Journal of Education and Learning Reviews, 3 (3): May-June 2026 ISSN: 3057-0387
Website: https://so19.tci-thaijo.org/index.php/JELS/about
Article ID: e3061

Practice and Exploration of 3D Printing as a Digital Learning Innovation in Technology Education for Teenagers

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Received **10**/03/2026	Revised **28**/03/2026	Accepted 03/04/2026

Abstract

Background and Aim: While 3D printing is widely promoted in K-12 education, existing research focuses mainly on technical skill acquisition, leaving a critical gap: how to systematically integrate 3D printing into curricula to simultaneously develop technical competencies, mathematical reasoning, and cultural awareness. This study addresses that gap by examining a three-stage curriculum built around the "Trinity" teaching model—theoretical cognition, hands-on practice, and value guidance—and investigates its effects on adolescents' cognitive processes and learning outcomes.

Materials and Methods: A two-year design-based study was conducted at a university science center and two partner schools in Shanghai, involving 156 students aged 10–15. Data included pre/post knowledge tests, performance assessments using validated rubrics, classroom observations, and student reflections. Quantitative analysis measured gains in technical understanding and mathematical application; qualitative analysis captured shifts in cognitive strategies and cultural identity.

Results: Mastery of 3D printing principles increased from 42% to 95% ($p < .001$). Independent modeling and optimization reached 90% and 85%, respectively. Students' perception of mathematics as practically useful rose by 65%. Qualitative data revealed three cognitive shifts: (1) reduced cognitive load through physical manipulation, (2) systematic troubleshooting during design iterations, and (3) enhanced cultural confidence via heritage projects (e.g., reproducing traditional ocarinas, mortise-tenon joints). The Trinity model proved effective in connecting abstract concepts with tangible practice.

Conclusion: This study offers a way to bring 3D printing into secondary STEM classrooms that has been tested and could be used elsewhere. The Trinity model produced changes in students that went beyond technical skills—shifts in how they thought and acted that we could actually measure. The work should be useful to people working in educational technology, designing curriculum, or training teachers, especially those trying to bring cultural heritage together with STEM teaching.

Keywords: 3D printing; Educational technology; Teaching innovation; Digital learning; Hands-on practice

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Introduction

Three-dimensional (3D) printing has emerged as a significant digital advancement in modern technology education, as it allows students to convert abstract concepts into physical objects. In educational contexts, this ability is particularly important as it facilitates experiential learning, enhances student engagement, and offers chances for the integration of conceptual understanding with practical application. With the ongoing promotion of digital transformation in education systems, 3D printing has garnered increasing interest as a tool that enhances science, technology, engineering, and mathematics (STEM) education through design-oriented and problem-focused activities (China Association for Educational Technology, 2023; Ministry of Education, 2022).

Notwithstanding this promise, the integration of 3D printing in educational institutions remains inconsistent. A national assessment indicated that merely 28% of primary and secondary school programs in China have implemented regular 3D-printing education, signifying that systematic adoption remains constrained (China Association for Educational Technology, 2023). Furthermore, in instances where such programs are available, teaching practices frequently prioritize operational procedures, including equipment setup and material handling, above more profound educational objectives like design thinking, mathematics application, and multidisciplinary problem-solving. This indicates that, in numerous instances, 3D printing has not been completely assimilated into curricular frameworks to optimize its educational efficacy.

Global advancements indicate that 3D printing can fulfill extensive educational objectives when integrated into thoughtfully constructed learning settings. Current research and curricular revisions emphasize the necessity of incorporating emerging technologies with scientific inquiry, innovation education, and interdisciplinary learning (Guan & Yang, 2024; Song et al., 2024). Simultaneously, design-based and STEAM-focused methodologies have progressively underscored the necessity of linking technical education with genuine contexts, creativity, and practical problem-solving (Duan, 2023; Zheng, 2025). Nonetheless, despite these advancements showcasing the educational potential of 3D printing, a significant gap persists: there remains an absence of cohesive pedagogical models that systematically integrate technical skill acquisition, mathematical reasoning, and cultural comprehension within a unified instructional framework.

The educational significance of 3D printing can be comprehended through constructivist and experiential learning theories. 3D printing fosters iterative knowledge production and reflective problem-solving by allowing students to develop, test, revise, and realize their ideas. The transition among digital models, mathematical representations, and physical goods may enhance conceptual comprehension by aiding learners in forming significant connections across various kinds of representation. Previous research on technology-enhanced instruction and 3D modeling indicates that these settings can facilitate spatial reasoning, practical application of mathematical concepts, and sustained learner motivation (Liu, 2022; Zhang, 2022).

