STEM Education
https://www.aimspress.com/journal/steme

STEM Education, 5(2): 171–186
DOI:10.3934/steme.2025009
Received: 09 September 2024
Revised: 04 December 2024
Accepted: 01 January 2025
Published: 17 February 2025

Research article

Hands-on STEM learning experiences using digital technologies

Gaia Fior, Carlo Fonda and Enrique Canessa*

SciFabLab, International Centre for Theoretical Physics (ICTP), 34151 Trieste, Italy

* **Correspondence:** Email: canessae@ictp.it.

Academic Editor: Feng-Kuang Chiang

Abstract: The facilitation of STEM education can be enhanced by the provision of opportunities for learners through the utilization of tangible and visual examples that lead to gain a better understanding of STEM topics. The objective of this work was to present an account of our experiences and activities with this novel approach carried out on schools in the Italian FVG region and also shown and tested on large, free public activities like Maker Faires and Science Picnics. The projects and experiences discussed—in which students develop a range of core competencies such as creativity, critical thinking, experimentation, prototyping, collaboration and problem-solving—include tangible complex 3D printed structures, large microcontroller board replicas and the visualization of wind dynamics and tiny invisible elementary particles, among others. These hands-on experiences demonstrate the benefits on the use of digital fabrication technologies implemented within a FabLab for STEM learning. We have identified and proposed a set of valid examples for possible engagements that are beyond today's standard education and may provide more authentic learning to nurture 21st-century skills.

Keywords: STEM education, school support, inclusion, fabrication laboratory

1. Introduction

The present approach to develop hands-on science, technology, engineering, and mathematics (STEM) learning experiences using digital technologies is motivated by the 2030 UN agenda for sustainable development, which provides a global framework for progress and sustainable development. In order to achieve these goals, it is essential to implement innovative strategies that will lead to improvements in STEM education and the creation of opportunities for more scholars. In particular, the Sustainable Development Goal 4 of the UN 2030 Agenda aims to *"ensure inclusive and equitable quality education and promote lifelong learning opportunities for all"* [1].

In the last decade, online education has transformed society to new levels in the way people teach and learn [2]. Additionally, a number of other significant digital innovations are currently in place which collectively aim to facilitate the achievement of the 2030 UN goals. Examples are the use of 3D printing for the production of Mathematics and Physics educational structures, the application of microcontrollers and tiny computers for sensor-based experiments [3]. These are becoming increasingly popular, which are helping to stimulate scholars' curiosity and encourage a more profound understanding of specific subjects. Thus, today, learning is facilitated under a personal context in which scholars engage in reflection, imagination, comprehension and comparison of solutions through the use of tangible examples. The implementation of digitally controlled technologies for tangible and visual STEM learning is enabling scholars to access the highest quality education.

The skills needed to make good on the UN's agenda need to be nurtured over many years, and to start working in (elementary, primary and secondary) schools is certainly one of the necessary steps. It is also necessary to identify and test a set of valid examples for possible engagements that are beyond today's standard education, which usually include videos and other multimedia forms, and provide an authentic learning to nurture 21st-century skills. Digital Fabrication Laboratories (FabLabs) can help in the process, since they are a global network of local labs, enabling invention by providing access to tools for rapid digital fabrication. In these places, the transformation of an idea into a tangible object is possible, making it a potential pedagogical tool in STEM education. The establishment of FabLabs in academia can play a relevant role as a resource for the creation of pedagogical objects and devices to support sustainable development within the educational context.

Implementing STEM learning in classrooms is a challenge, and therefore it is important to pay attention to problems in current STEM learning, and see how hands-on experiences or the use of digital technologies can solve such problems. Some important issues in current STEM education include, for example, finding the necessary financial funding to obtain resources for its implementation as well as how the load on the educators' work can be optimized. Both of these problems can benefit by the use of digital fabrication technologies implemented within a FabLab for STEM learning. There are a myriad of digital resources and tools that can be downloaded for free on the internet. Instructors should become a guide in this process and improve learning efficiency. However, teachers frequently lack digital expertise and receive little training in this context.

Engaging educational objects and materials to inspire students with demos and do-it-yourself (DIY) constructions to better grasp complex STEM concepts can be developed in collaboration with a local FabLab community with ongoing technical training and advice. Collaborations between schools and FabLab partners can lead to unique learning opportunities, such as developing the needed objects and examples. A visit to these open space facilities or the co-organization of informative workshops hosted at FabLabs open the path to solve some of the problems of implementation in current STEM learning. In the end, all these efforts will be rewarded giving scholars the possibility to develop essential 21st-century skills. Integrating STEM education into schools can then be a reality.

