-based activities participants had to address a problem, often presented as a design challenge, and develop different solutions to solve it.

These interventions provided some of the “ingredients” described by Davies et al. (2013) and discussed in Chapter 1.3. For instance, all interventions involved the production of artefacts using new or different technologies and the participants were encouraged to explore. In some cases (Carbonell-Carrera et al., 2019; Prabhu et al., 2020; Lille & Romero, 2017) functional constraints were added for the outcome, which according to Gehlbach (1987), should stimulate the creative intellect. In some cases, only constraints to the final product were given such as in Lille and Romero (2017), but the participants were free to choose which problem to address. In other cases, both the problem and the outcome had to have specific characteristics, such as in Carbonell-Carrera et al. (2019) and Prabhu et al. (2020).

To answer this research question, it can be argued that contexts, education levels, and domains where the interventions were performed has had limited variety in the last ten years, with Engineering and STEAM/STEM being the most studied domains and tertiary education the most common education level investigated. The 3D printing and modelling system was also the most prominent digital fabrication tool studied to measure improvements on students’ creativity.

8.5 How researchers have addressed digital fabrication to foster students' creativity?

In all of the articles in the corpus but two, creativity was studied either through the lens of process (Austin, 2017; Carbonell-Carrera et al., 2017; Carbonell-Carrera et al., 2019; García & Fernandez, 2018; Lille & Romero, 2017; Lin et al., 2021; Melián Díaz et al., 2020; Saorín et al., 2017; Unterfrauner et al., 2021; Walan, 2021; Weng et al., 2022), person (Unterfrauner et al., 2021; Stansberry et al., 2015; Prabhu et al., 2020; Austin, 2017), or product (Chien, 2017; Chien & Chu, 2017; Prabhu et al., 2020). Even in those studies where the researchers focused on more than one aspect, these were studied individually, as if they were separate elements, independent from one another, following the "traditional" views on creativity. None of the studies focused on the press aspect, as in the interaction between an individual and its environment (Rhodes, 1961). As shown in a literature review of the different approaches to measuring creativity by Said-Metwaly et al. (2017a), the press approach is indeed the less common among all the approaches (4.12% of a total of 152 studies). The authors point out the "lack of research-based evidence" (p. 244) for this approach, although, for example, "numerous factors have been found to influence the development of creativity in learning environments" (p. 257), such those found by Davies et al. (2013) and listed in Chapter 1.3 of this research. Said et al. (2017a) ascribe the lack of research focusing on this approach to some concerns about the term "climate" (as in the environment in which creativity occurs), since several definitions exist for this term. Additionally:

> individuals may have different perceptions of climate as they conceptualize or understand situations differently according to their own personality, education or culture. Thus, the effect of the same climate on individuals' creativity may be different due to their distinct internal representations of the climate, not to the climate per se. (Said et al., 2017, p. 258)

As mentioned in the Theoretical framework of this research, modern view of creativity research is shifting towards a more holistic, ecological, sociocultural approach, where all these characteristics are interrelated; where the individuals cannot be distanced from their social context and their culture (Glăveanu, 2013, 2015), and where creative products are not simply the material transposition of one's ideas: they are also the ideas. This also reinforces the suggestion that qualitative studies should be preferred when studying creativity, as they allow to observe and record the "unfolding of action", as it unravels.

Proponents of a sociocultural perspective on creativity argue (Glăveanu, 2013; Withagen & van der Kamp, 2018) against the "traditional" cognitive perspective discussed above, which assumes:

1) that novel ideas generate in a person's mind and "precede the[ir] actual materialization" (Withagen & van der Kamp, 2018, p. 1).
2) that creative process, person, product, and press are four distinct components of creativity (Rhodes, 1961)

As mentioned in the Results chapter, all the 15 studies in the corpus employed a "traditional" definition of creativity. Some studies, however, were more "modern" in their approach.

Stansberry, Thompson and Kymes (2015), while adhering to a definition of creativity related to novelty and usefulness, also suggest that there is an "interaction" (p. 436) among different components, as defined by Plucker, Beghetto and Dow (2004) : "Creativity is the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context" (2004, p. 90). In their study on enhancing teachers' creativity through digital fabrication, Stansberry et al. (2015) see all the "facets" of creativity (person, process, product, press) as being interrelated:

> We posit that teachers must experience being the person who creates, engage in the processes involved in the creation of ideas, embrace the press or influence of environment, and exhibit pride in the product that results from creative activity to be prepared to teach creativity. (p. 437)

The main limitation of this study is that the researchers used a commercial instrument (the AULIVE Survey) to measure the teachers' creative self-efficacy. The validity and reliability of this instrument is therefore in question[20].

Walan (2021) used Engeström's activity theory (AT) model as a framework to her study. The AT model is based on a social-cultural perspective and takes into account the person and their motivation, the culture, the environment, the role of the artefact and the complexity of real life (Engeström, 2014). In this study, making and drama were the mediating artefacts. The author made observations and took field notes during 9 sessions, interviewed individually the drama teacher and the project leader, and conducted a group interview with the participants (ten girls aged 7–11). It would have been interesting if the author had described how the community, the division of labour, the rules, and the mediating artefact (elements of the AT model) had influenced the outcome. The study seemed promising but lacked a more thorough analysis of the results with respect to the improvement of the participants' creativity.

8.6 Major potential contribution of Digital Fabrication in education: Opportunity

Regardless of the creativity definition that was adopted by the researcher, it appeared throughout the discussion that the main contribution of digital fabrication (as in digital tools or related activities) was giving students the opportunity to generate ideas, discuss them with their peers, experiment and create, not being afraid to fail. Opportunity to learn, to change and exchange ideas, opportunity for a space where one can do all the above things. Also, affordances of the tools and materials gave inputs to the creative process: "Without the physical

[20] *Creativity assessment instruments were discussed previously in this chapter.*

materials, the process would have been difficult for the students. The students developed their plans based on the supplies available" (Austin, 2017, p. 96).

