J. Empir. Soc. Sci. Stud. 7(1)

Empirical Investigation of the Impact of 3D Printing on Multiple Dimensions of Student Engagement in STEM Education

Yogiraj Kamat[1]
Siddhesh Nasnodkar[2]

Abstract

The present study employs Elastic Net Regression to empirically examine the impact of various variables, including the use of 3D Printing, on four distinct types of engagement (Behavioral, Cognitive, Emotional, and Tech). A total of 318 STEM students were involved in the study, and we estimated 4 models for each dimension of student engagement. The independent variables investigated include Attendance Rate, Class Participation, Assignment Completion Rate, Participation in Extracurricular Activities, Teacher-Student Interaction, Tangible Visualization with 3D Printing, External Stressors, and Class Size. In Behavioral Engagement model, our results showed that traditional metrics like Teacher-Student Interaction, Class Participation, and Attendance Rate had strong positive effects, while the impact of 3D Printing was neutral to positive. For Cognitive Engagement, 3D Printing showed a robust positive effect, comparable to that of Teacher-Student Interaction and Assignment Completion Rate. Emotional Engagement was primarily influenced by relational factors like Teacher-Student Interaction and Participation in Extracurricular Activities; 3D Printing had a neutral to positive effect. In the case of Tech Engagement, metrics like Assignment Completion Rate and Teacher-Student Interaction showed the most considerable positive impact, while 3D Printing showed a neutral to positive influence, specifically when the Learning Management System (LMS) supported Tangible Visualization tools. External Stressors were consistently negative across all types of engagement, while Class Size generally had a neutral to negative effect. The findings our study may contribute to the broader understanding of the factors affecting student engagement in STEM disciplines and provide initial empirical evidence of the potential benefits and limitations of integrating 3D Printing into STEM educational settings.

Keywords: 3D Printing, Elastic Net Regression, Empirical Analysis, STEM Education, Student Engagement

Authors:
[1]**Yogiraj Kamat**, iWeb Technology Solutions, yogiraj@iwebtechno.com
ORCID: 0009-0005-7646-8827
[2]**Siddhesh Nasnodkar**, iWeb Technology Solutions, siddhesh@iwebtechno.com
ORCID :0009-0007-3464-1470

Introduction

3D printing, also known as additive manufacturing, is a process where materials like plastic or metal are systematically layered to create a three-dimensional object [1], [2]. This is fundamentally different from traditional ink-based printing systems that generate two-dimensional end products, such as ink on paper [3], [4]. Initially, 3D printing gained prominence in the field of engineering, specifically for creating prototypes to evaluate form, fit, and function [5], [6]. The technology allows for rapid prototyping, giving engineers a quick and cost-effective method to test out designs before they are finalized. This is particularly valuable in fields that require a high level of customization and rapid iterations, such as aerospace and automotive engineering [7],[8].

The scope of 3D printing has expanded significantly due to advances in the materials that can be used in the printing process. While the early stages of 3D printing were limited by the types of materials that could be employed, breakthroughs in material science have made it possible to produce objects that are functionally and structurally comparable to those made through traditional manufacturing techniques [9]. Plastics, metals, and even biocompatible materials can now be 3D printed [10], leading to applications far beyond mere prototyping. Medical fields, for example, have seen the introduction of 3D printed prosthetics and implants, while the fashion industry is exploring 3D printed fabrics and accessories [11].

The use of 3D printing (3DP) has shown promising results across multiple disciplines [12], [13], [14], [15], notably within science, technology, engineering, and mathematics (STEM). In the context of chemistry classes, educators have employed 3DP technology to create tactile models of atomic structures, enhancing the traditional learning methods [16]. Research has indicated a positive correlation between the incorporation of 3DP in teaching chemistry and improved student comprehension. This hands-on approach allows for a tangible understanding of otherwise abstract concepts, reinforcing pedagogical strategies [17]. In physics, a notable example comes from Japan where high school students gained insights into audio frequency through an inventive project involving the 3D printing of police whistles [18]. This approach not only facilitated a deeper understanding of the subject matter but also linked theoretical knowledge to practical applications.
One case involved introducing students to the operational mechanics of 3D printers, which served as an educational tool for illustrating core principles in engineering. Other innovative teaching strategies have combined computational thinking exercises using both Minecraft and 3DP, as well as design thinking

exercises via a 3D printed city planning game named Kidville [19,20]. These exercises extend the application of 3DP to cultivate various skills, such as logical reasoning, spatial awareness, and planning. Additionally, this technology has been used as a tool for fostering creativity, technical drawing capabilities, and product design skills, with specific applications evident in projects that tasked students with the creation of prosthetic hands. A transmedia book project within a project-based learning environment demonstrated an increase in mathematical achievement when 3DP was integrated into the curriculum [21]. Students fabricated three-dimensional shapes, which subsequently improved their understanding of geometric principles. Furthermore, educators have sought to enhance STEM education by employing 3DP in unique fields such as paleontology. In one specific instance, K-12 students learned about the prehistoric shark, Carcharocles megalodon, through the use of 3D printed reproductions of its teeth, serving as both an educational and engaging experience [22]. Beyond the classroom, 3DP has been increasingly adopted for various STEM outreach activities, thereby extending its educational impact to broader audiences [23], [24].

Learning engagement is an important factor that has a strong influence on the quality and success of any educational setting [25], [26]. Educators, administrators, and policy makers often focus on engagement as a key element to improve academic performance and create a positive learning experience. The term "student engagement" may seem unclear because it's a complex idea, but many researchers agree that it involves students making an effort to be actively involved in the learning process [27], [28]. Despite its complexity, there is a general agreement in educational research that engaged students are those who show a willingness to learn, actively participate in educational activities, and engage in classroom interactions.

To understand learning engagement better, it can be looked at through various indicators that are behavioral, cognitive, social, and emotional in nature [29], [30]. For example, behavioral signs of engagement might include attending class regularly, participating in classroom discussions, and completing assignments on time. On the cognitive side, indicators could include putting mental effort into understanding challenging topics and applying problem-solving skills. Social signs of engagement might include working well in group projects and having positive interactions with classmates and teachers. Emotional indicators could be seen as showing interest and excitement in learning or being able to keep going even when faced with academic difficulties [31].

Behavioral engagement refers to the observable actions taken by students that demonstrate their involvement in the educational process. This can include a range of activities such as attending classes regularly, actively participating in classroom discussions, and completing assignments in a timely manner. Behavioral engagement serves as a readily visible indicator for educators to gauge a student's willingness to comply with the structural requirements of an educational setting, such as following rules, meeting deadlines, and engaging in classroom activities [32].

Cognitive engagement, on the other hand, involves the mental effort and thought processes that students invest in their learning [33]. This type of engagement is characterized by a student's willingness to understand complex topics, apply problem-solving skills, and think critically about the information presented to them [34, 35]. Cognitive engagement is less easily observed than behavioral engagement, but it can be inferred from a student's ability to grasp complicated subjects, ask insightful questions, and apply knowledge in practical situations [36, 37]. Emotional engagement relates to the feelings and attitudes that students have towards their learning environment and educational tasks. It includes factors such as interest, enthusiasm, and motivation, which directly influence a student's willingness to engage with educational material. Emotional engagement is often considered a precursor to both behavioral and cognitive engagement, as positive emotions can catalyze actions and cognitive investment in learning tasks [38, 39].