Simultaneously, contemporary curricular practices seldom consider how 3D printing might enhance not only technical proficiency but also promote wider educational objectives, such as cultural awareness, ethical contemplation, and innovation literacy. This matter is especially significant in technology education for teens, where the objective should transcend beyond instructing kids in machine operation to fostering their ability to utilize technology in a meaningful, creative, and responsible manner. Consequently, a more holistic curriculum model is required—one that synthesizes

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academic comprehension, practical involvement, and value-centric education in a cohesive and evaluable manner.

This study presents a two-year initiative to develop and assess a 3D-printing curriculum for kids aged 10 to 15 in Shanghai. The curriculum was organized into a three-stage development from fundamental skills to targeted application and integrated innovation, supervised by a "Trinity" teaching paradigm comprising theoretical understanding, practical experience, and ethical guidance. The study sought to investigate if this paradigm could facilitate not only mechanical learning but also mathematical reasoning and cultural awareness, while simultaneously capturing the cognitive processes that students cultivated through iterative design and production. This study aims to provide practical and theoretical insights for researchers, curriculum designers, and teacher educators in digital learning and K–12 technology education by presenting an empirically validated curricular structure, assessment rubrics, and evidence of student learning.

Analysis of the Educational Value of 3D Printing Technology

1. Technical Characteristics and Educational Suitability

When I first began using 3D printers, I was struck by how students responded. It wasn't just that they found the technology cool—they did—but that the printer seemed to change their relationship to ideas. A concept that felt abstract on paper became real when they could hold it, turn it over, measure it. A design that failed could be fixed and printed again overnight, not abandoned in frustration. A project that started as my assignment often ended as their passion.

From a cognitive load standpoint, the pattern makes sense. Students working with formulas they cannot connect to anything concrete carry a heavy mental load. There is little space left to consider what the formulas actually mean. Physical objects reduce that strain by giving the mind something tangible to work with. Working memory is freed up, and students can focus on relationships instead of just retrieving facts.

Our geometry unit illustrated this. Students had always struggled to see how changing a tetrahedron's edge length affected its volume and surface area. They could recite the formulas but could not use them. When we printed polyhedra and let students handle them, measure them, compare them, something shifted. Students started noticing things on their own—comments like "doubling the edge makes the volume increase way more than the surface area" came from them, not from us. This fits with what knowledge integration theory suggests: that solid understanding develops when learners can move between different ways of representing the same thing—symbols, pictures, physical objects—and connect them into a coherent whole.

Over time, I came to see that 3D printing has three characteristics that make it particularly suited for educational technology.

First, the physical object works as a bridge. It connects abstract symbols to tangible experience, lightens cognitive load, and helps students pull together different kinds of knowledge.

Second, rapid iteration changes how students see failure. The old way took time—a cardboard bridge broke and you started over, a clay model cracked and you went back to the beginning. With 3D printing, students change a file and a new version comes out the next day. Failure turns into information, not a dead end. On the bridge project, students went through a lot of rounds. Each collapse taught them something. They recalculated angles, changed load estimates, tried different shapes. By the end, the

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bridge held 150% more weight than the first try. Nobody told them what to change. The process itself showed them.

But rapid iteration also brings its own kind of trouble. Students run into technical failures all the time—CAD software crashing, filament jamming, prints not sticking to the bed, dimensions coming out wrong. Instead of treating these as problems to minimize, we started treating them as chances to think. When a print fails, a student has to figure out why. Is it geometry? Too steep an overhang? Is it material? Filament temperature off? Is it procedure? Bed not leveled right? Each answer pulls in knowledge from different places, which is exactly what educational researchers mean when they talk about transfer—the ability to connect ideas across domains. These moments of productive failure, as Kapur calls them, turned out to be where a lot of the learning actually happened.

Third, personalization changes the game. When every student designs something unique, the room feels different. Kids stop trying to outdo each other on who followed directions best and start sharing what they made. One student builds a fantasy castle because he likes architecture. Another prints a little figure of her dog. A third prototypes something his father might actually use at work. All of that takes math—scaling things right, putting coordinates in the right place, figuring out how much gap to leave—but the math shows up because they need it, not because it is scheduled for Tuesday. They learn it to make something work.