In Weng et al. (2022) the researchers were able to observe that "having gained some basic knowledge about functions and parameters, the students were able to explore parameter settings outside of the problem situation to create new artifacts" (p. 379). This observation from the researcher hints at the fact that once the participants had understood the "technology", their creativity was able to unleash. This is in line with what argued by Suero Montero et al. (2018) Corsini and Moultrie (2018) about the opportunities that open up when students start mastering the tool and interact with it, the materials, and their environment.

This might suggest that, after the learning curve has been crossed, the students can concentrate on creating. It might also imply that great care should be taken when designing a course on digital fabrication so as to make this phase as comprehensive as possible for those students that might struggle with the technology and would feel "hindered" by it instead of stimulated, as suggested by Nemorin (2017).

In Chien (2017), the participants that had access to a 3D modelling software produced more complex and sophisticated designs. This demonstrates that tools facilitating the modelling of designs that are difficult to achieve manually can indeed increase the occurrence of original ideas. "3D printing allows students to visualize dynamic virtual objects and produce visible and tangible models" (Chien, 2017, p. 2944).

In Lin et al. (2021), DF tools (notably 3D printing machines) made it possible to reduce time associated with traditional making processes, therefore allowing students to spend more time "imagining" and producing new ideas.

In Austin study (2017) one teacher stated that: "When given the opportunity, students follow through on their ideas. Having materials gives them both ideas and a means for completing their ideas" (p.87). This answer also seems to suggest that having access to tools and materials was stimulating creative idea generation and materialisation. Contact with tools and materials made students "react" when new or previously unconsidered "affordances" (of the design environment, the tools, the materials) were discovered and taken into account to generate new ideas or solve impromptu, unexpected "problems". This evidence strongly suggests that one of the main contributions of digital fabrication towards an increase in students' creativity is that it gave them the "opportunity" to be creative.

8.7. Limitations and perspectives

8.7.1 Limitations

This systematic literature review provides a summary of empirical research on digital fabrication as a means to foster creativity in educational contexts.

The search revealed only a limited number of research conducted, in the last decade, on this subject. It is therefore impossible to generalise these results. Even though it has been possible to analyse and compare several studies on digital fabrication as a means to foster students' creativity, the results do not allow for a predictive value to these observations. Despite this review being systematic, it was conducted so as to be exploratory in nature.

On the methodological level, the reliability of the coding process cannot be guaranteed, as no inter-code agreement was performed to validate the codes, the categories, and subcategories used to analyse the data. This was due to the nature of this research, a Master's thesis, and the consequent limited resources that could be allocated to the study.

Additionally, some studies might not have appeared in our search. This could be due to the choice of the databases or search terms. Other key terms in the search queries might have made it possible to find other references and thus enrich the corpus. The search was also limited to studies in English, French, and Italian. Some studies might have been overlooked in the first step of the evaluation because the title or the abstract did not meet the inclusion criteria.

Despite all these limitations, it is undeniable that the complexity of creativity and the lack of consensus on its definition add to the difficulties of this type of research, which is subject to the choices of the researchers in terms of frameworks or creativity definition, and the instruments to assess it.

8.8. Perspectives for future research

Everybody has the potential to be creative. Creativity, however, is a situated act (Corsini & Moultrie, 2018; Mishra, & Henriksen, 2013) that can occur or not, depending on the circumstances (the context, internal or external factors). A person can be creative in some situations but not in some others (Sternberg, 2020). The question is not whether it is possible to teach, learn, or foster creativity, but rather how. This research has presented limited evidence, collected in the literature in the last ten years, that digital fabrication is successful in fostering student's creativity. The majority of the studies were conducted in one domain (Engineering) or with a specific focus on STEM or STEAM only. There is therefore a need for more diverse fields of investigations, as well as more research in general.

Although the majority of the studies were quantitative, the richest data were collected in the qualitative and mixed methods studies. These kinds of inquiries made it possible to capture more fine-grained data about the experience of the participants. Qualitative studies allow participants to be questioned about the process. Questions like "How did you get the idea for your project? How did you get started making your project? What happened when you got stuck? How did you solve this problem? What was it like working on this problem?" (Weng et al, 2022, p. 376-377) allowed the researchers to understand what factors or situations - related to the intervention - could have stimulated the participants. In quantitative research it was less easy to see themes emerge or make connections: the results were not interpreted or explained by the researchers.

For instance, themes such as opportunity, motivation, engagement, collaboration, or communication cannot emerge from statistical analysis. In addition, quantitative methods and quantitative instruments for creativity assessment do not allow for this deeper understanding as they either measure the creativity of the final product or the "score" of a psychometric test completely out of the context of the intervention. For instance, psychometrics instruments like the TTCT measure creativity while proposing some figural and graphics tasks unrelated to the intervention, it is therefore only possible to measure that a certain variable has (or has not) increased but not how. The debate is also still ongoing on the validity of psychometric tests to measure creativity (Almeida et al., 2008; Barbot et al., 2011; Hocevar & Bachelor, 1989; Kim, 2006a; Treffinger et al., 1971).

Research in education should focus on understanding creativity to determine an actionable and operational definition by which it could be observed and measured, and it should investigate how creativity is experienced and "felt" by the students. It should not be interested in "innovations" or trying at all costs to cultivate creative "genius". It should stop measuring the creative performance of the students and rather try to understand the unfolding of creativity, identify the characteristics and variables of cognitive processes associated with creativity and implement activities that stimulate these cognitive processes.

This is something a quantitative (psychometric) study would hardly be able to catch as it will only measure a "before" and a "after" but not what happens in between: the "creative moment(s)", as in the moment(s) students thought they had been creative, or they had produced something creative.

We therefore suggest using qualitative methods - such as textual analysis or repertory grid techniques - to further study creativity in general and how digital fabrication can stimulate creativity in educational settings in particular. Research should also further investigate the influence of the environment (the press) that stimulates creativity in education, as scientific evidence is lacking in this respect.