Teachers need to find available FabLabs and Makerspaces in their areas and be aware of the possibilities offered within these offices. Being updated with new technical progress, they help to open new opportunities and connections to integrate STEM subjects within the school curriculum. A better perception of STEM subjects by teachers and students through hands-on activities, applications and examples will help to gain interest in STEM subjects and can become suitable for all kinds of students—without any gender distinction and concrete opportunities for inclusion. By exposing students to visual and tangible STEM education, they gain extra valuable insights into problem-solving and teamwork. STEM lessons should cater to diverse student needs by visual and tangible education designed in FabLabs.

In this work, we describe some of our experiences applying a hands-on and visual approach to STEM education, developed in our Scientific Fabrication Laboratory (SciFabLab) which is equipped with the necessary facilities to build specific devices for that purpose. The specifications of these devices are openly shared online. We argue that placing learning literally in the hands of the younger generations is a more effective approach for all, especially when it does not pose any special technical requirements on the teachers' side.

Educational efforts toward a better understanding of science through the utilization of tangible and visual examples, as those illustrated and explained in our paper, are only being explored recently because of the new available digital technologies. The selection of projects and hands-on experiences discussed in our paper aims to demonstrate and promote the benefits of the use of digital fabrication technologies implemented within a FabLab for STEM learning. Ours outcomes are based on our own experiences for science dissemination and STEM education, which were not only carried out in some schools in Italy but also at large, free public events like Maker Faires and Science Picnics.

Furthermore, our objective is also to develop techniques and processes that will enable new generations of students to participate fully in the educational process, in a manner that can be inclusive to incorporate individuals with physical disabilities [4]. As discussed in this work, STEM activities can be adapted to accommodate specific needs with the objective of overcoming some students' physical limitations and impairments.

2. Previous works

Some 21 st-century skills are difficult to teach only by traditional methods, i.e., without the use of highly sophisticated information and communications technologies (ICT). However, further studies on the design, creation and implementation of new instruments in which the teaching-learning process can be more personalized is still needed, see a review in [5]. The use of ICT has been recurrent in the last decade, especially due to the massive diffusion of portable PCs, tablets and smartphones [2]. Nevertheless, alternative digital technologies available at FabLabs can be employed to assist in the development of innovative pedagogical approaches that are accessible to all students and that facilitate their understanding on the relevance of scientific concepts [3].

FabLabs facilitate the implementation of tangible and visual STEM learning, thereby opening up new possibilities. The following sections will present a selection of our projects and experiences, in which students develop a range of core competencies, including creativity, critical thinking, experimentation and collaboration, prototyping and problem-solving. A discussion to better understand the influence of Makerspaces and FabLabs on today's innovation processes can be found in [6]. STEM education opportunities for everyone via the implementation of Makerspaces and FabLabs in vulnerable and marginal communities is discussed in [7]. On the other hand, the potential aspects of FabLabs in relation to traditional books as a pedagogical tool, and how teachers perceive these tools for teaching Chemistry to their students, was investigated in [8].

The evidence gathered from these implementations lend support to STEM learning practices via FabLabs. We have verified that these new visual and tangible practices become a rewarding and meaningful experience for all participants. These novel implementations can also help to enlarge adoption of educational digital tools in local communities and surrounding areas through word of mouth among students and teachers.

3. Some STEM prototypes for all

The following section presents a selection of tangible and visual examples of STEM devices that can be reproduced at any FabLab. FabLabs are typically equipped with low-cost, state-of-the-art, and versatile computer-controlled rapid prototyping tools including 3D printers and scanners, laser engraving, and CNC cutting machines driven by open-source software. FabLabs provide a working space for invention, creativity, and resourcefulness, and they are strongly rooted in a local community of makers. STEM students can learn more effectively through practice and be more productive through experience with the prototypes produced in these FabLabs.

The aim of our FabLab is also to disseminate scientific knowledge and to provide opportunities to all class of students to engage with STEM. The outcomes reported here are the output of experiences derived from research activities conducted at the ICTP Scientific Fabrication Laboratory of Trieste, Italy, over the past few years. These experiences were conducted as hands-on, one-off learning experiences in some schools in Italy and in activities during events such as Science Picnics and Maker Faires.

3.1. 3D STEM objects

The current state of low-cost 3D printing technologies is such that they have reached a level of maturity that allows for their unlimited potential to be realized in the field of STEM education. The capacity to reproduce 3D objects of varying complexity, ranging from intricate mathematical structures up to sophisticated biological specimens, has not only benefited schools and higher-education institutions in countries with limited scientific infrastructure to sustain their STEM education programs, but it has also facilitated the rapid growth of digital STEM content around the world.

Typically, 3D printing with FDM (fused deposition modeling) technology is conducted using spools of thermo-plastic filament like polylactic acid (PLA)—an environmentally friendly material derived from corn starch. A number of free or proprietary tools for 3D modeling and printing are available on the internet, facilitating the work required to design and print the objects.

