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Renovating project-based learning in Israel to foster learning STEM, computational thinking and design arts

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Abstract

Project-based learning (PBL) and design-based learning (DBL) are among the best educational tools for fostering lifelong learning skills. In Israeli high schools, every year thousands of students prepare final projects in subjects such as electronics, computer science, mechatronics and design arts. However, a number of issues have arisen in implementing PBL or DBL in schools, for example, the students are very loaded in their final year of high school, many students are not prepared enough to work independently on their projects, and there is very little collaboration between students majoring in various technological areas. This paper shows how the Israeli education system is trying to renovate PBL and DBL in technological classes, for example, by deploying the project work over three years of high school, encouraging interdisciplinary projects, and using online documentation of the design process. The factors that facilitate or hinder project work in school are also discussed.

Keywords: Renovation, technology, projects, design, interdisciplinary, high-school

Introduction

The OECD (2018) report, *The Future of Education and Skills 2030*, states that the future is uncertain and we cannot predict it; but we need to be open and ready for it. Children entering the education system today will be young adults by 2030. Schools are required to prepare them for jobs that have not yet been created, for technologies that have not yet been invented, and for solving problems that have not yet been anticipated. Heinrich, Bhattacharya and Rayudu (2007), and Nordgren (2002) emphasize that rapid technological change, increasing globalization, and a changing world of employment with multiple roles during one's professional life are necessitating a change from knowledge to learning societies. Full participation requires lifelong learning skills, meaning the ability to solve problems, work both independently and on a team, communicate effectively in different formats, and self-direct one's learning and professional development needs.

It is widely agreed that project-based learning (PBL) and design-based learning (DBL) are among the best tools that education has for achieving these goals (Thomas et al., 1999). The Israeli education system has a long history of engaging high school students in project-based learning (PBL) and design-based learning (DBL) in technology and engineering in subjects such as electronics engineering and mechanical engineering (Mioduser & Betzer, 2008; Barak, 2002, 2005, 2012, 2018; Barak & Dopplet, 1999). The students work in pairs or small groups on a design project such as robotics or computer-controlled systems during their final year in high school (12th grade) and prepare a printed booklet on their project.

However, in addition to the educational advantages of PBL and DBL, a number of issues have arisen in recent years in implementing these methods in school. One problem is that the students are very loaded in their final year of high school and can spend only a little time working on their projects. A second is that many students are not prepared enough to work independently on the different phases of project design, such as investigating, planning, constructing, testing and troubleshooting. Another issue is that students are divided into separate classes for electronics, mechatronics, computers or art design, with little interface between these groups. Since many modern technological artefacts and systems assimilate these areas, educators are increasingly interested in developing interdisciplinary projects based on collaboration between students majoring in different areas. Consequently, the Ministry of Education, in collaboration with experts from academia, have launched a reform in some aspects of PBL and DBL in technology and engineering studies, which is discussed in this paper.

The present paper addresses the following questions:

1. What is the role of project-based learning and design-based learning in technology and engineering education in Israeli high schools?
2. What are the objectives and methodology of renovating PBL and DBL in Israeli technology classes?
3. What are the factors that might facilitate or hinder the application of PBL or DBL in technology and engineering education?

Ideas for further development and research are also suggested.

Data sources for this article

Data for this study were obtained through the researcher's involvement in developing and researching technology and engineering education in Israel. This includes, for example, developing innovative curricula in subjects such as electronics, control systems and robotics; involvement in teachers' pre-service and in-service training; evaluation of the implementation of new curricula in schools, in particular project-based learning; participating on national committees for updating the curriculum in science, technology and engineering studies in K-12 education; and attending national project competitions in electronics and mechatronics. Information on the methodology of the data collection and analysis is provided in the author's publications cited in this paper (Barak, 2002, 2005, 2012, 2018; Barak & Doppelt, 1999; Barak & Assal, 2018; Doppelt & Barak, 2020). This involved visiting schools, interviewing teachers and students, conducting knowledge exams, administering attitude questionnaires in classes, and giving formal matriculation exams to students who prepared final projects in electronics and robotics.