9. Conclusion

This research highlighted the importance of creativity (Azzam, 2009; Dawes & Wegerif, 2004; Glăveanu et al., 2020; Mishra & Henriksen, 2013) among the so-called 21st century skills in education and the need to incorporate creativity in educational programs or curricula.

Teaching of creativity, however, is not an easy or straightforward task. Creative products (or ideas) cannot be specified beforehand (Gehlbach, 1987) and designing instruction and assessment aimed at creativity as the outcome is challenging. Creative-supportive environment are those providing opportunity for discovery and use of imagination (Beghetto & Kaufman, 2014; Nickerson, 2019); that involve the making of artefacts and give students access to new tools and technologies (Davies et al., 2013) ; where the tasks are authentic (Davies et al., 2013) and framed within the boundaries of functional constraints (Gehlbach, 1987). There is some evidence that digital fabrication might provide the tools and the types of activities that would stimulate and promote students' creativity, as it gives participants opportunities to create something new and useful while making, thus experiencing creativity (Corsini & Moultrie, 2018; Fields & Lee, 2016; Hatch, 2014; Regalla, 2016).

There are, however, counter arguments to these statements. First and foremost, a classroom is different from a makerspace as students (and educators) are constrained to strict requirements, standards, programmes, curricula, evaluations and examinations (Halverson & Sheridan, 2014; Lorenzo & Lorenzo, 2018; Nemorin, 2017) that might hinder creativity instead of enhancing it. Other authors argue that digital fabrication could actually hinder students' freedom of action (Corsini & Moultrie, 2018; Nemorin, 2017). Creativity could, for example, be "constrained by a computer application" (Nemorin, 2017, p. 533) as students might feel discouraged by the software complexity, or even detached from their artefact as they are less involved "manually" in its fabrication (Nemorin, 2017).

This research started with the premises that, whilst there is a lot of interest around creativity, making as a school activity, and digital fabrication as a way to foster creativity in education, empirical research on its effectiveness - which could provide an explanation on how digital fabrication affects students' creativity - seems scarce (Corsini & Moultrie, 2018; Hsu et al., 2017; Nemorin, 2017; Suero Montero et al., 2018). This review of the literature on digital fabrication in the classroom as a means to foster students' creativity was motivated by these observations.

It confirmed that only a limited amount of research, in the last ten years, has investigated the question of how digital fabrication fosters creativity in educational contexts. The studies analysed were conducted in different contexts and with different populations. Out of the 15 studies the researcher was able to find, more than a half were focused on STEAM or STEM and almost a half were conducted specifically in the Engineering domain. These results came as no surprise since and are in line with a literature review conducted by Novak et al. (2021) on 3D technology in educational settings mentioned in the previous sections.

The results have shown that researchers have addressed creativity through the prism of three main definitions: as implying novelty and usefulness, as a form of divergent thinking or as a form of problem-solving. Eleven different creativity assessment instruments were utilised and the researcher counted 51 creativity traits measured across the 15 studies. In eleven studies the researchers studied the creative process, in four the creative person, and in three the creative product. None of the studies focused on the creative press and the influence of the environment on students' creativity. Even in those studies where the researchers focused on more than one aspect, these were studied individually, as if they were separate elements, independent of one another, following the "traditional" views on creativity.

In all the studies, digital fabrication has helped stimulate one or more creativity characteristics related to these definitions. The most significant result is the stimulation of participants' originality. Twelve studies revealed that participants improved this characteristic. None of the studies, however, thoroughly investigated how digital fabrication and makerspaces activities had contributed to this result. The focus was - as often is in creative studies - on the outcome: the novel idea or the novel product and little was said on how this characteristic was stimulated by the intervention. Usefulness was only observed in three studies out of the ten that employed the broad definition of creativity. It is worth reflecting on the applicability of this definition in the context of education, especially on primary and secondary education: do ideas and products generated in a pedagogical activity really need to be useful to be creative?

Several studies directly associated creativity with divergent thinking even though some expert scholars on creativity have reassessed (if not rejected) the link between divergent thinking and creativity (Runco, 2008; Haase et al., 2018) as "several researchers have pointed out that DT is not creativity per se". (Haase et al., 2018, p. 8)".

Another characteristic that was increased in several studies is what has been broadly identified as Exploration[21]. Participants were not afraid to take risks, or to try new things, and were willing to explore new solutions. This characteristic relates with modern socio-cultural view of creativity in the way new affordances (of the environment, the tools, or the materials for example) emerge and influence the creative expression of individuals or groups (Glăveanu, 2013, 2015). In the context of digital fabrication and making, participants are encouraged to explore: explore the technology, the problem, the materials, the solutions. They can "test" and explore in a safe and less energy consuming way as they can immediately visualise (virtually) the outcome of their creative ideas. The main contribution of digital fabrication (as in digital tools or related activities) was giving students the opportunity to generate ideas, discuss them with their peers, experiment and create, not being afraid to fail. Opportunity to learn, to change

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[21] *the ability to make something different from what is usual or from the way most people do things, go beyond conventions, explore*

and exchange ideas, opportunity for a space where one can do all the above things. Also, affordances of the tools and materials gave inputs to the creative process.

This might suggest that, after the learning curve has been crossed, the students can concentrate on creating. It might also imply that great care should be taken when designing a course on digital fabrication, so as to make this phase as comprehensive as possible for those students that might struggle with the technology and would feel “hindered” by it, instead of stimulated, as suggested by Nemorin (2017).

Finally, in the perspective of cultivating and encouraging the acquisition of 21st century skills, digital fabrication could serve a twofold purpose: help students to achieve their creative potential, while at the same time developing their digital skills.