Figure 1. Left: Examples of complex 3D printed mathematical structures. Right: Scale model of a giant, extinct elephantid genus Mammuthus.

3.2. Highly visual cloud chamber—*Physics in action!*

A facility for studying tiny, invisible elementary particles that enter our atmosphere from the outer space (cosmic rays) or that are generated by the decay of radioactive elements within the earth itself, and then pass right through our bodies, is the well-known apparatus known as Wilson's cloud chamber. This apparatus was invented in the early 1900s by Charles Wilson as one of the first particle detectors. The majority of these particles are generated by the decay of natural radon found in the air (itself a product of radioactive elements decay in the ground) while a certain percentage, which varies with altitude, does originate from the cosmic radiation we receive from outer space (primary and secondary cosmic rays).

Figure 2. Typical particle tracks in a cloud chamber device (left). the full video is available at https://www.youtube.com/watch?v=IwyLzqrRJbw. Right: Public interest on the DIY cloud chamber.

To build a cloud chamber for educational purposes, one needs a transparent box with a black bottom metal tray maintained at a temperature of approximately -30 degrees Celsius, accompanied by the presence of a stable cloud of minute droplets of isopropyl alcohol, typically generated by condensation from a liquid state. After a period of time, the top lid of the chamber, which has been soaked in warm alcohol, produces a cloud that reaches the cold metal bottom. When a charged particle passes through at a high speed, it generates a visible track of larger droplets by a mechanism known as coalescence. The droplets of alcohol can then be detected due to their ability to diffuse the light emitted by the strips of LEDs positioned on the sides, as illustrated in Figure 2.

The particles that can be observed in a cloud chamber can be broadly classified into three categories: alpha particles, beta particles, and muons. Alpha particles are composed of two protons and two neutrons. They have a short, fat track and are produced by the decay of radon. Beta particles are electrons (or anti-electrons, a.k.a. positrons), usually following long, straight paths or zigzag paths, depending on the energy and momentum of the particles. Muons are particles emitted from the decay of secondary cosmic rays and can be observed as short, vertical tracks. Further details on the construction and operation of a cloud chamber can be found in [9].

3.3. Galileo and Leonardo mechanical clocks

The first application of a pendulum in a clock using an escapement system is attributed to Galileo Galilei from his original drawings. Following the discovery of the isochronism of a pendulum by Galileo's observation of a swinging lamp in Pisa Cathedral (dating back to 1600), a working gravity-powered clock can be made on a laser cutter with the addition of standard bearings and a few parts made from plywood. As shown in Figure 3 (left), the design of a Galileo mechanical clock can be written using OpenSCAD—a free, fully customized software.

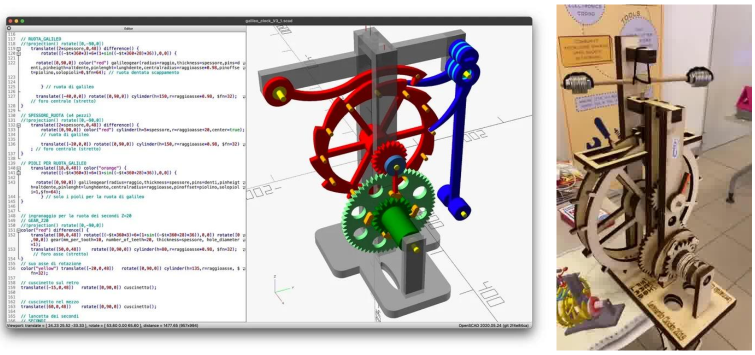

Figure 3. OpenSCAD design of a Galileo mechanical clock (left). The video demonstration is available at: https://www.youtube.com/watch?v=a6B1bxgxAc4. Right: Leonardo mechanical clock. The video demostration is available at: https://www.youtube.com/shorts/g4hkIHu89kE.

Galileo's clock mechanism uses gravitational potential energy as its power source, and carries two arcs; a small, lower arc that receives the impulse, while an upper, wide arc lifts a detent. This model has been designed in collaboration with the "Amici dell'orologeria Pesarina" association, engaged for many years in the dissemination of knowledge concerning watchmaking, a tradition present in the area of Pesariis (an ancient village in the mountains of the Friuli Venezia Giulia (FVG) region, Italy) since 1600, and its dissemination in local schools. The request was to produce a model escapement that could be made cheaply and then to introduce a kit into secondary schools so that students could experience the mechanisms first-hand. The files for this build can be downloaded freely (https://www.thingiverse.com/thing:5549040) and can be further customized in OpenSCAD easily.