Literature review

Project-based learning in the technological class

According to Thomas (2000), projects are complex tasks based on challenging questions or problems that involve students in design, problem-solving, decision-making, or investigative activities. Projects give students the opportunity to work relatively autonomously over extended periods and end up with realistic products or systems. Project-based learning draws considerably from the constructivist philosophy of learning attributed to prominent philosophers of education such as Jean Piaget (1896-1980) and John Dewey (1859-1952). Constructivist pedagogy encourages pupils to build new knowledge based on existing knowledge and their own experience. Papert and Harel (1991) and Kafai and Resnick (1996) proposed the concept of *constructionism*, according to which pupils are more deeply involved in their learning if they construct artefacts they can share with others, for example, peers or parents, and that this construction engages the learner in complex tasks and problem-solving efforts. However, the pedagogical literature is increasingly aware of the need to adapt the complexity level of PBL assignments to the students' prior knowledge and skills, and provide instruction and scaffolding in order to reduce cognitive load and enable students to learn in a complex domain (Crismond, 2011).

Design-based learning (DBL): The engineering method

Dym et al. (2005) argue that engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints. Design-based learning is a unique form of project-based learning derived from the engineering design method. Resnick (1998) shows that there are many reasons why design projects can provide rich opportunities for learning.

- Design activities engage children as active participants, giving them a greater sense of control over, and personal involvement in, the learning process in contrast to traditional school activities in which teachers aim to convey new information to the students.
- Design activities are often interdisciplinary, bringing together concepts from the arts, mathematics, and sciences.
- Design activities encourage pluralistic thinking, avoiding the right/wrong dichotomy prevalent in most school math and science activities, suggesting instead that multiple strategies and solutions are possible.
- Design activities provide a context for reflection. A child's constructions serve as external shadows of the child's internal mental models, providing an opportunity for children to reflect on, then revise and extend their internal models of the world.
- Design activities encourage children to put themselves in the minds of others, since they need to think through how other people will understand and use their constructions.

Burghardt and Hacker (2004) suggested the informed design cycle using eight stages.

1. *Clarify design specifications and constraints.* Describe the problem clearly and fully, noting constraints and specifications.

2. *Research and investigate the problem*. Search for and discuss solutions to solve this or similar problems. Complete a series of guided-knowledge and skill-builder activities that will help students identify the variables that affect the performance of the design, and inform students' knowledge and skill base.
3. *Generate alternative designs*. Do not stop when you have one solution. Approach the challenge in new ways and describe alternatives.
4. *Choose and justify optimal design*. Rate and rank the alternatives against the design specifications and constraints. Justify your choice. Your chosen alternative will guide your preliminary design.
5. *Develop a prototype*. Make a model of the solution. Identify and explain modifications to refine the design.
6. *Test and evaluate the design solution*. Develop and carry out a test to assess the performance of the design solution. Complete or review KSBs focused on developing a fair test.
7. *Redesign the solution with modifications*. Examine your design and examine the designs of others to see where improvements can be made. Identify the variables that affect performance and determine the concepts that underlie these variables. Explain how to enhance the performance of the design using these concepts and variables.
8. *Communicate your achievements*. Complete a design portfolio or design report that documents the previous steps. Make a group presentation to the class justifying your design solution.

The design process described above appears in the literature in different variations using five, six, or seven stages (Mehalik et al., 2008). However, it is important to note that design is an iterative cycle in which a designer can move back or forth between one stage and another, rather than a linear process, which may be implied from the stages list above. Doppelt and Barak (2020) note that stages 3 and 4, *Generate alternative designs* and *Choose and justify optimal design*, are central to the engineering design because engineering is merely a process of optimization and trade-off. Engineering optimization helps engineers find the most effective and efficient solutions to problems. In many cases, designers cannot develop a product or system that fully meets all requirements, for example, in terms of performance, ease of use, reliability, safety, or cost. They develop several solutions and systematically check for the optimal one. Crismond (2011) writes that engineering and technology educators want students to learn STEM ideas, but also gain competence in engineering design. The author emphasizes ideas like optimization, reasoning about trade-offs, troubleshooting, and meeting criteria while staying within prescribed constraints.