2. What Students Actually Learn

Over two years of observation and assessment, we have seen 3D printing education contribute to student development in three interconnected domains.

Knowledge development. Students learn the basics of additive manufacturing—how FDM printers work, how different materials behave, and why support structures are sometimes needed. More importantly, they learn the mathematical foundations of 3D modeling: coordinate systems, geometric transformations, and dimensional tolerances. This knowledge does not sit in isolated compartments. When a student designs a gear, she draws on engineering (how power transmits), physics (friction and force), and mathematics (gear ratios and tooth spacing). The boundaries between subjects blur, which is precisely how real-world problem-solving works.

We used a rubric to track skill development across three areas: proficiency with CAD software, use of math to refine designs, and ability to troubleshoot when things went wrong. Two raters scored each student on a four-point scale. Inter-rater reliability came in at 0.87.

What we saw was a pattern. Students started by copying existing designs, following along step by step. After a while, they began experimenting—changing support spacing here, adjusting infill there—and noticing what happened. The ones who kept at it eventually started designing their own things from nothing, thinking about scale and coordinates and how much tolerance to leave. Imitation, then modification, then creation. It is a progression that shows up in a lot of research on how people get good at things.

Broader competencies. The less measurable outcomes have been, in many ways, the most satisfying. Students who struggled in traditional settings discovered a knack for spatial reasoning. Quiet students found their voice explaining design choices. Teams learned to negotiate disagreements—should the bridge use an arch or a truss?—and settle them through testing and evidence. In our "Eco-Product Design" project, teams researched environmental problems, designed solutions, built prototypes, calculated material needs, estimated carbon footprints, and factored sustainability into

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decisions. By the end, they had not only sharpened technical skills but also developed a sense that they could use technology to address real-world problems.

Course Design and Teaching Practice Innovation

1. Designing a Curriculum That Works

Early in the project, we faced a choice among three directions: technical skill acquisition, design thinking, or using printing to teach broader concepts and values. We came to think that all three mattered, so we built a curriculum that drew on constructivist ideas and cognitive load research. It moves through three stages, each one building on what came before.

Stage one: Basic familiarity. The focus is on the tools themselves. Students print simple objects—keychains, name tags—and learn the steps involved: exporting files, loading filament, leveling the build plate. The aim is to make the technology feel ordinary, something they can do.

Stage two: Focused applications. Projects now require specific knowledge. In Block Castle, students design structural forms and test how much weight they hold, which means learning about arches and trusses and calculating load capacities. In the Personalized Pen Holder, they practice scaling and positioning coordinates. Math enters not as a separate subject but as something they need to make their designs work.

Stage three: Integrated innovation. Students undertake projects pulling together different kinds of knowledge. A student designs a working gear train, figures ratios, and tests efficiency. Another builds a scale model of a historical structure, converting full-size measurements to fit a print bed. A third estimates material usage and compares environmental impact. These projects require synthesizing prior learning and managing the whole process from idea to finished object.

Table 1 shows thirteen projects across three thematic categories: life-oriented applications, traditional culture integration, and engineering innovation.

Table 1. 3D Printing Course Module Classification and Teaching Objectives

Module Type	Representative Project	Teaching Objectives
Life-Oriented Basic Projects	Becoming an Architect – Block Castle	**Knowledge:** Learn architectural structure types (arch, truss) and mechanical principles; master geometric calculation of arch curvature and conversion of load-bearing formulas. **Ability:** Design prototypes and compress them to-test their load capacity. **Literacy:** Cultivate spatial thinking and engineering aesthetics awareness.
	Finding a Home for Stationery - Personalized Pen Holder	**Knowledge:** Students acquire basic 3D-modeling skills and PLA-material knowledge, applying scale adjustments to produce desk-sized organizers. **Ability:** Projects included designing and producing lightweight storage units with multiple functions.