The Leonardo Da Vinci clock depicted in Figure 3 (right) is another wooden pendulum clock that can be constructed in a FabLab for educational purposes (https://www.thingiverse.com/thing:4328105). This clock model is powered by a horizontal rotary pendulum, and utilizes the weight contained in a canister and some gears to measure time. The canister has stored potential energy gained by raising it up against gravity. The potential energy is converted to kinetic energy allowing the gears to move their parts. By adjusting the weight and balance of the pendulum, the clock's speed can then be controlled.

3.4. Giant Galton board

A large Galton board allows students to visualize the preferred trajectories of falling (ping-pong) balls while being fed into the device from the top at arbitrary rates. Due to the differing initial conditions established by the participants, the gravitational force and the presence of ordered, fixed obstacles along their paths, the individual balls experience random elastic collisions as they descend. The falling balls' positions will not concentrate at specific locations. Instead, they will be characterized by a distribution (with one or more peaks) resulting from the influence of the stochastic effects due to the presence, or absence, of the obstacles. The spatial distribution of the falling balls with homogeneous obstacles is observed to exhibit a symmetric bell-shaped (Gaussian) curve, see Figure 4.

The observation of individual ball trajectories represents the dynamics of a single ensemble member, whereas the bell statistical distribution of the final balls' positions represents the total ensemble average for the system. This device can serve as a learning platform for explaining weather forecast models, as they use the equations governing the atmosphere in conjunction with a stochastic algorithm called

Figure 4. Giant Galton board of descent ping-pong balls.

"Monte Carlo" to generate a weather forecast (corresponding to the resulting distribution of the balls). The model, as well as the device, exhibits a high degree of sensitivity to its initial conditions (of the dropped balls), where even minor initial perturbations give rise to divergent weather predictions. The presence or absence of the obstacles correspond to the various parameters of the underlying model, and they can be moved to "tune" the results.

3.5. Augmented Reality Sandbox

The Augmented Reality (AR) Sandbox is an educational hands-on exhibit developed by the University of California, Davis, USA. It combines a box filled with real sand with virtual topography and simulated water. The apparatus is constructed using a Microsoft Kinect 3D camera, in addition to a video projector and a Linux PC to achieve extensive real-time computer simulations and visualization. The AR Sandbox allows the reconstruction of geographical models through the shaping of the sand. These models are then augmented by an elevation color map, topographic contour lines, and simulated liquid water.

Figure 5. The Sandbox unit (left) which displays a mountain with a crater lake, surrounded by several smaller lakes (right). This tool is an invaluable resource for educators and learners alike, facilitating the acquisition of knowledge and understanding in the domains of topography, geography, natural sciences and water flow.

The device, illustrated in Figure 5, has been employed for science communication projects involving experiments on geological hazards and volcano alerts. The system is useful for illustrating concepts related to modeling volcanoes, including the processes involved in volcano deformation and the study of magma reservoirs.

A variety of hands-on experiments can be conducted, such as placing a small, inflated balloon beneath the sand. Deflating the balloon can then demonstrate the effect of a collapsing volcano magmatic chamber. It is also possible to illustrate the impact of the rising sea level on coastal areas: for instance, Easter Island, located in the southeastern Pacific Ocean, is highly vulnerable to the effects of climate change, and this can be visually demonstrated with great clarity by varying digitally the height of the sea level.

3.6. 2D-to-3D image conversion via Artificial Intelligence (AI) model

3D visualization has the potential to enhance the understanding of STEM among young students, thereby facilitating more effective learning. Virtual learning opens up new worlds in STEM education, particularly in the context of abstract concepts and the development of specific experiences [10]. Virtual learning can facilitate the exploration of the interior of a human cell, traverse planetary surfaces, or navigate subterranean magma chambers. These are examples of the "intangible world" that can be experienced in virtual learning environments. In order for this to be achieved, it is necessary to recreate a realistic 3D environment. It would be even more beneficial if the viewer were able to perceive this content more naturally, i.e., without the need for special 3D glasses.

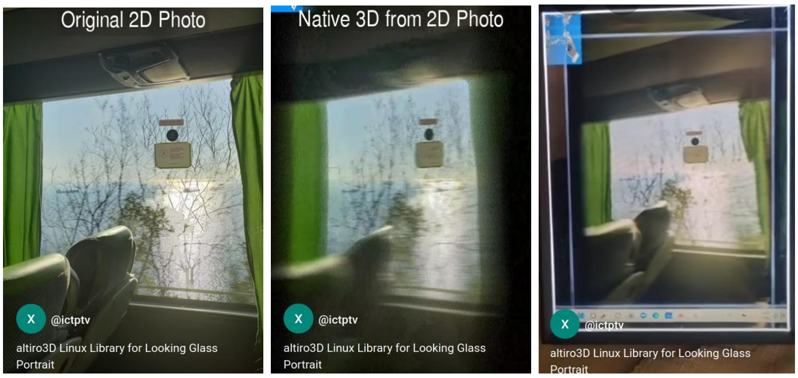

Figure 6. Outputs of the "altiro3D" algorithm to represent reality. Left: Original, single RGB image. Center: Multiview synthesis of a single image carried out through AI. Right: 3D display on a headset-free lenticular 3D screen. The video demonstration is available at: https://www.youtube.com/shorts/hJDVb2TzBr0.