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Annexes

Annex 1: Categories & Codes

1.1 Category: Creativity characteristics

CATEGORY & CODE	DESCRIPTION	CHARACTERISTICS INCLUDED
Perseverance Creativity:perseverance	The ability to continuing to try to do something despite difficulties	Abreaction, resistance to closure, persistence, paradox
Exploration Creativity:Exploration	The ability to make something different from what is usual or from the way most people do things, go beyond conventions, explore	Boldness, Exploration, Extending or breaking boundaries, Exploring new solution, Curiosity, Internal visualisation, Synthesis of lines or circles, Figurative expansion, Using inspirational sources to guide creative research
Originality Creativity:Originality	“The ability to produce ideas well beyond the obvious, commonplace, banal, or established” (Torrance, 2008, p. 9)	Originality/Original thinking/Original ideas, Novelty, Fantasy/Willingness to fantasise, Uniqueness Unconventionality Unusual visualisation, Initiating imagination,
Synthesis Creativity:Synthesis	The ability to abstract concepts from ideas	Abstractness of titles/Abstraction, Complexity, Conceiving imagination, Connectivity (creative integration)/Connection, Humour/Sense of humour, Perspective, Unusual visualisation, Transforming imagination,
Expressive communication Creativity:Expressive communication	The “ability to clearly and powerfully communicate an idea or tell a story” (Torrance, 2008, p. 4)	Collaboration and Communication, Elaboration, Emotional expressiveness, Expressiveness of titles, Richness of images, Storytelling articulation

Imagery abilities Creativity:Imagery abilities	The ability to visually represent ideas	Imaginative scope, Movement or action, Expressive richness, Graphic ability/Graphic Skills
Usefulness Creativity:Usefulness	The ability to come up with multiple relevant, useful, accurate, and appropriate ideas to solve a problem	Value, Usefulness, accuracy, precision, or integrity, Functionality
Self-efficacy Creativity:Self-efficacy	The participants believe their creativity has been enhanced, their creative competence has improved	
Fluency Creativity:fluency	"The total number of relevant responses." (Torrance, 2008, p. 3)	
Flexibility Creativity:flexibility	"The number of spontaneous shifts from one category of meaning to another" (Wallach, 1968, p. 274)	

1.2 Category: Level of Education

CATEGORY + CODE	DESCRIPTION	EXAMPLE
EDLEV:Primary education	*"Programmes typically designed to provide students with fundamental skills in reading, writing and mathematics and to establish a solid foundation for learning."*	Elementary school
EDLEV:Secondary education	*"First stage of secondary education building on primary education, typically with a more subject-oriented curriculum."* *or* *"Second/final stage of secondary education preparing for tertiary education and/or providing skills relevant to employment. Usually with an increased range of subject options and streams."*	Middle school
EDLEV:Tertiary education	*Programmes designed to provide intermediate (Bachelor's or equivalent) or advanced (Master's or equivalent) academic and/or professional knowledge, skills and competencies leading to a second tertiary degree or equivalent qualification.*	College, University
EDLEV:Professional development	*"In a broad sense, professional development may include formal types of vocational education, typically post-secondary or poly-technical training leading to qualification or credential required to obtain or retain employment. Professional development may also come in the form of pre-service or in-service professional development programs. These programs may be formal, or informal, group or individualized"*	In-service program

1.3 Category: Domain

CATEGORY + CODE	EXAMPLE
DOM:Engineering	Mechanical, Graphics, Agricultural
DOM:Computer science	
DOM:STEM	
DOM:STEAM	
DOM:Education technology	
DOM: Design	Industrial design
DOM:General education	Elementary school

1.4 Category: Setting

CATEGORY + CODE	EXAMPLE
SETT:School/Class	Classroom
SETT:Company	Engineering company
SETT:Outside school	Summer schools, makerspaces, youth centre
SETT:School media centre	School media centre

1.5 Category: Intervention

CATEGORY + CODE
INT:Workshop
INT:Lecture
INT:Program
INT:Course
INT:Online course
INT:Curriculum
INT:makerspace activities
INT:Sponsored program
INT:Classroom activities
INT:Design Challenge
INT:Problem-solving activities

1.5 Category: Instruments

CATEGORY + CODE
INSTR:Scale
INSTR:Questionnaire
INSTR:Psychometric Test
INSTR:Rating
INSTR:Survey

Annex 2: List of all Creativity Characteristics used in the Corpus

CREATIVITY CHARACT.	DESCRIPTION/DEFINITION	HOW IT WAS MEASURED	REFERENCE
Abreaction	The resistance of a person to the natural tendency to close the openings of a drawing. “It is the control that the person has not to close the openings that the test presents without being carried away by the natural tendency for it to be closed. It can be manifested in two ways, leaving the opening open or closing it by an indirect path (by more than two strokes, away from the closing points or using original closures)” (Carbonell-Carrera et al., 2017, p. 7494)	Abreaction Test of Creativity	Carbonell-Carrera et al., 2017
			Carbonell-Carrera et al., 2019
			Melián Díaz et al., 2020
Abstractness of titles/Abstraction	The ability to abstract concepts from ideas “the subject’s synthesizing and organizing processes of thinking. At the highest level, there is the ability to capture the essence of the information involved, to know what is important, and to enable the viewer to see the picture more deeply and richly” (Torrance, 2008, p. 3)	Torrance Test of Creative Thinking	Austin, 2017
		AULIVE Survey	StanSberry et al., 2015