The steps of optimization and trade-off mentioned above (stages 3, 4) that are at the heart of the engineering design process are less central to the general model of project-based learning. In Israeli schools, for example, teachers who guide students in preparing design-based projects in mechatronics stress the optimization process. However, in electronics classes, the teachers are likely use project-based learning and emphasize to a lesser extent the need to offer several solutions to a problem and choose the optimal one based on the criteria. DBL differs from PBL mainly in this aspect. In the present paper, we will use the term PBL in technology and engineering education that also includes DBL.

Technology and engineering education in Israel: Adaptation to students on a broad achievement spectrum

Up until the 1980s, senior secondary education consisted of general high schools intended only for high-achieving students and vocational schools for low-achieving students. This system has gradually changed, and most high schools today are comprehensive schools meant to provide a home for students on the entire spectrum of achievement. To achieve these goals, technology studies in high school comprise three main routes: engineering, technological, and occupational.

The *engineering route*, includes subjects at the forefront of engineering, such as electronics, mechatronics, computer engineering and biotechnology engineering. These subjects are oriented towards the most talented students who also study the highest-level courses (5 study units) in mathematics, physics and English for the *Bagrut* national matriculation exams. Many of these students pursue engineering studies at university after graduating from high school.

The *technological route*, includes quasi-engineering subjects such as electricity, control and energy systems, computerized manufacturing systems, car mechanics, construction and architecture, industry and management, design arts, fashion design, and media and publication. These subjects are often oriented towards students having a high or medium level of achievement, for example, those who study mathematics or English at the level of 3-4 (out of 5) study units for the *Bagrut* exams. These students are also candidates for post-secondary studies in technological colleges for a degree of qualified technician or practical engineer.

The *occupational route*, includes subjects such as health systems, tourism, hotels, marine systems, agriculture and hairstyling. Students who learn these subjects acquire basic knowledge and skills that will help them integrate into a workplace or start their own business.

More than 50 percent of high school students major in technology education as an elective subject in one of the routes described above. The talented students study subjects such as electronics, computer engineering or mechatronics engineering for 12-15 hours a week (out of 35-45 hours at school). Students who major in technology learn in the same school with students who major in other subjects, for example, science or the humanities. All students study compulsory subjects such as Hebrew, English and mathematics. Although project-based learning is optional for students in all three groups mentioned above, the majority of students who cope with PBL are from the engineering or technological routes. One challenge for the reform addressed in this paper is to encourage collaboration between students and teachers majoring in diverse technological routes.

Technological and pedagogical changes that require renovating PBL

The digital revolution that has taken place in recent decades has dramatically affected almost all aspects of life, teaching and learning in school, and PBL in particular. Below are some examples of how the digital revolution is affecting PBL.

- The extensive use of programmable devices such as the Arduino micro-controller makes it possible to build sophisticated systems such as a robotic, smart home or alarm system quite easily. Programmable micro-controllers largely replace the need to design analog or digital circuits based on discrete components such as diodes, transistors or logic gates (Barak, 2018).

- The students are increasingly involved in using computer simulation and learn little about using laboratory equipment such as a signal generator and oscilloscope for planning, constructing and troubleshooting their projects.
- The extensive use of ICT has provided students with access to infinite materials and projects. The negative aspect of this development is that it is sometimes difficult to distinguish between using ready-made designs that students have found on the Internet or work they have prepared on their own.
- The interdisciplinary nature of technology today requires schools to engage students in interdisciplinary projects that integrate devices and knowledge from mechanics, electronics, computing and product art design.
- The digital revolution makes it possible to move all project design and documentation into a digital medium only, with the principle of 'no paper.'