A visual 3D scene representation of a learning environment serves as a medium through which the integration of STEM learning may be effectively transformed into a tangible and meaningful experience. It has tremendous potential to revolutionize education, yet it remains to be further explored. The free library "altiro3D", which enables the representation of reality from a single 2D RGB image or flat video, has also been developed in our Scientific FabLab [11]. This software allows the synthesis of multiple N-viewpoints images or video to create a realistic (real-time) 3D immersive experience when displayed on a lenticular, free-view LCD screen as shown in Figure 6. altiro3D does not require heavy computing runtime and can support a wide range of application scenarios in education and science. The synthesis of multiple views from a single image is achieved through the integration of machine learning together with deep learning algorithms, as well as simple inpainting techniques, which map all image pixels.

4. Some STEM prototypes for schools

To better distinguish our few exemples of hands-on STEM activities conducted in primary and secondary Italian schools, we described next some of our STEM prototypes for schools, giving all the useful information available.

4.1. Large microcontroller board replica

Microcontrollers, such as the popular Arduino Uno, can be employed in a multitude of educational projects including robotics, the monitoring of thermodynamic variables via sensors (e.g., humidity, temperature, pressure, etc), RGB LED-based controllers, and GPS trackers, among others. This technology is becoming increasingly accessible, offering a high degree of affordability and versatility. The introduction of microcontrollers to primary school students can be facilitated through the use of block-based coding.

A comprehensive examination of the use of microcontrollers in primary and secondary schools has revealed that the primary obstacle to their implementation is the limited scale of electronic components and the associated difficulty in handling them. This has prompted us to develop a larger version of the most commonly used microcontroller, Arduino Uno, together with a prototype board and some electronic components with magnetic connections. The larger (9:1) scale facilitates the handling of the attached components while maintaining the overall set's ease of transportation. The scale model was constructed using a laser cutter and a combination of 3D printed components, connectors and pins.

The fully functioning giant replica in Figure 7 not only allows an instructor to explain and demonstrate how to use the microcontroller to students in a classroom setting, but it also benefits students with visual impairments or motor skill difficulties, enabling them to participate actively in the lectures.

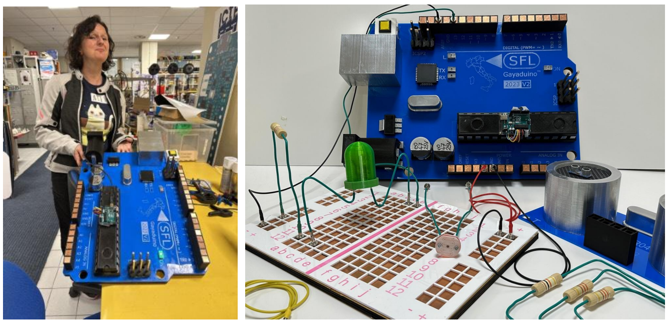

Figure 7. Large microcontroller Arduino board replica.

4.2. DIY lift generator for STEM: *Tubora*

In order to teach wind dynamics (testing which object flies the best and which does not), a DIY wind tube can be built using just simple elements such as a fan and a transparent plastic tube as shown in Figure 8. This system is designed to regulate the pull of air throughout the tube and, in addition, the tube can be configured to point at different angles.

Placing the fan on the underside of the large tube, and inserting objects of varying materials, students can observe the different aerodynamic characteristics of each object. As they collect and analyze data

Figure 8. *Tubora*: An invaluable resource for students engaged in STEM studies of aerodynamics or the mechanics of parachutes.

to ascertain the mechanisms underlying the movement of objects in a forward or downward direction, or their retention in the air at varying angles of flow, they gain insight into the most intriguing aspects of natural physics, namely the phenomena associated with objects in an airflow, aerodynamics and variable drag forces.

The versatility of this exhibit is noteworthy. It allows children in the first years of primary school (aged 6–8) to construct paper objects in a creative manner, thereby determining the probability of them flying out of the tube. This provides students with the opportunity to experiment with different shapes, testing them each time, and to color them in an imaginative way. In addition to cones and paper airplanes, students can investigate the efficacy of twirling paper helicopters. This involves varying factors such as the type of paper, the addition of paperclips, the size of the wings, and so forth.