Tech engagement, or technological engagement, refers to the manner in which students interact with educational technology platforms or digital tools as part of their learning experience. This can include the use of educational software for course management, participation in online forums, utilization of digital resources for research, and interaction with multimedia presentations [40, 41]. Tech engagement is increasingly relevant in contemporary educational contexts where digital literacy is considered a vital skill. It provides a medium for extending both behavioral and cognitive engagement into the digital sphere, allowing for a more varied and potentially enriching educational experience.

Methods

This study employed a set of ten specific items to measure the integration of 3D printing in STEM education, focusing on tangible visualization methods. The items were designed to assess various facets of hands-on learning and interactive education. Item TV1 investigated the frequency with which 3D printed models of complex molecules or structures were used. TV2 measured the extent to which interactive physical simulations were utilized to clarify physics concepts. TV3 focused on the use of augmented reality overlays on physical objects as a learning aid. TV4 evaluated the utilization of tactile graphs and charts to make educational material accessible for visually impaired students. TV5 looked at how often physical mock-ups were employed for engineering or architectural design projects. TV6 evaluated the use of hands-on kits for demonstrating electronic circuits. TV7 assessed the frequency of studying with scale models to understand ecological systems or environments. TV8 measured engagement with kinetic sculptures to explain principles of motion and energy. TV9 evaluated the use of tangible interfaces for manipulating digital data, and TV10 assessed the usage of physical representations, such as geometric shapes or fractals, for elucidating mathematical concepts. Participants were asked to rate their engagement with each item on a five-point scale ranging from "Never" to "Always."

Table 1. Items for Tangible Visualization with 3D Printing (TV3DP)

Item No.	Item
TV1	Use 3D printed models of complex molecules or structures.

TV2	Engage interactive physical simulations for physics concepts.
TV3	Use augmented reality overlays on physical objects for learning.
TV4	Utilization of tactile graphs and charts for visually impaired accessibility.
TV5	Working with physical mock-ups of engineering or architectural designs.
TV6	Use of hands-on kits for demonstrating electronic circuits.
TV7	Study with scale models of ecological systems or environments.
TV8	Engagement with kinetic sculptures for motion and energy principles.
TV9	Use of tangible interfaces for manipulating digital data.
TV10	Use physical representations like geometric shapes or fractals for math concepts.

Table 2 outlines a comprehensive framework for assessing various dimensions of student engagement in STEM (Science, Technology, Engineering, Mathematics) fields. For the category of Behavioral engagement, items range from attendance and preparedness to more nuanced activities like peer collaboration and active class participation. For instance, B1 focuses on how frequently a student misses class, while B2 assesses the level of preparation before lab sessions through pre-lab readings. B3 through B8 go deeper into proactive behaviors like collaborating on challenging projects (B3), dedicating weekends to research or study (B4), and actively participating in study groups or class discussions (B7, B8). These indicators help educators evaluate the level of physical and practical involvement of students in the academic environment.

The Cognitive engagement category aims to quantify the mental investment students make in their academic pursuits. Items in this category, denoted as I1 through I8, assess various aspects from embracing complex problems in courses (I1) to the optimistic view of contributing to technological advancements (I6). Items like I2 and I3 delve into the strategic approach to coursework and finding subjects like math and physics intellectually stimulating, respectively. On the other hand, I5 and I7 evaluate a student's belief in the larger impact of their education, such as leading to innovative breakthroughs in STEM or the ability to integrate concepts from different disciplines when problem-solving. These indicators are useful for understanding the cognitive depth and breadth that students bring to their academic endeavors.

The third category focuses on Emotional engagement, denoted by items E1 through E8. These items aim to capture the emotional and affective components that contribute to a student's overall academic experience. Factors such as feeling a sense of belonging in the academic community (E1), being passionate about experiments and projects in class (E2), and valuing diverse perspectives in discussions (E8) are considered here. This category helps in assessing how emotional factors like a sense of community, pride, and passion influence a student's engagement with their studies. Finally, the Tech Engagement in Learning Management Systems (LMS) category measures students' interaction with digital platforms for learning. This category covers aspects such as engagement in online workshops (L1), valuing online resources like research papers (L2), and the frequency of using LMS platforms for research and assignments (L7).

Table 2. Items for different dimensions of the engagement of STEM students.

Category	Notation	Description
Behavioral engagement		
	B1	Rarely misses class
	B2	Always prepared with pre-lab readings before attending labs.
	B3	Collaborate with peers on challenging projects or experiments.
	B4	Dedicate weekends to research or study.
	B5	Seek feedback from professors about my project progress.
	B6	Dedicate significant time to independent research.
	B7	Engage in study groups or workshops.
	B8	Actively participate in class discussions or seminars.
Cognitive engagement		
	I1	Embrace the complex problems presented in courses.
	I2	Strategically approach coursework and projects.
	I3	Find subjects like mathematics and physics to be intellectually stimulating.
	I4	Exceed expectations in projects or assignments.
	I5	Believe my education will lead to innovative breakthroughs in the STEM field.
	I6	Optimistic about contributing to advancements in technology.
	I7	Integrate concepts from various disciplines when problem-solving.
	I8	Relish the process of discovery and innovation.
Emotional engagement		
	E1	Feel a sense of belonging in the student community.
	E2	Passionate about the experiments and projects in classes.
	E3	Take pride in being a university student.
	E4	Discuss career paths with mentors or advisors.
	E5	Engage in deep technical discussions with peers from different STEM backgrounds.
	E6	Excited about breakthroughs and discoveries in my field.
	E7	Feel connected to the community on campus.
	E8	Value diverse perspectives in class discussions.
Tech Engagement in Learning Management Systems (LMS)		
	L1	Engage in online workshops or tutorials.

	L2	Value online resources like research papers and software tools.
	L3	Professors mandate the use of tech for coursework.
	L4	Collaborate online for group projects or research.
	L5	Online forums provide new insights and methodologies.
	L6	Access online databases or libraries specific to courses.
	L7	Use LMS platforms for research and assignments.

Elastic Net Regression

Elastic Net Regression is a regularized linear regression technique that blends the strengths of both Lasso (Least Absolute Shrinkage and Selection Operator) and Ridge regression models [42]. This hybrid approach is particularly useful when the number of predictors (features) is greater than the number of observations or when features are highly correlated. The objective function in Elastic Net aims to minimize the sum of squared residuals, similar to ordinary least squares (OLS), but it also includes two additional terms for regularization [43]. Specifically, the objective function is:

$$J(\theta) = \frac{1}{2n}\sum_{i=1}^{n}(y_i - \theta^T x_i)^2 + \alpha\rho\sum_{j=1}^{m}\left|\theta_j\right| + \frac{\alpha(1-\rho)}{2}\sum_{j=1}^{m}\theta_j^{\,2}$$

where α is the regularization parameter and ρ is the mixing parameter that governs the balance between Lasso and Ridge regularization techniques.