In the light of the technological changes that are affecting PBL described above, educators have recognized the need to deploy PBL over three years of schooling (instead of one year) to prepare students gradually to cope with PBL.

Gradual development of PBL: The P3 Task Taxonomy

The literature on problem-based learning (Barrows, 1985; Savery & Duffy, 1995; Thomas, 2000) stresses that PBL is derived from the constructivism philosophical view on how we come to understand or know. Among the instructional principles associated with PBL (Savery & Duffy, 1995) are to anchor all learning activities to a larger task or problem; support the learner in developing ownership for the overall problem or task; design an authentic task; design the task and the learning environment to reflect the complexity of the environment they should be able to function in at the end of learning; give the learner ownership of the process used to develop a solution; design the learning environment to support and challenge the learner's thinking; encourage testing ideas against alternative views and alternative contexts; and provide opportunity for and support reflection on both the content learned and the learning process.

However, our experience shows that students might encounter difficulties in coping with constructivist-oriented instructional methods as described above because these instructional approaches are likely to be ineffective with novice learners. Kirschner, Sweller and Clark (2006) write that unguided or minimally guided learning approaches are less effective and less efficient than learning approaches that place a strong effort on guiding the student learning process. Only when learners have sufficiently high prior knowledge that provides internal guidance does the advantage of guidance begin to be reduced. Some supporters of PBL (Alfieri, 2011; Blumenfeld et al., 1991; Dolmans et al., 2005; Hmelo-Silver, 2004; Hmelo-Silver et al., 2007) stress that it is important to tailor the scope and complexity level of assignments to the students' prior knowledge and skills, and provide instruction and scaffolding in order to reduce cognitive load and enable students to learn in a complex domain (Crismond, 2011).

To cope with this challenge, Barak (2018) and Barak and Assal (2018) proposed the P3 Task Taxonomy as a tool to distinguish between three levels of student assignments:

- *Practice:* exercises and closed-ended tasks in which the solution is known in advance and the learners can check if they arrived at the correct answer;

- *Problem-solving:* small-scale, open-ended tasks in which students might use different solution methods and arrive at different answers; and
- *Projects:* challenging tasks in which the problem is ill defined. Students will take part in defining and refining the problem, setting objectives, identifying constraints and choosing the solution method.

The pedagogical considerations described above helped in designing the PBL reform in Israeli high schools, as discussed in the following sections.

Fostering interdisciplinary projects to learn STEM, computational thinking (CT) and design arts

Educators today are increasingly aware of the importance of guiding students to address explicitly technological, mathematical, scientific, engineering, computational, or design arts aspects of their projects, as illustrated in Figure 1.

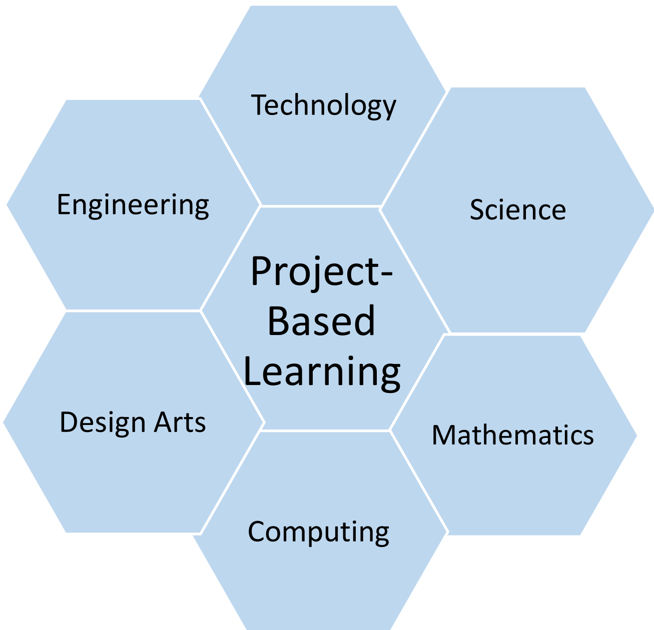

Figure 1: Interdisciplinary aspects of a PBL in technology education.

