CHAPTER 6

Design-Based Learning in Electronics and Mechatronics

Exploring the Application in Schools

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1 Introduction

Design-based learning (DBL) is an educational approach grounded in the processes of inquiry and reasoning towards generating innovative artifacts, systems and solutions (Gomez Puente, van Eijck, & Jochems, 2013). Design-based learning belongs to the family of constructivist, pupil-centered teaching-learning methodologies, such as learning by doing (Dewey, 1977; Kolodner et al., 1998), problem-based learning (Pecore, 2013) and project-based learning (Barak & Doppelt, 1999; Pecore, 2015). All these instructional approaches aim at promoting pupils' motivation to learn and fostering learners' cognitive and affective skills such as self-directed learning (SDL), critical thinking, creative thinking, reflective thinking and collaborative learning. While the educational literature has largely discussed and investigated the concepts of problem-based learning and project-based learning, less has been written or demonstrated about design-based learning. For example, how does DBL differ from problem- or project-based learning? How do pupils accomplish the design process? What factors might encourage or hinder the integration of DBL into traditional schooling? The current chapter aims at addressing these issues by closely examining two examples of applying DBL, one in American middle schools and the other in Israeli high schools. Conclusions for implementing DBL in schools are also suggested.

2 Literature Review

2.1 *The Engineering Design Process*

Design-based learning intends to engage pupils in the process of problem solving and new product development based on the engineering methodology. According to Tayal (2013), Hynes (2012) and Kelley (2008), the engineering design process is the set of steps that a designer takes to go from first identifying

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a problem or need to creating and developing a solution in the end that solves the problem or meets the needs. The engineering design process is often presented by the following steps:

1. Define the problem.
2. Do background research.
3. Specify requirements.
4. Generate alternative solutions.
5. Choose the best solution.
6. Do development work.
7. Create a prototype.
8. Test, improve and redesign.

The engineering design steps described above appear in the literature in different versions, sometimes in five or six steps. However, it is important to note that engineering design is an iterative cycle, as opposed to a linear process, as highlighted later in this article (Crismond, 2011).

2.2 *Design-Based Learning Versus Problem-Based Learning*

Problem-based learning (Hmelo-Silver, 2004; Pecore, 2013; Dolmans et al., 2005), has to do mainly with science education, because it is derived from the scientific method. The problem, the research process and the findings are primarily associated with the world of science and the researcher. In design-based learning, in contrast, the objectives, development process and outcomes are strongly associated with the customer or user population. The differences

TABLE 6.1 The engineering design process vs. the scientific inquiry process

Engineering design process	Scientific inquiry method
Define the problem/need	State your question
Do background research	Do background research
Specify requirements	Formulate your hypothesis, identify variables
Create alternative solutions, choose the best one and develop it	Design experiment, establish procedure
Build a prototype	Test your hypothesis by doing an experiment
Test and redesign as necessary	Analyze your results and draw conclusions
Communicate results	Communicate results

between the engineering design process and the scientific method are presented in Table 6.1 (Tayal, 2013).

2.3 *Engineering Design: A Process of Optimization and Tradeoff*

Burghardt and Hacker (2004) described design as a pedagogical strategy that has great potential to:
- Engage pupils as active participants, giving them greater control over the learning process;
- Assist pupils to integrate learning from language, the arts, mathematics and science;
- Encourage pluralistic thinking, avoiding a right/wrong dichotomy and suggesting instead that multiple solutions are possible;
- Provide pupils with an opportunity to reflect upon, revise and extend their internal models of the world;
- Encourage pupils to put themselves in the minds of others as they think about how their designs will be understood and used (Resnick, 1998).

Burghardt and Hacker (2004) proposed the 'informed design cycle' that comprises the following 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-building activities that will help pupils identify the variables that affect the performance of the design and inform pupils' 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 the 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, carry out, and document reliable and accurate tests to assess the performance of the design solution.
7. *Redesign the solution with modifications*. Examine your design and look at the designs of others to see where improvements could be made. Identify the variables that affect performance and determine the concepts that underlie these variables. Explain how to enhance performance of the design using these concepts and variables.

8. *Communicate your achievements*. Complete a design portfolio or design report that documents the previously mentioned steps. Make a group presentation to the class justifying your design solution.

Stages 3 and 4, *Generate alternative designs* and *Choose and justify the optimal design*, are central to the engineering design model described above, because engineering is merely a process of optimization and tradeoff. 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 pupils to learn STEM ideas, but also gain competence in engineering design. They suggest emphasizing ideas such as optimization, reasoning about tradeoffs, troubleshooting and meeting criteria while staying within prescribed constraints.

2.4 *Problem-, Project- and Design-Based Learning*

Mills and Treagust (2003) suggested the following comparison between problem-based learning and project-based learning:
– Project tasks are closer to professional reality and therefore take longer than problem-based learning;
– Project work is more directed to the application of knowledge, whereas problem-based learning is more directed to the acquisition of knowledge;
– Project-based learning is usually accompanied by subject courses (for example, mathematics, physics or electronics), whereas problem-based learning is not;
– Management of time and resources by the pupils, as well as task and role differentiation, is more important in project-based learning.

Project-based learning is very close to design-based learning, but project work usually does not involve the optimization process, namely, creating several alternative solutions and choosing an optimal one, as required in DBL. In project work, pupils frequently develop a specific solution to a problem or a need, for example, an artifact or a system, to their liking.