The regularization term in the objective function is composed of two components: a L1 penalty term ($|\theta j|$) and a L2 penalty term θj squared. The L1 penalty encourages sparsity by potentially reducing some coefficients to zero, thereby effectively excluding certain predictors from the model. This feature is especially useful in high-dimensional datasets where feature selection is important. The L2 penalty, on the other hand, tends to produce non-zero coefficients that are close to zero but not exactly zero, which is beneficial in cases of multicollinearity among predictors. The mixing parameter ρ allows for a compromise between the Lasso and Ridge regularization techniques. When ρ=1, Elastic Net reduces to Lasso regression, and when ρ=0, it becomes Ridge regression. Therefore, Elastic Net offers greater flexibility in model tuning [44,45].

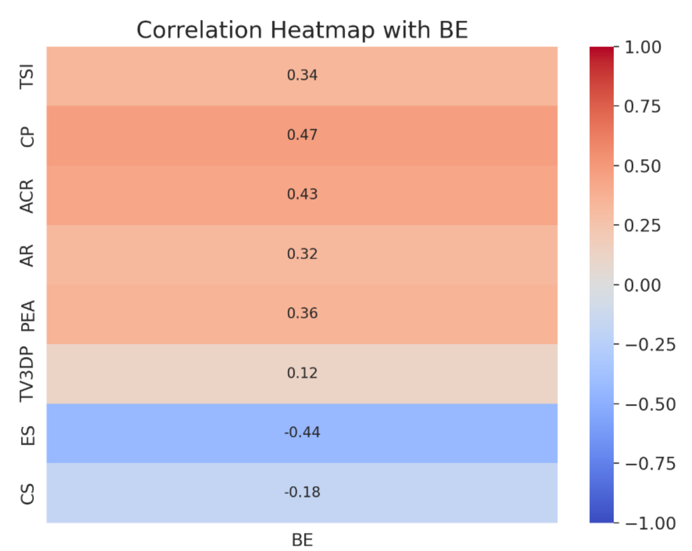
Parameter estimation in Elastic Net Regression is typically achieved through optimization algorithms such as gradient descent or coordinate descent. Because the objective function is convex, global minimization can be assured. The choice of regularization parameter α and the mixing parameter ρ is often determined using techniques like cross-validation. Specifically, a grid search across a range of α and ρ values can be performed to identify the combination that results in the lowest cross-validation error. This makes Elastic Net adaptable to various types of data and modeling challenges.

Results

Behavioral Engagement (BE)

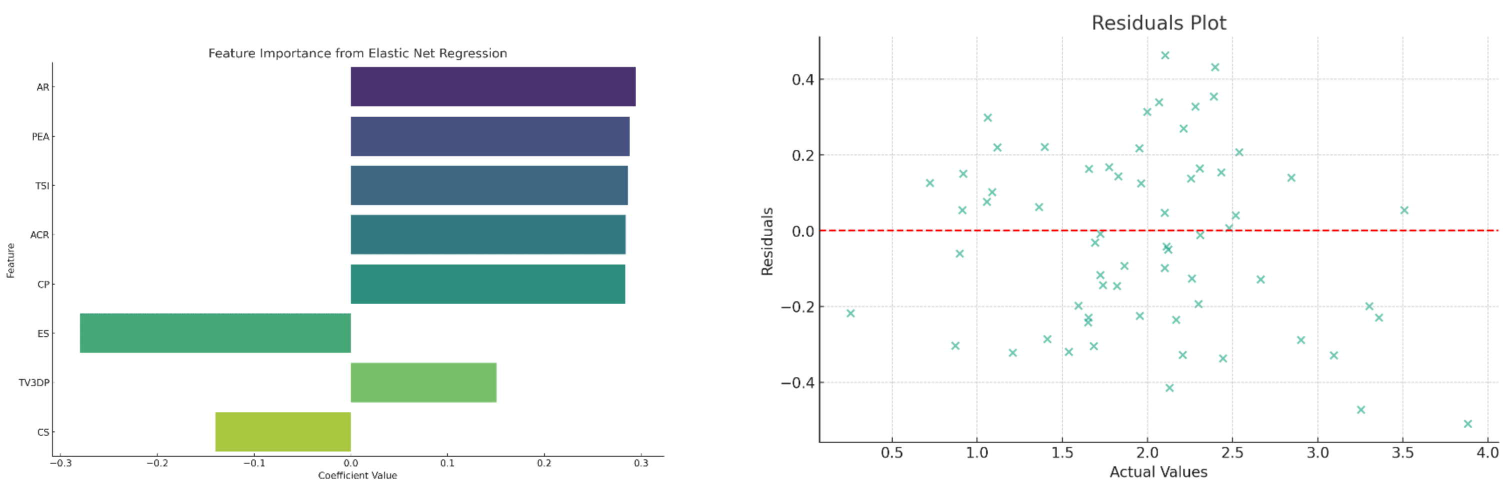
The results in Table 3 indicate the elastic net regression coefficients and metrics for various features affecting behavioral engagement (BE) in educational settings. One of the standout points is that the Teacher-Student Interaction (TSI), with a coefficient value of approximately 0.2863, has a positive effect on behavioral engagement. This is consistent with the understanding that personalized feedback, support, and motivation from teachers are influential in promoting student engagement. Other variables that also positively affect behavioral engagement include Class Participation (CP) with a coefficient of approximately 0.2837, Assignment Completion Rate (ACR) with a coefficient of about 0.2840, Attendance Rate (AR) with a coefficient of roughly 0.2945, and Participation in Extracurricular Activities (PEA) with a coefficient of around 0.2883. These variables have coefficients that are closely clustered, suggesting that they have a nearly comparable influence on the dependent variable, BE.

Figure 1. Correlation heatmap [BE model]



Tangible Visualization with 3D Printing (TV3DP) shows a coefficient of approximately 0.1505, indicating a neutral to positive effect on behavioral engagement. This means that 3D printing can potentially boost engagement but its impact may not be as universally applicable or potent as some of the other positive variables. Conversely, External Stressors (ES) and Class Size (CS) have negative coefficients of about -0.2800 and -0.1402, respectively. The negative coefficient for ES underscores the fact that personal, family, or health issues can significantly hamper student engagement by diverting attention and energy away from academic tasks. Similarly, larger class sizes, denoted by the CS variable, can limit individualized attention and interaction, leading to decreased engagement.

Figure 2. Coefficients and residual plots from Elastic Net [BE model]



The model's performance metrics provide additional context for the interpretability of these results. The Mean Squared Error (MSE) is approximately 0.0096, while the Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) are roughly 0.0982 and 0.0749, respectively. These metrics are relatively low, indicating that the model fits the data well and that the errors between the predicted and observed values of the dependent variable, Behavioral Engagement, are minimal. Thus, the coefficients should be considered highly informative for understanding the factors that influence student engagement in educational settings.