Boldness	“The confidence to push boundaries beyond accepted conventions … also the ability to eliminate fear of what others think of you.” (StanSberry et al., 2015, p.445)	AULIVE Survey	StanSberry et al., 2015
Collaboration and Communication	“Communicate their own original ideas with others in a group so that their team members understand the meaning of the ideas. (P21, collaboration, communication)” (Austin, 2017, p. 150)	Questionnaire created by the researcher “based on the key components of creativity defined and described by the Partnership for 21st Century Learning (2016)”	Austin, 2017
Complexity	“The ability to carry large quantities of information and be able to manipulate and manage the relationships between such information” (StanSberry et al., 2015, p.445)	AULIVE Survey	StanSberry et al., 2015
Conceiving imagination	“Conceiving imagination can be defined as the capability to mentally grasp the core of a phenomenon using personal intuition and sensibility, and the capability to formulate effective ideas for achieving a goal through concentration and logical dialectics.” (Liang & Chia, 2014, p. 111)	Imaginative capability measurement scale	Lin et al., 2021
Connectivity (creative	Connectivity (creative integration): “the fact that a drawing connects	Abreaction Test of Creativity	Melián Díaz et al., 2020 Carbonell-Carrera et al., 2019

integration) /Connection	several of the 12 figures that are arranged in the test. The tendency is to make a unique composition with each one of the figures" (Carbonell-Carrera et al., 2017, p. 7494)		Carbonell-Carrera et al., 2017
			Saorín et al., 2017
	Connection: "The ability to make connections between things that don't initially have an apparent connection" (StanSberry et al., 2015, p.445)	AULIVE Survey	StanSberry et al., 2015
Curiosity	"The desire to change or improve things that everyone else accepts as the norm" (StanSberry et al., 2015, p.445)	AULIVE Survey	StanSberry et al., 2015
Elaboration	"To elaborate is to treat something in detail, carefully and meticulously." (Carbonell-Carrera et al., 2017, p. 7494) "The imagination and exposition of detail" (Torrance, 2008, p. 3)	Abreaction Test of Creativity	Carbonell-Carrera et al., 2019
			Carbonell-Carrera et al., 2017
			Melián Díaz et al., 2020
			Saorín et al., 2017
		Torrance Test of Creative Thinking	Austin, 2017
Emotional expressiveness	"Communication of feelings and emotions through titles and drawings" (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017

Expressive richness	“It measures whether the drawing represents static objects or whether moving objects are represented” (Carbonell-Carrera et al., 2017, p. 7494)	Abreaction Test of Creativity	Carbonell-Carrera et al., 2017
			Melián Díaz et al., 2020
			Carbonell-Carrera et al., 2019
			Saorín et al., 2017
Expressiveness of titles	“This notes a person’s use of titles that go beyond simple description and communicate something about the pictures that the graphic cues themselves do not express without the title.” (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Extending or breaking boundaries	“Extend the lines, up, down or out ; split the imaginary rectangle” (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Fantasy/Willingness to fantasise	The representation of something that does not exist (Carbonell-Carrera et al., 2017)	Abreaction Test of Creativity	Melián Díaz et al., 2020
			Carbonell-Carrera et al., 2019
			Saorín et al., 2017
			Carbonell-Carrera et al., 2017

	Fantasy from literature, tv, and movies as well as original fantasy (Torrance, 2008)	Torrance Test of Creative Thinking Renzulli Scale	Austin, 2017
Figurative expansion	"It measures the space occupied by the drawing … This factor responds to an attitude or tendency to face risks and to exceed limits given" (Carbonell-Carrera et al., 2017, p. 7494)	Abreaction Test of Creativity	Carbonell-Carrera et al., 2017
			Carbonell-Carrera et al., 2019
			Melián Díaz et al., 2020
			Saorín et al., 2017
Flexibility	"Refers to the number of different categories of ideas" (Torrance, 2008, p. 9) "Take risks or try out their own ideas to create new products, works, or innovations. (P21, flexibility)" (Austin, 2017, p. 150)	Torrance Test of Creative Thinking Questionnaire created by the researcher "based on the key components of creativity defined and described by the Partnership for 21st Century Learning (2016)"	Austin, 2017
		Hu & Adey (Scientific Creativity Test) scale	García & Fernandez, 2018
Fluency/Fluent thinking	"the total number of relevant responses." (Torrance, 2008, p. 3)	Torrance Test of Creative Thinking Renzulli Scale	Austin, 2017

	"develop multiple ideas for solving problems, creating innovations or making new creations. (P21, fluency)" (Austin, 2017, p. 150)	Hu & Adey (Scientific Creativity Test) scale	García & Fernandez, 2018
Functionality Durability Usability	The functionality (in terms of durability and usability) of the artefact	Revised Creative Product Semantic Scale	Chien & Chu, 2018
			Chien, 2017
Graphic ability/Graphic Skills	"the following elements of the drawing are valued: coordinated movements, firmness in the stroke, sureness of movements, speed and precision, proportion in the parts of the picture, and mastery of certain techniques such as perspective and shading" (Carbonell-Carrera et al., 2017, p. 7494).	Abreaction Test of Creativity	Carbonell-Carrera et al., 2017
			Melián Díaz et al., 2020
			Saorín et al., 2017
			Carbonell-Carrera et al., 2019
Humour/Sense of humour	"an individual perceives and depicts conceptual and perceptual incongruity, unusual combinations, and surprise" (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking Renzulli Scale	Austin, 2017
Imaginative scope	"Imaginative scope: the role of each given figure within the drawn object. If the figure is a main element of the composition, the person will have a less imaginative scope." (Carbonell-Carrera et al., 2017, p. 7494)	Abreaction Test of Creativity	Melián Díaz et al., 2020

	“the degree to which the figure is a secondary element of the image”		
Initiating imagination	“Initiating imagination can be defined as the capability to explore the unknown and productively originate novel ideas.” (Liang & Chia, 2014, p. 111)	Imaginative capability measurement scale	Lin et al., 2021
Internal visualisation	“This measure indicates that a subject is able to visualize beyond exteriors and pay attention to the internal, dynamic workings of things.” (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Movement or action	“Including movement or action responses in the figure” (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Novelty	“The novelty dimension includes 3 variables : form (overall originality of the form design), materiality (originality in the selection of materials), Structure (originality in the design parts)” (Chien & Chu, 2018, p. 1054)	Revised Creative Product Semantic Scale	Chier, 2017
			Chien & Chu, 2018
	Novelty of ideas	Questionnaire created by the researcher “based on the key components of creativity defined and described by the Partnership for 21st Century Learning (2016)”	Austin, 2017