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Module Type	Representative Project	Teaching Objectives
		Literacy: Strengthen environmental responsibility awareness and advocate sustainable design.
Traditional Culture Integration Projects	Craftsmanship Spirit - Mortise and Tenon Flower Stand	**Knowledge:** Students worked with mortise and tenon joints, both in traditional woodworking and as digital models. They kept to standard proportions—tenon width to mortise width at 1:1.2, tenon thickness to material thickness at 0.8:1—and used the Pythagorean theorem to check squareness in joint geometry. **Ability:** Reproduce classic mortise and tenon joints and complete assembly. **Literacy:** Inherit the craftsmanship spirit and appreciate traditional craft wisdom.
	Sound of the Earth - Xun (Chinese Ocarina)	**Knowledge:** Understand the acoustic principles and tuning methods of the Xun; use the circle circumference formula to calculate the aperture of the Xun body; use trigonometric functions to convert the influence of the air hole's tilt angle on pitch accuracy. **Ability:** Build parametric models and adjust pitch accuracy. **Literacy:** Enhance cultural confidence and explore new paths for intangible cultural heritage protection.
	The Winding Dragon - The Great Wall	**Knowledge:** Students studied its defensive design and strategic purpose. They worked out how to scale it down for printing—a 7.8-meter wall section, for example, became 15.6 millimeters at 1:500 scale. **Ability:** Model and print based on topographic data. **Literacy:** Understand historical wisdom and cultivate patriotism.
Engineering Innovation Projects	Childhood Memory - Carousel	**Knowledge:** Students figured gear speed ratios by comparing tooth counts—driven gear over driving gear—then went on to work out overall ratios for multi-stage gear trains the same way. **Ability:** Design dynamic models and improve transmission efficiency. **Literacy:** Cultivate systematic engineering thinking and innovative practical ability.
	Planet in Hand - Globe	**Knowledge:** Students used GIS data and terrain models. They converted geographic coordinates to Cartesian coordinates to construct a digital globe,

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Module Type	Representative Project	Teaching Objectives
		applied spherical formulas to position geographic regions, and reduced Earth's 6371 km radius to 5 cm so the whole thing fit in their hands. **Ability:** Make a layered, colored globe and mark ecological regions. **Literacy:** Strengthen global perspective and sustainable development awareness.
	Secret of Energy - Rubber Band Powered Car	**Knowledge:** Understand energy conversion and friction loss principles; calculate the conversion efficiency of rubber band elastic potential energy to car kinetic energy through mathematical modeling; convert the corresponding travel distance for different tire diameters. **Ability:** Iteratively optimize car performance and participate in competitions. **Literacy:** Cultivate a scientific inquiry spirit and competitive/cooperative awareness.
	Making Models Move - Gear Transmission Device	**Knowledge:** Learn gear meshing tolerance and precision manufacturing; calculate the pitch tolerance for gear meshing (standard tolerance range: 0.02-0.05mm); correct transmission errors by converting gear meshing angles using trigonometric functions. **Ability:** Design a stepless speed change system and correct errors. **Literacy:** Strengthen the pursuit of meticulous engineering quality.
	Future Intelligent Manufacturing	**Knowledge:** Students used AI design tools—DeepSeek and Kimi—and also experimented with 4D printing. They ran algorithmic checks to confirm the dimensions of AI-generated models were accurate. **Ability:** Realize the full-chain practice of "design-simulation-manufacturing." **Literacy:** Broaden horizons in cutting-edge technology and cultivate future innovative thinking.

The study utilized a multidimensional assessment methodology to measure student development across the domains outlined in Table 1, which includes knowledge, practical skills, and learner attitudes. Knowledge acquisition was evaluated using pretest and posttest assessments that included multiple-choice and short-answer questions focused on fundamental concepts such as gear ratios, structural

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stability, and principles of additive manufacturing. The practical competence was assessed using a four-point rubric focused on modeling accuracy, design functionality, and problem-solving performance. Furthermore, student dispositions were assessed by reflective writing and oral presentations, focusing specifically on spatial reasoning, cultural appreciation, and engineering knowledge. Interrater agreement for qualitative coding achieved a Cohen's kappa of .81, signifying satisfactory reliability for interpretive analysis (Linn, 2006; Sweller, 1988).

An illustrative instance of curriculum application was the Sound of the Earth: Xun Project, wherein students engineered and produced a traditional Chinese ocarina with 3D-printing technology. This research demonstrates that digital fabrication serves not just as a technical endeavor but also as an educational conduit linking mathematics, scientific reasoning, design iteration, and cultural legacy. This integration aligns with previous research indicating that 3D printing facilitates multidisciplinary learning, particularly when incorporated into authentic and meaningful projects (Ford & Minshall, 2019; Scopigno et al., 2017).