Table 3. Coefficients and Metrics from Elastic Net Regression [BE model]

Feature/Metric	Value
TSI	≈ 0.2863
CP	≈0.2837
ACR	≈ 0.2840
AR	≈ 0.2945
PEA	≈ 0.2883
TV3DP	≈ 0.1505
ES	≈ -0.2800
CS	≈ -0.1402
MSE	≈ 0.0096
RMSE	≈ 0.0982
MAE	≈ 0.0749

Table 4. dependent variable: Behavioral Engagement (BE)

Independent Variable	Effect on Behavioral Engagement (BE)	
Teacher-Student Interaction (TSI)	Positive	Direct interactions with teachers can significantly influence a student's engagement, providing personalized feedback, support, and motivation.
Class Participation (CP)	Positive	Active participation in class discussions or group activities often indicates and promotes higher behavioral engagement.
Assignment Completion Rate (ACR)	Positive	Completing assignments on time is both an indicator of engagement and a factor that can boost confidence and involvement in class.
Attendance Rate (AR)	Positive	Regular attendance is foundational for engagement; missing classes can lead to disconnection from the learning environment.
Participation in Extracurricular Activities (EA or PEA)	Positive	Involvement in extracurriculars can enhance a student's connection to the school community, potentially increasing classroom engagement.
Tangible Visualization with 3D Printing (TV3DP)	Neutral to Positive	3D printing can enhance understanding and interest in certain subjects, potentially boosting engagement, but its applicability varies.
External Stressors (ES)	Negative	Personal, family, or health issues can divert attention and energy away from academic tasks, reducing engagement.
Class Size (CS)	Neutral to Negative	Larger class sizes might reduce opportunities for individualized attention and interaction, potentially diminishing engagement.

Cognitive Engagement (CE):

The coefficients and metrics presented in Table 5 indicate how various factors influence Cognitive Engagement (CE) in students, as determined by an Elastic Net Regression model. The Teacher-Student Interaction (TSI) variable has a coefficient value of approximately 0.2262, affirming that personalized feedback, guidance, and mentoring have a positive influence on students' deeper cognitive processing of academic material. Other variables positively affecting cognitive engagement include Assignment Completion Rate (ACR) with a coefficient of about 0.2121, Tangible Visualization with 3D Printing (TV3DP) with a coefficient of roughly 0.2309, Class Participation (CP) with a coefficient of around 0.2021, and Attendance Rate (AR) with a coefficient of approximately 0.2000. The TV3DP variable, in particular, stands out as having a notable positive effect on cognitive engagement by making abstract concepts more tangible and hence promoting deeper cognitive understanding.

In contrast to the positive variables, External Stressors (ES) have a negative coefficient of about -0.2291, illustrating that stressors can act as significant distractions that reduce a student's cognitive effort in academic tasks. Class Size (CS), with a negative coefficient of approximately -0.0809, also indicates a neutral to negative effect on cognitive engagement, possibly because larger class sizes may limit opportunities for in-depth discussions or personalized feedback. Notably, Participation in Extracurricular Activities (PEA) has a lower positive coefficient value of around 0.0906, suggesting that while extracurricular activities can enhance cognitive skills, their direct link to academic cognitive engagement might be less pronounced compared to their influence on behavioral engagement.

Regarding the model's performance, the Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE) are approximately 0.04546, 0.21312, and 0.17609, respectively. These metrics are higher compared to those in the behavioral engagement model, indicating a somewhat less accurate fit between the predicted and actual values of cognitive engagement. This implies that while the coefficients are informative for understanding what influences cognitive engagement, they should perhaps be considered in the context of other contributing variables or conditions that might not be captured by this particular model.

Figure 3. Correlation heatmap [CE model]

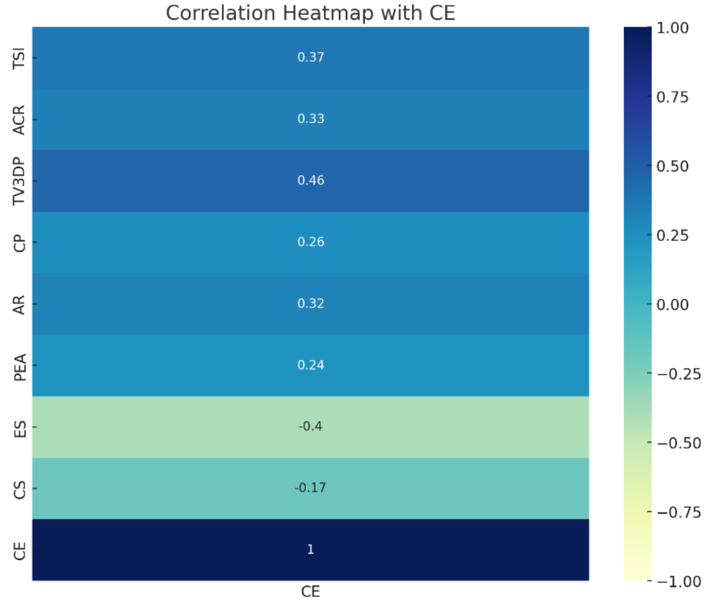


Figure 4. Coefficients and residual plots from Elastic Net

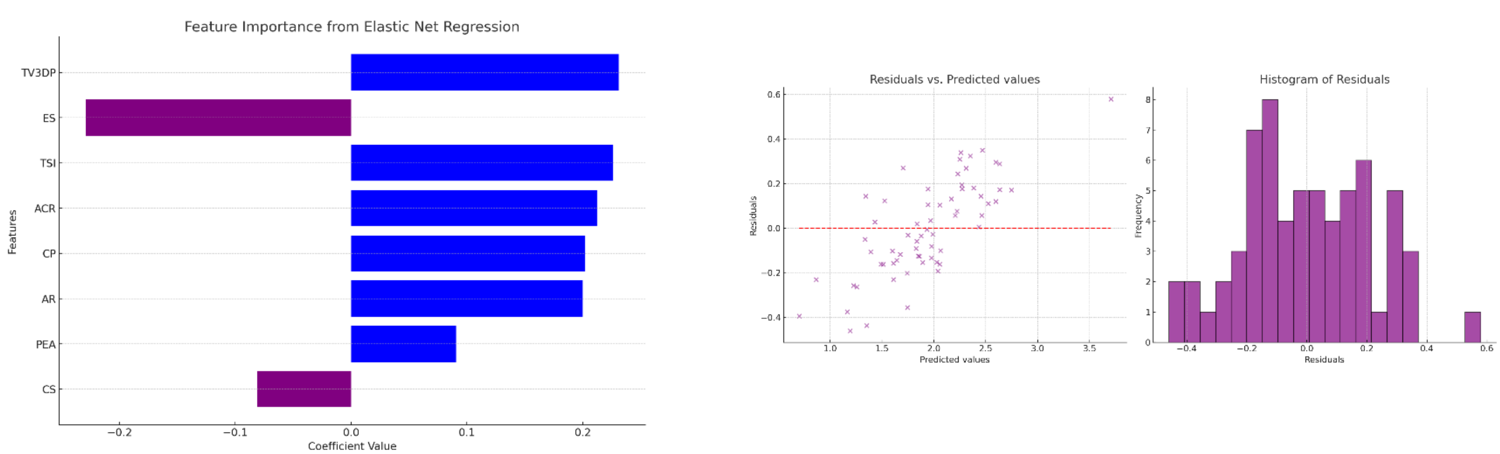


Table 5. Coefficients and Metrics from Elastic Net Regression [CE model]