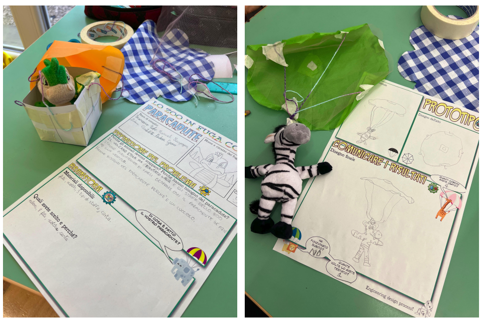

Figure 9. Examples of activity sheets for the STEM Engineering activity. The Runaway Zoo.

They are presented with an object (specifically a small, lightweight stuffed animal) that is too heavy to be lifted by the fan alone. Each group is provided with the same materials (paper, tulle, cotton and umbrella fabric, plastic bags, string, masking tape) and must design the most efficient solution to allow the "skydiver" to rise and escape from the tube. The students will have the opportunity to experiment with different approaches to the design of the parachute canopy. They will select the material they wish to use for the main canopy and then proceed through the engineering design process, which involves defining the problem, brainstorming potential solutions, creating prototypes and testing them in a wind tunnel. Each group will also be required to complete a record sheet, which will help them document their choices, the reasons behind them, and some background information on the plush animal and its need to escape. They are also required to draft sketches of the front and top views of their prototype to complete their task thus fulfilling the final step of the engineering design process (document and share), see Figure 9. This parachute challenge offers the opportunity to investigate a multitude of aspects related to flight and the effects of force on an object. It also provides an opportunity to examine the engineering design process, which is a systematic approach to problem-solving.

5. Discussion

One of the objectives of this work is to include an account of some of our experiences and activities carried out in Italian schools using digital technologies from FabLabs. Our school experiences and public activities are not only directed to school-aged childrens, but are also being developed for interested scholars of all ages.

The current configuration of public primary and secondary schools in Italy presents certain challenges. The minimum number of pupils per class in primary schools is 15, with a maximum of 26 pupils permitted, except in the case of disabled pupils. In secondary schools, the minimum number of students per class is 18, with a maximum of 27 students permitted [12].

A further challenge is posed by the increasing number of students from other countries, in the 2021/2022 academic year, 10.6% of students in Italy were from other countries, with the figure in the FVG region reaching 15.4% and 22.7% in the province of Gorizia [13]. A considerable number of educational institutions are currently undergoing renewal work, with classes being temporarily relocated to smaller classrooms or to alternative buildings that have been converted into schools. The challenges of working in such circumstances are considerable, particularly when the classes are overcrowded and a significant proportion of students lack proficiency in the local language. The ages of participants in our activities during the academic year 2023/24 were as follows. As far as laboratory hand-ons classes were concerned, there were 172 workshops carried out for the primary school years 1–5 (students having 6 to 11 years of age in correspondence). The age groups consisted of 12% in the 1st class, 15% in the 2nd, 19% in the 3rd, 24% in the 4th, 24% in the 5th year, and 6% in multiple age groups classes.

STEM curricula are highly engaging for students, particularly those with language difficulties. The hands-on nature of many STEM subjects enables all students to participate fully, regardless of their linguistic abilities. This phenomenon is further evidenced when students with disabilities are present in the classroom. According to our experiences, STEM activities can be modified to accommodate the specific needs of these students, with the objective of overcoming physical limitations and addressing mental impairments. During a lesson in which a class with a blind student was being taught, the possibility of combining a buzzer with the LED outcome of the experiment proved invaluable in fully involving the student in the lesson.

On another occasion, a student in a wheelchair was able to participate completely in the activity by having all the educational materials relocated to the correct height for him to reach. In another instance, a student with an autism spectrum disorder had the time needed to fully appreciate the effects of air thrust on a small parachute, while his fellow students were engaged in the collection of data and the preparation of a subsequent demonstration.

While curricula teachers interact with students throughout the academic year, structuring their lessons over a long time span, STEM laboratories are often conducted by external educators with the aid of specific materials and teaching aids, and must accommodate the needs of the school timetable. The principal objective of these laboratories is to stimulate interest among students and provide the curricula teachers with insights into alternative pedagogical approaches to technical subjects. The lessons provided can then be further developed during the school year.

The experiences of one of the authors (G.F., also an assistant in the SciFabLab) on providing one-off, hands-on learning activities in primary and secondary schools over the past decade has been predominantly focused on the delivery of engaging, 1.5 to 3-hour-long sessions that engage the entire class, while also providing all the necessary materials. This approach has the dual benefit of relieving teachers of the burden of providing materials while also allowing for more focused and effective learning.

Figure 10. Students' STEM activities for Italian schools from the FVG region carried out at the Scientific FabLab of ICTP.

Students currently engaged in primary and secondary education have experienced the challenges of the Covid-19 lockdown and a prolonged period of distance learning, which has resulted in significant difficulties in working in groups and reduced dexterity. This kind of learning, utilizing hands-on experience using digital technologies, can be extremely useful in addressing both of these problems. In our experience, dividing the class into four groups is optimal, as it allows for more focused and effective learning while allowing a single educator (which is the typical situation) to monitor the progress of each group, ensuring that all groups remain on track while providing additional challenges to the more advanced group.