Originality/Original thinking/Original ideas	"Give solution that do not follow a stereotype". It "measures the ability to make different responses to the rest of the group (unusual and unconventional responses)" (Carbonell-Carrera et al., 2017, p. 7494)	Abreaction Test of Creativity	Carbonell-Carrera et al., 2017
			Saorín et al., 2017
			Carbonell-Carrera et al., 2019
			Melián Díaz et al., 2020
		Hu & Adey (Scientific Creativity Test) scale	García & Fernandez, 2018
	"The subject's ability to produce ideas well beyond the obvious, commonplace, banal, or established" (Torrance, 2008, p. 9) "Develop novel ideas for solving problems, creating innovations or making new creations. (P21, originality)" (Austin, 2017, p. 150)	Torrance Test of Creative Thinking Questionnaire created by the researcher "based on the key components of creativity defined and described by the Partnership for 21st Century Learning (2016)"	Austin, 2017
Paradox	"The ability to simultaneously accept and work with statements that are contradictory" (StanSberry et al., 2015, p.445)	AULIVE Survey	StanSberry et al., 2015

Persistence	"The ability to force oneself to keep trying to derive more and stronger solutions even when good ones have already been generated" (StanSberry et al., 2015, p.446)	AULIVE Survey	StanSberry et al., 2015
Perspective	"The ability to shift one's perspective on a situation - in terms of space and time, and other people" (StanSberry et al., 2015, p.446)	AULIVE Survey	StanSberry et al., 2015
Resistance to premature closure	Degree of openness "Persevere in testing their own new ideas (P21, resist premature closure)" (Austin, 2017, p. 150) "It is the control that the person has not to close the openings that the test presents without being carried away by the natural tendency for it to be closed" (Carbonell-Carrera et al., 2017, p. 7494)	Torrance Test of Creative Thinking Questionnaire created by the researcher "based on the key components of creativity defined and described by the Partnership for 21st Century Learning (2016)"	Austin, 2017
		Abreaction Test of Creativity	Carbonell-Carrera et al., 2017
			Carbonell-Carrera et al., 2019
			Saorín et al., 2017
Richness of imagery	"A subject's ability to create strong, sharp, distinct pictures in the mind of the beholder." (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017

Risk-taking/Willingness to take risks	Not provided	Test for Creative Thinking-Drawing Production TCTDP	Unterfrauner et al., 2021
Storytelling articulateness	“A subject’s ability to clearly and powerfully communicate an idea or tell a story by providing some kind of environment and sufficient detail to put things in context.” (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Synthesis of lines or circles	“The combination of two or more lines or circles is quite rare and points out an individual whose thinking departs from the commonplace and established, who is able to see relationships among rather diverse and unrelated elements, and who, under restrictive conditions, utilizes whatever freedom is allowed” (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Transforming imagination	“Transforming imagination can be defined as the capability to crystallize abstract ideas and reproduce mental images from less accurate recollections of reality, across different domains and in various situations” (Liang & Chia, 2014, p. 111)	Imaginative capability measurement scale	Lin et al., 2021
Uniqueness	“Evaluates the originality of the design in comparison to other designs generated in the sample.” (Prabhu et al., 2020, p.207)	CAT	Prabhu et al., 2020

Usefulness	"Evaluates the designs' ability to solve the given problem and its appropriateness" (Prabhu et al., 2020, p.207)	CAT	Prabhu et al., 2020
Unconventionality	Not provided	Test for Creative Thinking-Drawing Production TCTDP	Unterfrauner et al., 2021
Unusual visualisation	"This measure points out an individual who sees things in new ways as well as old ways and who can return repeatedly to a commonplace object or situation and perceive it in different ways." (Torrance, 2008, p. 4)	Torrance Test of Creative Thinking	Austin, 2017
Value	"Come up with new ideas that are tangible and useful (P21, value)" (Austin, 2017, p. 150)	Questionnaire created by the researcher "based on the key components of creativity defined and described by the Partnership for 21st Century Learning (2016)"	Austin, 2017
Collaborative creativity	Not provided	Rubrics with creativity criteria based on Cropley, Kaufman and Cropley (2011) and adapted to the curriculum creativity criteria	Lille , & Romero, 2017

		of PFÉQ by Romero and Vallerand (2016)	
Applied imagination	Not provided	AULIVE Survey	Austin, 2017
Composition and solution form	Not provided	Test for Creative Thinking-Drawing Production TCTDP	Unterfrauner et al., 2021
Conformity	Not provided	Renzulli Scale	Austin, 2017
Creative style	Not provided	Abreaction Test of Creativity	Carbonell-Carrera et al., 2019
	Not provided		Saorín et al., 2017
Creative imagination	Not provided	Deductive thematic content analysis	Walan, 2021
Diverse perspective	Not provided	Renzulli Scale	Austin, 2017
Imagination	Not provided	Renzulli Scale	Austin, 2017
Mental activity	Not provided	Renzulli Scale	Austin, 2017
Nature of responses	Not provided	Renzulli Scale	Austin, 2017
Willingness to manipulate ideas	Not provided	Renzulli Scale	Austin, 2017

Annex 3: List of databases

Databases

- ERIC
- JSTOR
- Web of Science
- Wiley online library
- Informit
- Pro Quest
- Learntechlib
- APA
- Mendeley
- Springer
- Scientific research (Creative Education)
- Design and Technology Education: An International Journal
- Science Direct
- Education Research Complete (EBSCO)
- Emerald
- Creativity Research Journal,
- Gifted Child Quarterly,
- Psychology of Aesthetics,
- Creativity, and the Arts,
- The Journal of Creative Behavior
- Thinking Skills and Creativity.
- Google Scholar