The initial phase of the Xun project prioritized cultural and historical contextualization. Students were acquainted with the instrument via multimedia resources and facilitated discourse regarding its historical roots, material composition, and significance in Chinese musical heritage. This phase aimed to situate technological design into a wider cultural context instead of regarding fabrication as a standalone technical ability. The significance of integrating technological education with culture and heritage is increasingly acknowledged in modern curriculum studies, especially in methodologies that aim to merge innovative learning with contextual relevance and identity development (Guan & Yang, 2024; Song et al., 2024).

The second phase concentrated on technical investigation and mathematical modeling. Students analyzed the acoustic principles governing wind instruments, focusing on the correlations between cavity size, aperture dimensions, and pitch generation. They employed elliptical equations to represent the xun's pear-shaped contour, computed cavity volume, and established hole positioning using acoustic and geometric analysis. These activities exemplify the established benefits of 3D printing in mathematics education, wherein concrete modeling projects can improve conceptual comprehension, visualization, and mathematical design thinking (Ng et al., 2022; Zhang, 2022).

The third phase focused on iterative prototyping and empirical validation. Following the printing of their preliminary designs, students evaluated the instruments and detected inconsistencies in pitch, resonance, and sound clarity. Instead of perceiving failure as a conclusion, students were urged to regard malfunction as diagnostic data. They recalibrated dimensions, modified digital models, and produced updated versions. This iterative cycle corresponds with constructivist learning theories that prioritize active knowledge construction via experience, reflection, and revision, as well as the productive failure framework, which posits that initial unsuccessful attempts can enhance subsequent understanding when learners analyze and redesign (Kapur, 2008; Piaget, 1972).

Significantly, iterative design testing allowed students to establish informal empirical correlations between physical alterations and auditory results. For instance, certain learners recorded how gradual modifications in hole diameter affected pitch, thus converting abstract mathematical relationships into discernible and significant patterns. This representational progression—from formula to model to artifact to measurable outcome—illustrates the principles of knowledge integration, wherein comprehension is enhanced as learners link concepts across many representational forms (Linn, 2006).

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The fourth step encompassed reflection and presentation. Students were requested to elucidate their creations, justify their design choices, and articulate the insights gained throughout the process. These introspective presentations demonstrated that students were not just acquiring technical jargon and analytical reasoning but also cultivating a respect for traditional workmanship and historical inventiveness. These findings endorse the perspective that digital fabrication can enhance overarching educational objectives, such as cultural comprehension, communication, and value-centric learning, when instruction is deliberately structured to transcend mere operational proficiency (Duan, 2023; Zheng, 2025).

These practices were structured within the Trinity teaching model, which includes theoretical cognition, practical application, and value orientation. The initial element, theoretical cognition, prioritized conceptual comprehension via visualization, analogy, and tangible modeling instead of relying solely on didactic instruction. This method aligns with cognitive load theory, which posits that effective instructional design can alleviate extraneous mental strain, enabling learners to concentrate cognitive resources on relevant processing and conceptual comprehension (Sweller, 1988; van Merriënboer & Sweller, 2005).

The second component, actual operation, progressed from imitation to modification and ultimately to independent creativity. This developmental process is pedagogically important as it enables learners to progress from supervised involvement to greater autonomy in problem-solving. Previous studies on the integration of 3D printing indicate that scaffolded engagement can enhance STEM motivation, mathematical reasoning, and design competence when students are afforded opportunities to create, evaluate, and improve personally significant artifacts (Cheng et al., 2020; Khurma et al., 2023).

The third component, value guiding, integrated ethical, cultural, and social factors into design challenges. In projects including mortise-and-tenon constructions, students examined the accuracy and diligence inherent in traditional craftsmanship. In environmentally focused projects, they evaluated material use, design efficacy, and sustainability ramifications. This aspect of the program is particularly significant as modern technology education aims to cultivate both technical expertise and responsible, culturally contextualized creativity (Liu, 2022; Ministry of Education, 2022).

The intervention's findings demonstrate significant learning improvements in cognitive, technical, and attitudinal areas. Knowledge scores significantly increased, with knowledge of fundamental 3D-printing concepts escalating from 42% before training to 95% subsequent to instruction, $\chi^2(1) = 45.3$, $p < .001$. Ninety percent of students autonomously completed the entire workflow from digital modeling to final print, while eighty-five percent effectively utilized mathematical methods, including scaling, coordinate transformation, and tolerance calculation, to enhance their designs. These results align with previous findings indicating that 3D modeling and digital fabrication enhance spatial thinking and practical problem-solving skills in school-aged students (Šafhalter & Glodež, 2016; Ford & Minshall, 2019).