Metric/Coefficient	Value
TSI	≈ 0.2262
ACR	≈ 0.2121
TV3DP	≈ 0.2309
CP	≈ 0.2021
AR	≈ 0.2000
PEA	≈ 0.0906
ES	≈ -0.2291
CS	≈ -0.0809
MSE	≈ 0.04546
RMSE	≈ 0.21312
MAE	≈ 0.17609

Table 6. dependent variable: Cognitive Engagement (CE):

Independent Variable	Effect on Cognitive Engagement (CE)	
Teacher-Student Interaction (TSI)	Positive	Personalized feedback, guidance, and mentoring can deepen a student's understanding and stimulate deeper cognitive processing of the material.
Assignment Completion Rate (ACR)	Positive	Regularly completing assignments indicates consistent cognitive effort and application of learning strategies.
Tangible Visualization with 3D Printing (TV3DP)	Positive	3D visualizations can enhance conceptual understanding, making abstract concepts more tangible and promoting deeper cognitive engagement.
Class Participation (CP)	Positive	Actively contributing to discussions requires processing of information and can indicate a deeper cognitive connection to the material.
Attendance Rate (AR)	Positive	Regular attendance ensures consistent exposure to learning material, which is foundational for cognitive engagement.
Participation in Extracurricular	Neutral to Positive	Extracurriculars can enhance cognitive skills like critical thinking and problem-solving, but the direct link to academic cognitive engagement might be less pronounced than behavioral engagement.

Activities (EA or PEA)		
External Stressors (ES)	Negative	Stressors can distract from academic focus, potentially reducing the cognitive effort a student invests in their studies.
Class Size (CS)	Neutral to Negative	Larger classes might offer fewer opportunities for in-depth discussions or personalized feedback, which could impact the depth of cognitive engagement.

Emotional Engagement (EE)

Table 7 presents the Elastic Net Regression coefficients and metrics for different features affecting Emotional Engagement (EE) in educational contexts. Teacher-Student Interaction (TSI), with a coefficient value of approximately 0.2815, appears to significantly contribute to positive emotional responses in students, affirming the idea that personal connections with teachers can foster a sense of belonging and validation. Class Participation (CP) also notably stands out with a coefficient of around 0.2940, suggesting that active class engagement can greatly contribute to a student's emotional well-being by fostering a sense of competence and belonging. Participation in Extracurricular Activities (PEA) follows closely, with a coefficient of about 0.2676, emphasizing that involvement in activities outside the classroom can improve emotional connections to the school environment.

External Stressors (ES) show a negative coefficient of approximately -0.3025, indicating that personal or family issues can significantly dampen emotional engagement in academic settings. Class Size (CS), with a negative coefficient of about -0.1435, also suggests a neutral to negative influence, as larger class sizes could potentially lead to feelings of anonymity or disconnection, thereby reducing emotional engagement. Meanwhile, Assignment Completion Rate (ACR) exhibits a coefficient close to zero (-0.0015), signaling that this variable might not have a strong correlation with emotional engagement, possibly because completing assignments is a form of commitment that may not necessarily reflect emotional sentiments toward the learning material.

The coefficients for Attendance Rate (AR) and Tangible Visualization with 3D Printing (TV3DP) are approximately 0.1402 and 0.1337, respectively. These values suggest a neutral to positive impact on emotional engagement. For instance, regular attendance may indicate positive feelings toward the school environment but may not strongly correlate with emotional engagement. Similarly, the use of 3D printing for tangible visualizations may make learning more enjoyable and interesting, although its direct impact on emotional engagement may not be as significant as other variables.

Figure 5. Correlation heatmap [EE model]

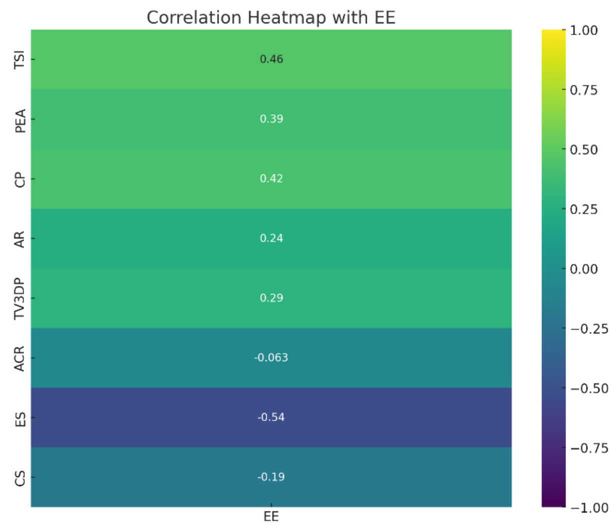


Figure 6. Coefficients and residual plots from Elastic Net [EE model]

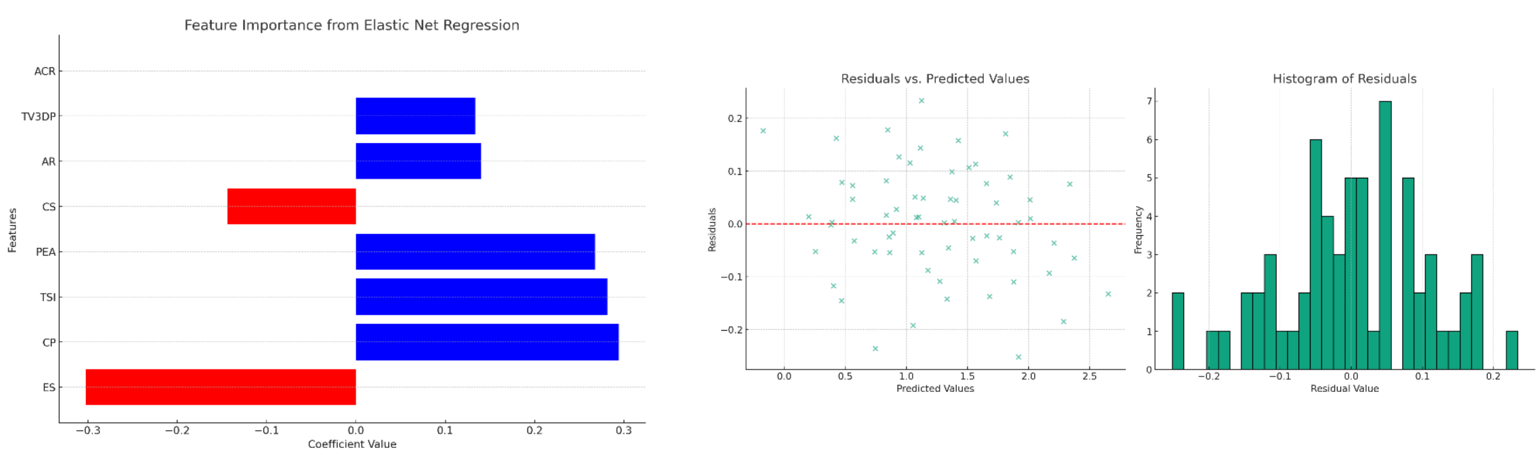


Table 7. Coefficients and Metrics from Elastic Net Regression [EE model]