Annex 4: Database research collection

Database	Date accessed	Keywords and criteria	Results (n)	Retained (n)
Eric	25/05/22	education creativity “digital fabrication” Peer reviewed only 2013-2022 Descriptor: creativity, Full text available	29	1
JSTOR	26/05/22	creativ* AND digital fabrication OR mak* AND education OR class Articles 2013-2022 Full text available	262	0
Web of Science	26/05/22	((ALL=(creativ*)) AND ALL=(digital fabrication)) AND ALL=(education*) NOT ALL=(Fab Lab) 2013-2022	8	2
Science Direct	26/05/22	creativity AND "digital fabrication" 2013-2022 Research articles Open Access and Open Archive	30	0
EBSCO	28/05/22	creativity AND “digital fabrication” (in ABSTRACT) 2013-2022 peer reviewed	26	2
Emerald	28/05/22	Creativity (in Abstract) AND “digital fabrication” (All fields) AND education (All fields) 2013-2022 Full text available, Journal articles, Case studies	1	0

Informit	28/05/22	creativ* AND “digital fabrication” Full text available, Open Access, Peer reviewed, Journal, Educational 2013-2022	0	0
Pro Quest	28/05/22	creativ* (in abstract) AND "digital fabrication" (everywhere) full text peer reviewed 2013-2022 Article, Case study, Dissertation/Thesis	38	1
LearnTechLib	28/05/22	creativ* AND "digital fabrication" AND education* Full text, All publication 2013-2022	4	1
APA	28/05/22	Creativity (in Abstract) AND “digital fabrication” (in Any field) Full text, Peer-reviewed, Open Access, Journal Article 2013-2022	0	0
Mendeley	28/05/22	creativ* AND "digital fabrication" 2013-2022 Journal, Open Access	25	0
Wiley Online Library	29/05/22	creativ* AND "digital fabrication" AND education 2013-2022 Journal	80	0
Springer	29/05/22	creativ* "digital fabrication" 2013-2022 Articles	178	2
Creativity Research Journal	28/05/22	creativ* AND "digital fabrication" AND education Full access to, Article, Educational Research	52	2

		2013-2022		
The Journal of Creative Behavior	28/05/22	creativ* AND "digital fabrication" AND education 2013-2022 Journals, Subject: education	33	1
Thinking Skills and Creativity	28/05/22	creativ* AND "digital fabrication" 2013-2022	1	0
Psychology of Aesthetics, Creativity, and the Arts	28/05/22	making OR "digital fabrication" AND "creativity 2013-2022	25	0
Gifted Child Quarterly	28/05/22	creativ* AND "digital fabrication" 2013-2022 Full access	0	0
Scientific research (Creative Education)	29/05/22	creativity AND digital fabrication	9	0
Design and Technology Education: An International Journal	29/05/22	creativ* AND digital fabrication	1	0
Google Scholar	29/05/22	(all of the words): creativ* education research fabrication maker (exact phrase): digital fabrication (without the words): review conference book	223	2

		(where my words occur): anywhere in the article 2013-2022 English, italian, french		
	23/06/22	"créativité" "fabrication digitale" 2013-2022	44	1
			1075	**15**

Annex 5: Summary of results

Reference	Type of research	Intervention	Educational context, setting, domain	Digital Fabrication tool	Theoretical approach/framework/creativity definition | Focus	Creativity assessment instrument	Creativity characteristics enhanced
Austin, 2017	Mixed methods	Makerspaces activities, design tasks	Primary education (elementary school), school media centre, STEM	Lego WeDo Robotics and software, littleBits circuits	*"For the purposes of education, creativity is a skill students should cultivate to address the challenges of problem finding, problem solving, divergent thinking, and the creation of new ideas and products"* (p.25) "*... definition of creativity as an interaction between aptitude and process in an environment where a product is produced that is considered both novel and useful" (p.27)* Creative Process, creative person	Psychometric test (TTCT), Scale (Scales for Rating the Behavioral Characteristics of Superior Students: SRBCSS), Questionnaire (to address teacher perceptions on P21 competences)	Expressive communication (according to teachers) and indirect connections made with the themes of collaboration, value and novelty Significant difference in pre- and post- test total score Exploration, divergent thinking
Carbonell-Carrera et al., 2017	Quant.	Workshop, problem solving/based activities, makerspaces	Tertiary education (University), Engineering	3D modelling and printing	"*Creativity is defined as the generation of ideas in a novel and useful (or appropriate) way*" (p.7493)	Psychometric test (Abreaction Test to Evaluate Creativity)	Imagery abilities, Expressive communication, Synthesis, Originality, Exploration

		activities			"*Creativity in engineering", a way of thinking that contributes to new and original ideas, and that reaches high levels of usefulness in a functional and practical way that is easy to apply*" (p.7493) *"Bring different solutions to the same problem, in a creative and novel way." (p. 7493)* Creative process		Increased score in all components but especially imaginative scope, figurative expansion. Also Originality, Fantasy, Connectivity, Elaboration,
Carbonell-Carrera et al., 2019	Quant.	workshop, design challenge/task, makerspaces activities, problem solving activities	Tertiary education, Engineering, STEM	3D modelling and printing	"*Creativity in engineering" is understood as a way of thinking that brings new ideas which are original and easy to apply in a functional and practical way… a creativity workshop was proposed in order to find multiple solutions to the problem posed, according to divergent thinking*" (p.6035) *"Creativity is an important tool in the search for a more sustainable future, directly linked to innovation and*	Psychometric test (Abreaction Test to Evaluate Creativity)	Originality, Perseverance, Exploration, Imagery abilities