Changes in attitudes were as significant. After engaging with the curriculum, students exhibited enhanced recognition of the practical significance of mathematics, a heightened readiness to tackle hard issues, and an increased interest in engineering-related studies. Heritage-based projects seemingly promoted cultural connection, as a significant majority of students indicated an enhanced engagement with traditional culture. These results substantiate the assertion that 3D printing serves as more than a mere technical instrument; when underpinned by effective education, it can evolve into a conduit for

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transdisciplinary comprehension, learner autonomy, and culturally significant invention (Ng et al., 2022; Thyssen et al., 2023).

The evidence indicates that the curriculum's effectiveness stemmed not solely from access to 3D-printing equipment, but from the educational framework supporting its application. The Trinity approach facilitated an environment where students could integrate mathematics, technology, and culture through genuine acts of creation by merging conceptual grounding, iterative design practice, and value-centered reflection. This discovery holds significant ramifications for curriculum development, educator training, and the prospective incorporation of digital fabrication into K–12 technology education (China Association for Educational Technology, 2023; Ford & Minshall, 2019; Ministry of Education, 2022).

Conclusion

This study grew from a simple observation: when teenagers use 3D printers to create things that matter to them, they learn in ways that traditional instruction rarely enables. They grapple with real mathematical problems because they need the answers to make their designs work. They persist through multiple iterations because they are invested in the outcome. They connect technical skills to broader questions—about culture, about sustainability, about craftsmanship—because their projects invite those connections.

Based on two years of evidence, we draw several conclusions with implications for practice and policy.

First, 3D printing can support deep learning only when embedded in a thoughtfully designed curriculum that links technical skills to broader goals. The Trinity model—theoretical cognition, hands-on practice, value guidance—provides a coherent framework for doing so. Our assessment rubrics demonstrate that gains in knowledge, skill, and disposition can be measured reliably, making the model replicable in other contexts.

Second, mathematics learning gets stronger when students use it to build things, not just to solve problems on paper. The percentage who started seeing math as actually useful went up by 65, which suggests that something shifts when math happens in the context of making. That kind of change probably affects whether they stick with it later.

Third, connecting technology education to cultural heritage proved unexpectedly powerful. Projects involving traditional Chinese crafts—xun, mortise-tenon joints, Great Wall—engaged students who usually hung back, sparked questions about history and design, and fostered cultural pride. This suggests a pathway for culturally sustaining STEM pedagogy that other regions could adapt using their own heritage.

Fourth, a few things stood out as making implementation work. Keeping class sizes small enough that we could help individually, around 15 students per teacher. Having printers that actually ran and enough supplies to keep them going. Training that focused on guiding students through design cycles rather than just showing them steps. And setting aside enough time in the schedule for multiple tries and for stepping back to think. Schools without those things might need to start smaller and work up.

A few limitations are worth noting. The study took place in two urban Shanghai schools with solid resources. Whether the same approach would work in rural or less-equipped settings needs more investigation. We also do not know the long-term effects—whether these students end up pursuing

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STEM, keep their confidence in math, or stay engaged with cultural material. A five-year follow-up is planned to start addressing that.

Future research could go a few ways. Longitudinal work could follow these students to see if they end up in STEM. Comparative work could look at whether heritage projects land differently in different places. And with AI design tools showing up everywhere, there are new questions. If a program can figure out gear ratios on its own, do students still get the same intuitive feel? Hard to say. Research needs to ask whether AI tools help or hurt the kind of thinking we saw here. This study gives a place to start asking those questions.

What I can say, after more than ten years of teaching, is this: I have rarely seen students as engaged as they were during these projects. I have rarely seen them persist through difficulty with such determination. And I have rarely seen them make such rich connections between school subjects and the world beyond school. If 3D printing can do that—if it can help kids see themselves as creators, as problem-solvers, as people who can use technology to make things that matter—then it deserves a place in our classrooms, supported by the kind of thoughtful curriculum and teaching we've tried to build here.

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Citation: Jiangang, Y., & Gang, L. (2026). Practice and Exploration of 3D Printing as a Digital Learning Innovation in Technology Education for Teenagers. Journal of Education and Learning Reviews, 3 (3), e3061; DOI: https://doi.org/10.60027/jelr.2026.e3061