The six aspects of PBL illustrated in Figure 1 are not discrete but overlap one another to a certain extent. For example, engineering by definition is the division of technology that uses science and mathematics for design and problem-solving. These six components are often hidden in projects that the students do, and it is necessary to guide the learners to address these aspects directly in their project design, construction, testing and documentation. For example, Barak and Assal (2018) present a case of STEM-oriented tasks in robotics in which students explore the velocity of a robot by marking the distance the robot moves on the floor every few seconds. They use a spreadsheet to draw a graph of distance x (m) depending on time t (sec) and calculate the robot's average velocity v (m/s), as illustrated in Figure 2.

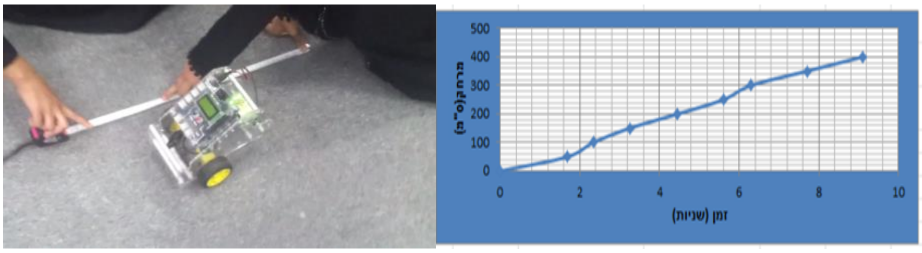

Figure 2: Robotics, STEM and computational thinking—exploring the velocity a robot moving on the floor.

In the example shown in Figure 2, the students deal with concepts in technology, physics and mathematics. This example also has to do with fostering computational thinking, including programming the robot and using the computer for data presentation and analysis. In the study from which this example was taken (Barak & Assal, 2018), the students liked this activity because it related to what they had learned in other subjects in school.

Today, more than in the past, technology teachers should encourage students to explicitly address aspects of technology, design, mathematics, physics, computing or arts in their project. Technological aspects of projects in robotics include concepts such as feedback and control, sensing, power conversion or amplification, and optimization. According to Yadav, Stephenson and Hong (2017), computational thinking (CT) refers to exposing students to computing ideas and principles within the context of the subject areas they are already learning, for example, mathematics, science, technology or the humanities. Wing (2006) defined computational thinking as "solving problems, designing systems, and understanding human behaviour by drawing on concepts fundamental to computer sciences" (pp?). It is important to note that the concept of CT is not restricted to just the teaching of computer science or programming, but also to the use of principles or tools from the computer world for investigation, planning or problem-solving. For example, in a project on temperature control in a greenhouse (as seen in the next section), students can use a temperature sensor connected to a computer to measure and store information on temperature changes in a greenhouse over 24 hours and analyse these data to design an adequate air-conditioning system.

An example of an interdisciplinary programme for teaching engineering and design arts

A team from the Ministry of Education in Israel, in cooperation with an industrial design expert from the Technion – Israel Institute of Technology (Krichman & Tarazi, 2016), developed a programme that brings together students majoring in design arts and students from engineering-oriented studies such as electronics, computers and mechatronics. The challenge for the mixed teams is to develop original and innovative devices or systems while using explicit knowledge and methods from design thinking and engineering. An important challenge of this programme is also to foster collaboration between the teachers from the different areas.

After one year of preparation, a pilot study was launched in seven high schools involving about 35 teachers and 150 students. Below is an example of a student project: a computer-controlled home greenhouse.