Feature/metrics	value
TSI	≈ 0.2815
PEA	≈ 0.2676
CP	≈ 0.2940
AR	≈ 0.1402
TV3DP	≈ 0.1337
ACR	≈ -0.0015
ES	≈ -0.3025
CS	≈ -0.1435

Table 8. dependent variable: Emotional Engagement (CE)

Independent Variable	Effect on Emotional Engagement (EE)	
Teacher-Student Interaction (TSI)	Positive	Personal connections with teachers can foster a sense of belonging and validation, enhancing positive emotional responses to learning.
Participation in Extracurricular Activities (EA or PEA)	Positive	Involvement in clubs or activities can boost school connectedness and positive feelings towards the school environment.
Class Participation (CP)	Positive	Actively engaging in class discussions can foster a sense of competence and belonging, enhancing emotional engagement.
Attendance Rate (AR)	Neutral to Positive	Regular attendance might indicate a student's positive feelings towards school, but it's also a basic requirement that might not directly correlate with emotional engagement.
Tangible Visualization with 3D Printing (TV3DP)	Neutral to Positive	Engaging with tangible visualizations can make learning more enjoyable and interesting, potentially boosting emotional engagement.
Assignment Completion Rate (ACR)	Neutral	While completing assignments indicates commitment, it might not directly reflect emotional feelings towards the learning material.
External Stressors (ES)	Negative	Personal or family issues can lead to negative emotions, which can hinder positive emotional engagement in school.
Class Size (CS)	Neutral to Negative	Larger classes might lead to feelings of anonymity or disconnection, potentially reducing emotional engagement.

Tech Engagement (TE)

In the Tech Engagement (TE) model, Table 9 provides Elastic Net Regression coefficients and metrics for various independent variables. The Assignment Completion Rate (ACR) shows a significant positive coefficient of approximately 0.2397, suggesting that if assignments are submitted through the LMS, a higher completion rate is indicative of more frequent and effective usage of the platform. Another positive indicator is Teacher-Student Interaction (TSI), with a coefficient value of about 0.2357. This metric implies that guidance and personalized feedback provided through the LMS have a strong influence on encouraging students to engage more effectively and frequently with the system. Tangible Visualization with 3D Printing (TV3DP) also appears to have a modest positive effect, with a coefficient of approximately 0.0953, though the impact is less compared to other positive variables like ACR and TSI.

Conversely, External Stressors (ES) manifest as a significant negative variable, with a coefficient of around -0.2561, signaling that personal or family issues could substantially reduce a student's motivation and capacity to engage with technology, thus leading to decreased usage of the LMS. The negative impact of Class Size (CS) is also notable with a coefficient of -0.116, indicating that in larger classes, the opportunity for individualized tech support or guidance might be compromised, potentially resulting in less effective engagement with the LMS. The variables for Class Participation (CP) and Attendance Rate (AR) show coefficients of approximately 0.0862 and 0.0003, respectively, suggesting that these aspects have only minimal to neutral effects on tech engagement within an LMS.

The model's performance metrics include a Mean Squared Error (MSE) of 0.0291, a Root Mean Squared Error (RMSE) of 0.1705, and a Mean Absolute Error (MAE) of 0.13. These values offer a reasonable level of confidence in the model's ability to predict Tech Engagement, although it is essential to consider that the coefficients are subject to the limitations of the data used in the analysis. The metrics indicate a decent fit of the model to the actual data points but also suggest that there may be other variables not captured in this analysis that could influence tech engagement.

Table 9. Coefficients and Metrics from Elastic Net Regression [TE model]

Coefficient/ Metric	Value
TSI	≈ 0.2357
ACR	≈ 0.2397
CP	≈ 0.0862
AR	≈ 0.0003
PEA	≈ 0.0007
TV3DP	≈ 0.0953
ES	≈ -0.2561
CS	-0.116
MSE	0.0291
RMSE	0.1705
MAE	0.13

Figure 7. Correlation heatmap

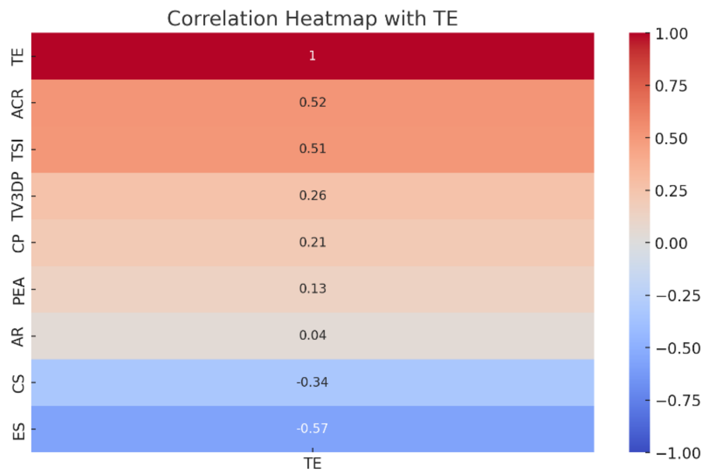


Figure 8. Coefficients and residual plots from Elastic Net

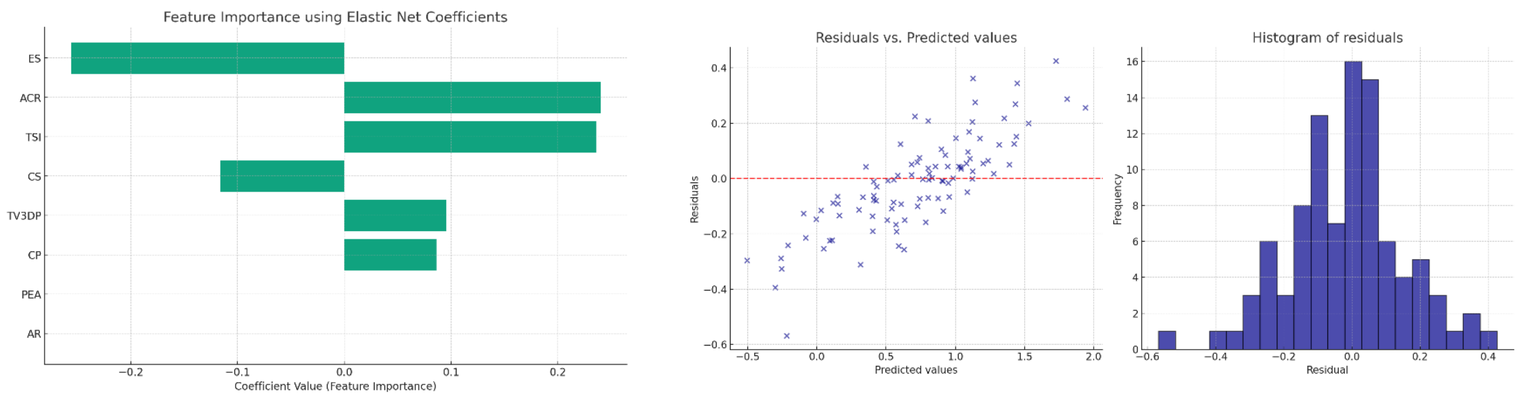


Table 10. dependent variable: Tech Engagement (TE)

Independent Variable	Effect on Tech Engagement in LMS (TE)	
Teacher-Student Interaction (TSI)	Positive	Guidance and feedback through the LMS can encourage students to utilize its features more effectively and frequently.
Assignment Completion Rate (ACR)	Positive	If assignments are submitted through the LMS, a higher completion rate indicates more frequent and effective use of the platform.