While working with smaller groups or a one-to-one approach would also be interesting, the limitations posed by the need to engage the whole class with a single educator limit the possibilities. An ideal configuration would have four groups of students, forcing them to work as teams to exchange ideas and compare their different approaches, allowing for a more focused and effective learning environment. Furthermore, this configuration has enabled teachers to examine the interactions between their students in a group setting, offering valuable insights. The decision regarding the composition of groups is always a challenging one, with students frequently attempting to maintain proximity to their acquaintances, thereby creating groups that are not optimally balanced. When working with primary school pupils, the involvement of teachers, who possess a comprehensive understanding of the students and are capable of dividing them (maintaining the separation of more challenging students and creating more balanced groups), can be invaluable in this regard. In the context of working with secondary school students, it is possible to allow them to choose their own groups, thereby giving them the opportunity to assume this responsibility.

In most cases, the curricula teachers participate, assisting students that are having difficulty and providing important context with references to lessons already given on similar topics. Frequently, they choose to discuss in advance the topics covered during such activities, stimulating students' curiosity before the laboratory, creating an optimal learning environment. The class is often requested to provide feedback on the STEM topics presented, which may take the form of a simple drawing or collaborative poster for primary school students, or a summary or more creative medium such as a video, comic, rap song, newscast, or other form for secondary students. The variety of media employed and the creativity displayed by classes that have previously encountered disciplinary problems during the laboratory is often noteworthy.

A recent extensive literature review indicates that digital technology can positively affect STEM education in terms of knowledge or skill acquisition and learning engagement in young children [14]. This fact was found regardless of gender but highly relevant to age. Learning from, with, and through technology occurs when the technology is easy to be used as a tool to deliver knowledge. In most cases, these technologies become limited within the context of early childhood education since they include computer programming, simulation software, robotics, 3D technology, video games, apps., etc. The new trends of emerging digital technologies, such as AI, in the STEM learning context become limited in children's education [15]. An important problem outlined in these existing approaches is the age of students. Our study differentiates with such reports because we actually motivate the primary and secondary schools to participate in STEM festivals. Ours are preliminary outcomes based on our experiences not only carried out in Italian schools but also during large, free public activities like Maker Faires and Science Picnics which allow anyone, of any age, to explore scientific concepts in simple, innovative ways. By this, we encourage the young science scholars to be creative and incentivize them to develop their own abilities for research, discovery and ingenuity.

Our goal in this article is to introduce readers on the importance of adopting digitally controlled technologies found in FabLabs for tangible and visual STEM learning. Educators may adjust their standard practices to incorporate hands-on STEM learning activities into their curriculum at their own pace and own needs. Not all scientific prototypes illustrated are for school-aged children, as with the Cloud Chamber and the AI-based 3D imaging. We aim at getting better understanding of science through the utilization of tangible and visual examples as those illustrated and explained in our paper. In our study we keep in mind the relevant work carried out by teachers as well as aim to reach a larger range of professionals, decision-makers, politicians, scientists and interested students in general. This works aims to be of benefit for the progress of society as a whole.

6. Conclusions

STEM students can greatly benefit when receiving training and education based on tangible and visual learning. The prototypes presented in this work as examples allows us to put concrete experiences in their hands. The aforementioned examples have been generated utilizing digital technologies that are readily accessible in any FabLab worldwide. We have discussed and assessed some of our experiences and activities done in Italian schools and large public events using and demonstrating such devices such as touching complex 3D structures, visualizing cosmic rays, and building the needed blocks to learn microcontrollers in class.

At present, it is difficult to compare the similarities and differences between our research on tangible and visual STEM learning experiences and existing studies since there are not many similar studies. It is premature to derive definitive conclusions because more data within different academic environments and experiences around the world are needed.

We have built upon and verified how visual and tangible STEM learning emphasizes student potential and opens a smooth connection between the understanding of abstract scientific phenomena and a deeper, more comprehensive learning experience. This novel approach in action is appealing to scholars and can sustain new generations of young science scholars in an inclusive way facilitating the quality of STEM education for all.

Author contributions

Gaia Fior: Conceptualization, Methodology creation, Data Curation, Validation, Writing - review & editing. Carlo Fonda: Conceptualization, Methodology creation, Investigation, Resources, Writing - review & editing. Enrique Canessa: Conceptualization, Methodology creation, Investigation, Formal analysis, Writing - review & editing. Supervision. All authors have approved the final version of the manuscript for publication.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

The authors would like to thank Sara Sossi, Erika Ronchin, and Marco Baruzzo who have helped with their ICTP SciFabLab STEM activities during the last few years. Sincere gratitude is also due to Fondazione Pietro Pittini (FPP) for partnering with us in many of these projects.