In one of the schools, a group of students chose to develop a home greenhouse for growing plants and spices. The small greenhouse is computer-controlled, including remote control by a mobile phone. The participants were one student majoring in design arts and three students majoring in electronics and computer engineering, together with their teachers. The students' design thinking investigated questions such as why people grow plants at home, the conditions for growing different types of plants, common locations of plants, for example, on the floor, on a table, on windowsills, or hung on a wall. They also learned how to build a computer-controlled system, which included the use of electronic sensors for measuring temperature, humidity and light intensity in the greenhouse. Figure 3 shows the design alternatives the students suggested and the proposed solution; Figure 4 shows the final greenhouse design as a transparent bubble hanging on a wall.

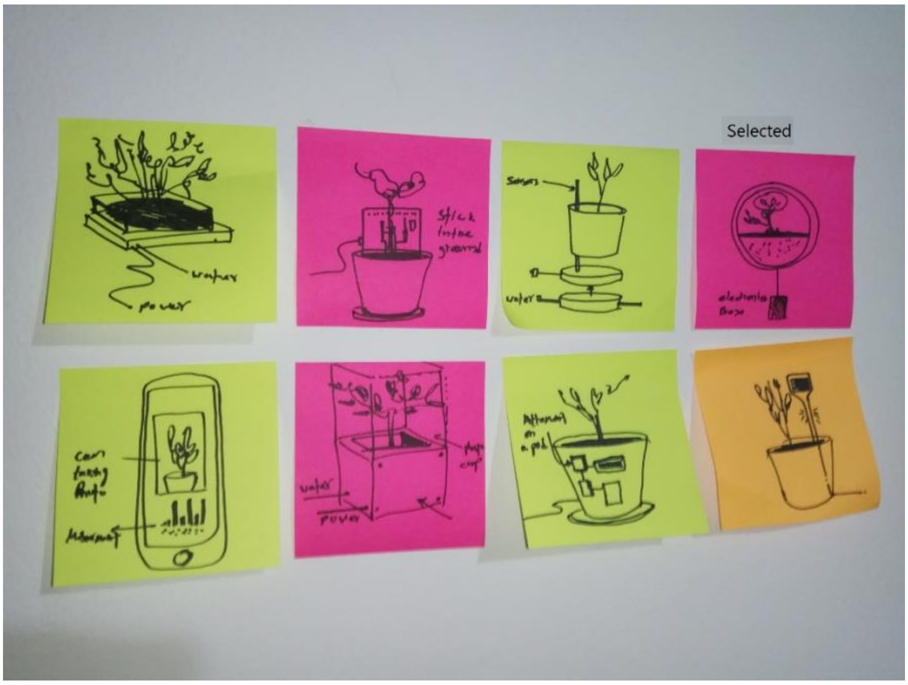

Figure 3: Design alternatives for the greenhouse proposed by the art design students.

Figure 4: A greenhouse in the form of a transparent bubble hanging on a wall.

The electronics and computer-engineering students developed the hardware and software to control the greenhouse through a mobile phone application, which also presents information about temperature, humidity and light in the greenhouse. The electronics hardware is located on the back of the greenhouse, as is shown partially in Figure 5. The back of the greenhouse also includes a small water tank, not shown here.

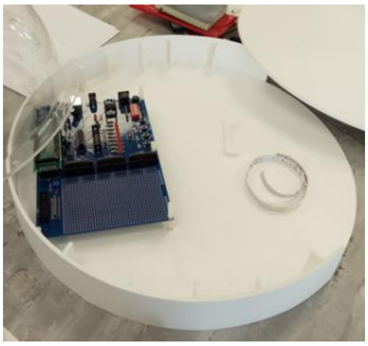

Figure 5: An electronics system located on the back of the greenhouse.

In conclusion, the greenhouse example demonstrates the potential of PBL as a platform for fostering collaboration between students and teachers from different fields of engineering and design arts. These students normally concentrate on learning relatively limited aspects of technology or engineering and do not interface with one another. In contrast, the interdisciplinary project exposes students and teachers to a wide spectrum of knowledge in design arts, engineering and computing. It is worth noting that if students majoring in science such as physics and biology were also engaged in project design, it could further enhance this programme.