Class Participation (CP)	Neutral to Positive	If class discussions or group activities are facilitated through the LMS, active participation can indicate higher tech engagement.
Attendance Rate (AR)	Neutral	While regular attendance might correlate with LMS usage, it doesn't necessarily indicate depth or quality of tech engagement.
Participation in Extracurricular Activities (EA or PEA)	Neutral	While extracurriculars can indicate overall school engagement, they might not have a direct correlation with LMS tech engagement unless the activities are coordinated through the LMS.
External Stressors (ES)	Negative	Personal or family issues can reduce a student's capacity or motivation to engage with technology, potentially leading to decreased LMS usage.
Class Size (CS)	Neutral to Negative	In larger classes, individualized tech support or guidance might be limited, potentially hindering effective LMS engagement.
Tangible Visualization with 3D Printing (TV3DP)	Neutral to Positive	While Tangible Visualization can complement technology, its direct impact on how students engage with LMS might be minimal. However, if the LMS integrates or supports the use of Tangible Visualization tools (e.g., through AR or VR), there might be a slight increase in tech engagement.

Conclusion

The purpose of the study was to investigate the influence of multiple independent variables, including the adoption of 3D Printing, on four specific kinds of engagement—Behavioral, Cognitive, Emotional, and Tech—within a group of 318 STEM students. Elastic Net Regression is employed as the analytical method for this empirical examination.

The study examined Behavioral Engagement (BE), Cognitive Engagement (CE), Emotional Engagement (EE), and Tech Engagement (TE) through Learning Management Systems (LMS). Across these different types of engagement, several common variables such as Teacher-Student Interaction (TSI), Assignment Completion Rate (ACR), and Class Participation (CP) consistently emerged as positive influencers. TSI often played a pivotal role, impacting not just academic performance but also emotional and technological engagement, highlighting the central role teachers play in the educational experience across various facets. ACR also demonstrated its importance, especially in tech engagement where the completion rate indicates effective usage of digital platforms. These variables seem to universally promote engagement, albeit to varying extents depending on the specific type of engagement under scrutiny.

Conversely, some variables consistently acted as hindrances to engagement. Notably, External Stressors (ES) repeatedly showed a significant negative impact across different types of engagement. The data suggests that personal or family issues can drastically reduce a student's ability and motivation to engage in both traditional and digital learning environments. Another common detrimental factor was Class Size (CS), which often indicated a neutral to negative effect, primarily due to reduced opportunities for individualized attention in larger classes. Both ES and CS are critical areas that educators and administrators should address to enhance overall engagement in educational settings.

Other variables had a mixed or nuanced impact depending on the type of engagement being examined. For instance, Participation in Extracurricular Activities (PEA) generally had a positive impact on behavioral and emotional engagement but showed limited direct correlation with cognitive and tech engagement. Attendance Rate (AR) was another variable that exhibited varying levels of influence, being more central to behavioral engagement than to emotional or technological forms. Tangible Visualization with 3D Printing (TV3DP) had a modest positive effect on engagement, although its impact was often subject-specific and depended on how well it was integrated into the broader learning environment.

The variable of Tangible Visualization with 3D Printing (TV3DP) presented an intriguing yet nuanced influence across different types of student engagement. In Behavioral and Cognitive Engagement models, TV3DP was seen as a neutral-to-positive factor. The data suggests that 3D visualizations can enhance conceptual understanding and make abstract concepts more tangible. This tangibility may lead to deeper cognitive engagement, as students find it easier to grasp complex ideas when they can physically interact with them. Moreover, 3D printing technology can potentially boost behavioral engagement by making the learning environment more interactive and engaging. However, its efficacy can be subject-specific and may vary depending on the applicability of 3D printing to the course material, suggesting that educators must carefully consider when and how to integrate this technology into their teaching practices.

In the Emotional Engagement model, TV3DP also demonstrated a neutral-to-positive impact. The data indicates that using tangible visualizations can make learning more enjoyable and interesting. When students find the educational process to be stimulating and engaging, they are more likely to develop positive emotional responses to it. However, it should be noted that the emotional impact of TV3DP could be less straightforward and may vary between individuals, depending on their personal interests and how they respond to interactive educational methods. Given that emotional engagement plays a crucial role in the overall learning experience, educators may need to adopt a more personalized approach to leveraging 3D printing technology in order to maximize its benefits.

Regarding Tech Engagement in Learning Management Systems (LMS), the role of TV3DP was again characterized as neutral-to-positive. While 3D printing on its own might not directly impact how students interact with digital learning platforms, the variable takes on significance when the LMS integrates or supports the use of 3D printing technology. If implemented effectively, TV3DP could serve as an additional feature within an LMS that could marginally increase tech engagement. This raises interesting implications for curriculum designers and educational technologists who are looking at innovative ways to enhance student engagement through LMS.

References

1. Gebhardt, A., Kessler, J. & Thurn, L. 3D printing: understanding additive manufacturing. (2018).
2. Vogel, B. J. Intellectual property and additive manufacturing/3D printing: strategies and challenges of applying traditional IP laws to a transformative technology. *Minn. JL Sci. & Tech.* (2016).
3. Talagani, M. R. *et al.* Numerical simulation of big area additive manufacturing (3D printing) of a full size car. *SAMPE J.* **51**, 27–36 (2015).
4. Sauerwein, M. & Doubrovski, E. L. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. *Materials Today Communications* **15**, 214–217 (2018).
5. Baumann, F. W. & Roller, D. Additive Manufacturing, Cloud-Based 3D Printing and Associated Services—Overview. *J. Mater. Process. Manuf. Sci.* **1**, 15 (2017).
6. Wimpenny, D. I., Pandey, P. M. & Kumar, L. J. *Advances in 3D Printing & Additive Manufacturing Technologies*. (Springer Nature Singapore, 2017).
7. Altaf, K. *et al.* Application of additive manufacturing/3D printing technologies and investment casting for prototype development of polycrystalline diamond compact (PDC) drill bit body. *ARPN Journal of Engineering and Applied Sciences* **11**, 6514–6518 (2016).
8. Colletti, R. C. A Study of Positions Available in Additive Manufacturing/3D Printing and the Education and Skill Requirements for These Positions. (search.proquest.com, 2016).
9. Karandikar, P., Watkins, M., McCormick, A., Givens, B. & Aghajanian, M. Additive manufacturing (3D printing) of ceramics: Microstructure, properties, and product examples. in *Proceedings of the 41st*

International Conference on Advanced Ceramics and Composites 175–187 (John Wiley & Sons, Inc., 2018).