					creative problem solving" (p. 1) Creative process		
Chien, 2017	Quant.	Course, classroom activities	Secondary education (high school), Engineering	3D modelling and printing, laser cutting	A creative product is a novel/original, sophisticated and functional product Creative product	Scale	Originality, Usefulness, Sophistication
Chien & Chu, 2018	Quant.	Course, Curriculum, design challenge/task	Tertiary and secondary education, STEAM, Engineering, Design	3D modelling and printing	A creative product is a novel/original, sophisticated and functional product Creative product	Scale (Revised Creative Product Semantic Scale - CPSS)	Synthesis, Originality, Usefulness, Sophistication (in college students only)
García & Fernandez, 2018	Quant.	Makerspaces activities	Secondary education (middle school), Science	Not specified	"*According to Guilford, creativity is mostly associated with 'divergent production' leading to a number of solutions of a particular problem*" (p.76) Creative process	Scale (Scientific Creativity Test' (SCT))	Scientific creativity for : use an object for a scientific purpose, test the ability of creating a scientific solution, detect the creative experimental ability
Lille & Romero, 2017	Qual.	Course, problem solving activities,	Tertiary education, STEAM, Education	Not specified	"*creativity as a… process that aims to design a new, innovative and pertinent way to respond to a potentially*	Ratings (creativity criteria based on Cropley,	Collaborative creativity, Synthesis, originality (using inspirational

		design tasks/challenge	technology		*problematic situation, which is valued by a group of references in a context-specific situation… creativity in educational contexts is defined by the balance residing between divergent, convergent and associative thinking.*” (p.1) *“a research project that aims to develop learners’ 21st-century competencies, such as creative problem-solving” (p.4)* Creative process	Kaufman and Cropley and adapted to the curriculum creativity criteria of PFÉQ by Romero and Vallerand) Qualitative data analysis Creativity peer assessment	sources to guide creative research, exploring new solution, select a solution while considering context)
Lin et al., 2021	Quant.	design tasks/challenge	Secondary education, STEM	3D modelling and printing	*“Imaginative capability as the foundation for all types of creativity… imaginative capability depends on experiences in our real life; individuals must use their personal experiences to create products to meet their needs*” (p.2) *“Characteristics of imaginative capability into three types: (i) “Initiating*	Scale (Imaginative Capability Measurement Scale)	Synthesis, Originality

					imagination" encompasses exploration, novelty, and making; (ii) "Conceiving imagination" includes effectiveness, diagnosis, feeling, intuition, and concentration; (iii) "Transforming imagination" includes figurativeness and adaptiveness." (p. 3) Creative process		
Melián Díaz et al., 2020	Quant.	Workshop, makerspaces activities, problem-solving activities	Tertiary education, Engineering, Computer Science	3D modelling and printing	*"Graphic creativity is one of the factors of creativity, essential for engineers… this ability has already shown relation to other skills that engineers need such as spatial ability, critical thinking, innovation capacity, problem solving and the generation of different solutions using visual and tangible tools"* (p.1152) Creative process	Psychometric test (Abreaction Test to Evaluate Creativity)	Synthesis, Originality, Exploration, Imagery abilities, Expressive communication → graphic creativity, imaginative scope, figurative expansion, connectivity
Prabhu et al., 2020	Quant.	Lecture, workshop, design challenge/task	Professional development, Company, Engineering,	3D modelling and printing	"*Creativity is domain-specific, and individuals demonstrate different levels of creativity in tasks from different domains*"	Rating, Scale (Creative Self-Efficacy (CSE) Scale)	Originality, creative self-efficacy

			Design		*(p.202)* "*Experts typically evaluate ideas on three dimensions: novelty, resolution, and elaboration and synthesis… creative products must be novel, relevant (useful), workable (feasible), and specific (elaborate), and the overall creativity of an idea can be obtained by taking an average of the ratings for these four components" (p.203)* Creative person, creative product	CAT	
Saorín et al., 2017	Quant.	Workshop, makerspaces activities	Tertiary education, STEAM, Engineering	3D modelling and printing	*"Ability to engage in a creative process so as to define or solve a problem, or to design a product"* (p.188) Creative process	Psychometric test (Test Abreaction for Evaluate Creativity), Students' perceptions questionnaire	Not specified→ creative competence Creative self-efficacy
Stansberry et al., 2015	Quant.	Online course, problem solving/based	Professional development, Education technology	Auto-cad software, a computer-controlled	*"Creativity is the interaction among aptitude, process and environment by which an individual or group produces a*	Survey (AULIVE Survey)	Exploration, Synthesis, Perseverance, Creative Self-efficacy

		activities, design challenge/task ,		die-cutting machine or a 3D printer	*perceptible product that is both novel and useful as defined within a social context… Root-Bernstein and Root-Bernstein focus on creativity as a set of cognitive skills that transcend disciplines…creative self-efficacy, defined as a self-judgement of one's own imaginative ability and perceived competence in generating novel and adaptive ideas, solutions and behaviors"* (p. 436) Creative person		→ abstraction, connection, perspective, Exploration, Creative Self-efficacy
Unterfrauner et al., 2021	Quant.	Programme, makerspaces activities	Primary and secondary education	Not specified	"*Creativity is perceived as the ability to find different solutions for the same problem in the sense of divergent thinking and to turn these possible solutions into new opportunities*" (p.408) Creative process, creative person	Psychometric test (Test for Creative Thinking-Drawing Production ((TCT- DP)) Survey for self-efficacy	Overall creativity
Walan, 2021	Qual.	Makerspaces activities	Informal settings, (age Primary	3D modelling and printing, laser cutting	*"a process over time, resulting in products that are novel. He adds that these can emerge*	Deductive thematic content analysis of the	Originality, self-efficacy

			education) outside school setting, STEM		*from elements that already exist, but are combined in new ways…The development of the creative imagination, then, is based on what is usually considered creative activity: pretend play, fantasy, and the making of creative products."* (p.26) Creative process	outcome of the activities (drama and making).	
Weng et al., 2022	Qual.	Online course, Programme, problem solving/based activities, design challenge/task	Primary and secondary education, STEM, Computer Science,	Scratch	*"Creativity suggests using innovative approaches to finish a task, find a solution, or design an invention… creativity (in the form of creative explorations, creative solutions, and creative expressions)"* (p.374) Creative process	MLA inductive analytic method of videos, numerical/ textual responses, semi-structured interview (questionnaire)	Imagery abilities, Synthesis, Expressive communication, Exploration, Originality Creative exploration, various creative solution, creative expression