Online documentation of project work over three years

As previously mentioned, PBL takes place in Israeli high schools within the framework of the *Bagrut* matriculation exams that the students take during their high school studies for which they receive a final grade in each subject they study. In the common PBL method, students work on their projects during their final year of high school (12th grade). An external examiner from the Ministry of Education evaluates the students' work based on the booklets they prepare on their project and an oral exam of 20-30 minutes held at school. However, the final grade refers only slightly to the process the students underwent while working on their projects. In the new method under development, the students work on their projects over three years (10th, 11th and 12th grades). They document all stages of the design process online, for example, by writing text and taking pictures of and making videos on their work, and uploading these materials to the Moodle environment provided to each student by the Ministry of Education. In the final evaluation, the examiner understands the process the students have experienced during the project work through the three-year documentation, which is a significant change in comparison to the traditional method, described above.

Factors facilitating or obstructing the implementation of the new PBL model: Three years of work on interdisciplinary projects

Interviews with students and teachers in two schools and during a national project competition revealed a number of factors that supported or hindered the implementation of the innovative PBL method. According to the teachers, a critical facilitating factor of the new PBL approach is the backing provided to the teachers. One of the teachers noted that the school management greatly supported the experimental programme to refresh and foster high school technology studies. Preparation of the programme took a whole year before it was implemented in class. In the preparation phase, teachers from two disciplines – electronics and design arts – were given free time (an hour or two a week) to work together, plan the students' projects and prepare the necessary infrastructure. The teachers participated in a regional training course and met with advisors from the Ministry of Education and ORT Israel, a non-government organization devoted to education in Israel to which the school belongs, to prepare the new programme. The second important aspect contributing to the programme's success was the establishment of the interdisciplinary lab equipped with innovative devices such as a 3D printer.

The participants reported that at the beginning, the teachers from different fields collaborated only slightly. Initially there were disagreements and debates about the selected projects and student guidance due to the differences in students' backgrounds and work patterns in electronics, computers and design arts classes. However, the teachers gradually overcame these difficulties and launched the programme successfully in the second year.

The main factor that hindered the programme's success was the method of matriculation exams used in Israel. Although the Ministry of Education strongly supported the new programme, an interdisciplinary matriculation exam has not yet been developed and the exams that the students took remained in the old system, namely, separate exams for electronics, computers and design arts. Towards high school graduation, the students focused on studying the material required for their specific exams, and their collaboration, including their interdisciplinary work, lessened. Consequently, schools will be able to accelerate the innovative interdisciplinary learning program only if the Ministry of Education adjusts the matriculation exams to this programme.

A number of schools that have already adopted the new method of three-year project work and online documentation have reported very positive feedback and satisfaction by the students and teachers. However, it is still unclear how a grade will be determined on the high school *Bagrut* diploma, which is a very important legal issue for students. For example, in working on the project over three years, students may replace the project topic or project team. It will be necessary to develop a methodology for assessing student work and determining the final grade.

Summary and conclusions

In this paper, we have seen that technology education plays a central role in Israeli high schools. The range of subjects learned within this framework, the spectrum of students who learn technology, and the number of hours a week spent on technology studies is higher than in many other countries. In particular, the Israeli education system is exceptional in that technology studies take place within the framework of comprehensive high schools rather than in separate technological or vocational schools.

Technology education in Israel has a tradition of more than two decades in implementing PBL in subjects such as electronics and computer engineering, mechanical engineering or design arts. We have seen that the reform in PBL in technology education currently taking place aims at encouraging interdisciplinary projects, for example, projects that bring together students majoring in electronics and computer engineering on the one hand, and students majoring in design arts on the other. The initial feedback from schools on applying the reform discussed in this paper is very positive, but broader systematic research will be required to evaluate the impact of these changes on students' learning patterns, achievements and motivation to pursue technological education in high school.

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