10. Jiang, R., Kleer, R. & Piller, F. T. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technol. Forecast. Soc. Change* **117**, 84–97 (2017).
11. Lichtenberger, J. P. *et al.* Using 3D Printing (Additive Manufacturing) to Produce Low-Cost Simulation Models for Medical Training. *Mil. Med.* **183**, 73–77 (2018).
12. Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q. & Hui, D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B* **143**, 172–196 (2018).
13. Straub, J. Initial Work on the Characterization of Additive Manufacturing (3D Printing) Using Software Image Analysis. *Machines* **3**, 55–71 (2015).
14. Bhushan, B. & Caspers, M. An overview of additive manufacturing (3D printing) for microfabrication. *Microsyst. Technol.* **23**, 1117–1124 (2017).
15. Ben-Ner, A. & Siemsen, E. Decentralization and Localization of Production: The Organizational and Economic Consequences of Additive Manufacturing (3D Printing). *Calif. Manage. Rev.* **59**, 5–23 (2017).
16. Bull, G., Chiu, J., Berry, R., Lipson, H. & Xie, C. Advancing Children's Engineering Through Desktop Manufacturing. in *Handbook of Research on Educational Communications and Technology* (eds. Spector, J. M., Merrill, M. D., Elen, J. & Bishop, M. J.) 675–688 (Springer New York, 2014).

17. Bull, G., Haj-Hariri, H., Atkins, R. & Moran, P. An educational framework for digital manufacturing in schools. *and Additive Manufacturing* (2015).

18. Makino, M. *et al.* 3D printing of police whistles for STEM education. *Microsyst. Technol.* **24**, 745–748 (2018).

19. Mahil, S. Fostering STEM+ education: Improve design thinking skills. in *2016 IEEE Global Engineering Education Conference (EDUCON)* 125–129 (2016).

20. Chery, D., Mburu, S., Ward, J. & Fontecchio, A. Integration of the Arts and Technology in GK-12 Science Courses. in *2015 IEEE Frontiers in Education Conference (FIE)* 1–4 (2015).

21. Dumond, D. *et al.* Pay it forward: Getting 3D printers into schools. in *2014 IEEE Integrated STEM Education Conference* 1–5 (2014).

22. Grant, C. A., MacFadden, B. J., Antonenko, P. & Perez, V. J. 3-D FOSSILS FOR K–12 EDUCATION: A CASE EXAMPLE USING THE GIANT EXTINCT SHARKCARCHAROCLES MEGALODON. *The Paleontological Society Papers* **22**, 197–209 (2016).

23. Araniva, R. & Kveven, A. STEM student engagement and achievement in a place-based learning community centered on the local Snohomish River estuary system. in *Salish Sea Ecosystem Conference* (cedar.wwu.edu, 2018).

24. Pelaez, C. & Pelaez, J. Breaking Down the Door: A Nonprofit Model Creating Pathways for Non-Traditional STEM Student Engagement. in vol. 2015 ED21E-05 (ui.adsabs.harvard.edu, 2015).

25. English, L. D. & King, D. T. STEM learning through engineering design: fourth-grade students' investigations in aerospace. *Int. J. STEM Educ.* **2**, (2015).

26. Museus, S. D. & Liverman, D. High-performing institutions and their implications for studying underrepresented minority students in STEM. *New Dir. Inst. Res.* **2010**, 17–27 (2010).

27. Wilson, D. *et al.* Belonging and academic engagement among undergraduate STEM students: A multi-institutional study. *Res. High. Educ.* **56**, 750–776 (2015).

28. Gasiewski, J. A., Eagan, M. K., Garcia, G. A., Hurtado, S. & Chang, M. J. From Gatekeeping to Engagement: A Multicontextual, Mixed Method Study of Student Academic Engagement in Introductory STEM Courses. *Res. High. Educ.* **53**, 229–261 (2012).

29. Roberts, T. *et al.* Students' perceptions of STEM learning after participating in a summer informal learning experience. *Int J STEM Educ* **5**, 35 (2018).

30. McDonald, C. V. STEM education: A review of the contribution of the disciplines of Science, Technology, Engineering and Mathematics. *Sci. Educ. Int.* **27**, 530–569 (2016).

31. Tanner, K. D. Structure matters: twenty-one teaching strategies to promote student engagement and cultivate classroom equity. *CBE Life Sci. Educ.* **12**, 322–331 (2013).

32. Shin, J. E. L., Levy, S. R. & London, B. Effects of role model exposure on STEM and non-STEM student engagement. *J. Appl. Soc. Psychol.* **46**, 410–427 (2016).

33. Kokkelenberg, E. C. & Sinha, E. Who succeeds in STEM studies? An analysis of Binghamton University undergraduate students. *Econ. Educ. Rev.* **29**, 935–946 (2010).

34. Kim, C. *et al.* Robotics to promote elementary education pre-service teachers' STEM engagement, learning, and teaching. *Comput. Educ.* **91**, 14–31 (2015).

35. Graham, M. J., Frederick, J., Byars-Winston, A., Hunter, A.-B. & Handelsman, J. Science education. Increasing persistence of college students in STEM. *Science* **341**, 1455–1456 (2013).

36. Matthews, K. E., Andrews, V. & Adams, P. Social learning spaces and student engagement. *Higher Education Research & Development* **30**, 105–120 (2011).

37. Ainley, M. & Ainley, J. Student engagement with science in early adolescence: The contribution of enjoyment to students' continuing interest in learning about science. *Contemp. Educ. Psychol.* **36**, 4–12 (2011).

38. Kennedy, T. J. & Odell, M. R. L. Engaging students in STEM education. *Sci. Educ. Int.* **25**, 246–258 (2014).

39. Bybee, R. W. *The Case for STEM Education: Challenges and Opportunities*. (NSTA Press, 2013).

40. Henrie, C. R., Halverson, L. R. & Graham, C. R. Measuring student engagement in technology-mediated learning: A review. *Comput. Educ.* **90**, 36–53 (2015).

41. Marks, H. M. Student Engagement in Instructional Activity: Patterns in the Elementary, Middle, and High School Years. *Am. Educ. Res. J.* **37**, 153–184 (2000).

42. Zou, H. & Hastie, T. Regression shrinkage and selection via the elastic net, with applications to microarrays. *JR Stat Soc Ser B* (2003).

43. Zou, H. & Hastie, T. Regularization and Variable Selection Via the Elastic Net. *J. R. Stat. Soc. Series B Stat. Methodol.* **67**, 301–320 (2005).

44. Liu, J., Liang, G., Siegmund, K. D. & Lewinger, J. P. Data integration by multi-tuning parameter elastic net regression. *BMC Bioinformatics* **19**, 369 (2018).

45. Zhang, Z. *et al.* Discriminative Elastic-Net Regularized Linear Regression. *IEEE Trans. Image Process.* **26**, 1466–1481 (2017).