Conflict of interest

The authors declare no conflict of interest in this paper.

Ethics declaration

The authors declare that the ethics committee approval was waived for the study.

References

1. SDG 4, *UN Sustainable Development Goal 4*, 2018. Retrieved Dec 2024. Available from: https://www.un.org/sustainabledevelopment/education/.
2. Canessa, E. and Tenze, L., Ideals and Virtual Realities. *Int. J. Emerging Technologies in Learning (iJET)*, 2021, 16(21): 201–209. https://doi.org/10.3991/ijet.v16i21.25493
3. Fonda, C. and Canessa, E., Making Ideas at Scientific Fabrication Laboratories. *Physics Education*, 2016, 51(6): 065016. https://doi.org/10.1088/0031-9120/51/6/065016
4. Canessa, E. and Fonda, C., Science and Inclusion. *J. Technology and Disability*, 2023, 35: 1–9. https://doi.org/10.3233/TAD-220387

5. González-Salamanca, J.C., Agudelo, O.L. and Salinas, J., Key Competences, Education for Sustainable Development and Strategies for the Development of 21st Century Skills. A Systematic Literature Review. *Sustainability*, 2020, 12(24): 10366. https://doi.org/10.3390/su122410366

6. Zakoth, D., Mauroner, O. and Emes, J., The role of makerspaces in innovation processes: an exploratory study. *R&D Management*, 2024, 54(2): 398–428. https://doi.org/10.1111/radm.12594

7. González-Nieto, N.A., Ching-Chiang, L.W.C., Fernández-Cárdenas, J.M., Reynaga-Peña, C.G., Santamaría-Cid-de-León, D., Díaz-de-León-Lastras, A., et al., *FabLabs in vulnerable communities: STEM education opportunities for everyone*. *Int. J. Interactive Design and Manufacturing (IJIDeM)*, 2020, 14(4): 1535–1555. https://doi.org/10.1007/s12008-020-00744-y

8. Fibonacci, A., Kadarohman, A., Hernani. and Fitriani, I.N., *Opportunities of Digital Fabrication Laboratory Technology as Innovative Chemistry Pedagogical Tools: Trends and Pre-Service Chemistry Teachers' Perspective*, *J. Innovation in Educational and Cultural Research*, 2024, 5(2): 207–217. https://doi.org/10.46843/jiecr.v5i2.1342

9. Baruzzo, M. and Fonda, C., *Cloud Chamber DIY: School Edition V2*. Retrieved Dec 2024. Available from: http://scifablab.ictp.it/2024/04/24/diy-cloud-chamber-school-v2/.

10. Reid, B. and Sykes, W., *Learning in 3D: Making STEM Real*. Retrieved Dec 2024. Available from: https://source.cognia.org/issue-article/learning-3d-making-stem-real/.

11. Canessa, E. and Tenze, L., *altiro3d: Scene representation from single image and novel view synthesis*. *Int. J. Inf. Tecnol.*, 2024, 16(1): 33–42. https://doi.org/10.1007/s41870-023-01590-3

12. Ministero dell'Istruzione e del Merito, Formazione classi. Available from: https://www.miur.gov.it/web/guest/formazione-classi (Retrieved Dec 2024).

13. Centro Studi e Ricerche IDOS and Istituto di Studi Politici San Pio V, *2023 Statistical dossier on immigration in Italy*, Arti Grafiche Picene srl, 2023, 233–238.

14. Hu, X., Fang, Y. and Liang, Y., Roles and Effect of Digital Technology on Young Children's STEM Education: A Scoping Review of Empirical Studies. *Educ. Sci.*, 2024, 14(4): 357. https://doi.org/10.3390/educsci14040357

15. Yang, W., Hu, X., Yeter, I.H., Su, J., Yang, Y. and Lee, J.C.K., Artificial intelligence education for young children: A case study of technology-enhanced embodied learning. *J. Comp. Assisted Learning*, 2024, 40(2): 465–477. https://doi.org/10.1111/jcal.12892

Author's biography

Gaia Fior (Masters in Natural Sciences) is assistant of the ICTP SciFabLab since its foundation and organizes, and collaborates with, STEM educational projects.

Carlo Fonda works at the Science, Technology and Innovation (STI) Unit of the ICTP in Trieste, Italy. He is the co-founder and manager of the ICTP SciFabLab and co-organizer of the Maker Faire Trieste since 2014.

Enrique Canessa (Ph.D in Physics) is with the Science, Technology and Innovation (STI) Unit of the ICTP in Trieste, Italy. He is the co-founder of the ICTP SciFabLab and co-organizer of the Maker Faire Trieste since 2014.