2.5 *Systems Thinking*

System thinking is an essential facet of engineering design cognition (Lammi & Becker, 2013; Schunn, 2008). Jeon and Lee (2015) note that in a knowledge-based information society in the 21st century, systems thinking is a very important human resources skill in science and technology, which is required in STEM education in order to understand and solve complex problems. Technological systems are included as a component of national technology curricula and standards for primary and secondary education, as well as corresponding teacher education around the world (Hallström & Klasander, 2017; Barak, 2018). Technological systems might impact pupils' understanding and the learning possibilities of technology (Svensson, 2012; see also Chapter 9, this volume). An example of fostering system thinking in design-based learning is presented later in this paper.

2.6 *Applying Design-Based Learning in the Science Class*

Recent educational literature is increasingly presenting studies examining the potential contribution of DBL or PBL to improving science studies in school (Applebaum et al., 2017; Fortus et al., 2004). For example, Apedoe, Reynolds, Ellefson, and Schunn (2008) presented an eight-week high school curriculum unit, the *Heating/Cooling System*, in which engineering design is used to teach pupils central and difficult chemistry concepts such as atomic interactions, reactions and energy changes in reactions. The findings indicated that pupils made significant gains towards understanding the fundamental concepts of atomic interactions, reactions and energy while learning the unit. Moreover, the pupils' increased interest in engineering careers suggested that exposure to engineering design in the context of high school science is an effective way of encouraging pupils to consider engineering as a viable career option. Van Breukelen (2017; see also Chapter 5, this volume) suggests that it will be valuable to study teachers' implementation of concept learning in DBL.

In the following sections, we closely examine two case studies of applying design-based learning in school, one in the context of teaching science in middle school and the other in teaching mechatronics engineering in high school.

3 Case Study 1 – Design-Based Learning in Electronics in Junior High Schools

Doppelt, Schunn, Silk, Mehalik, Reynolds, and Ward (2009) explored a program in which junior high school pupils designed and built electrical alarm systems to learn electricity concepts over a five-week period using authentic engineering design methods. The program was developed by a research group at the Learning Research and Development Center (LRDC), University of Pittsburg, USA. The research aimed at exploring how DBL is implemented in junior high schools, and assists pupils in learning science concepts in electrical circuits. The study took place in the eighth grade of an urban, public school district, with the systems approach implemented in 51 science classes (18 teachers and 985 pupils). The control group included 15 science classes (five teachers and 271 pupils) that learned the same subject in the conventional scripted enquiry method. The research explored the learning process that took place in the experimental classes, pupils' achievements and attitudes, and teachers' viewpoints about the course. Data were collected by a pre- and post-course exam on electrical circuits, observations in the classes, interviews with teachers and pupils, and an analysis of the pupils' portfolios. In the following sections, we address the main aspects of implementing DBL in these science classes.

3.1 *Pupils' Design Task*

The pupils' task was to design an electronic alarm system of their choice. They were guided to work according the following 'seven design steps' (Mehalik, Doppelt, & Schuun, 2008):

1. Describe current situation.
2. Identify needs.
3. Develop criteria.
4. Generate alternative solutions.
5. Choose a solution.
6. Create prototype and test.
7. Reflect and evaluate.

The pupils worked on their design projects over a period of about five weeks, five hours a week, and designed alarm systems such as a "medication device" or "someone stole my stuff" alarm.

For learning electronics, pupils used kits that included connection wires, resistors, LEDs and batteries available in the lab as part of the original scripted inquiry curriculum, and additional components such as buzzers, thermistors and photo resistors.

The authors noted that the seven stages of systems design mentioned above were generated from the researchers' experience in systems engineering and design, supplemented by a review of the best practices of empirical studies of design. They wrote that in a typical systems design implementation, the 'reflect and evaluate' stage would involve going back through the entire process iteratively in order to improve and adjust the design specifications as new knowledge and problems are encountered (Mehalik, Doppelt, & Schuun, 2008). Although it was not possible to have pupils repeat a complete second iteration of the entire process, scaffolding for both the pupils and the teacher encouraged pupils regularly to go back, review, re-use and refine what they had produced and documented in the earlier stages of this overall process.

3.2 *Specifying System Requirements Decision*

Providing scaffolding for pupils and teachers is an important component for successful implementation of DBL (Cox et al., 2017). The researchers collaborated with the teachers in order to develop a learning module for pupils and a guide for teachers. As part of the design process, the pupils were required to specify their alarm system requirements in a table, which was included in the Alarm System learning module as illustrated in Figure 6.1.

My team's choice of alarm is: medication device

Table 2.2.2: Alarm System Requirements

Must have requirements	Nice to have requirements
timer	beeps when battery runs out.
rechargable battery	a light will go off.
volume control	water proof
on/off switch	a clock
battery holder	
wires	

FIGURE 6.1 An example of how a pupil specified the system requirements

3.3 *Using a Performance Scale for Choosing the Optimal Solution*

An important stage of the systems design process is selecting the optimal solution from several alternatives. The pupils learned to evaluate the performance of their system components/solutions by preparing a 'performance scale' table, as illustrated in Figure 6.2. In this example, the pupils examined three design alternatives: A-Chip (code), B-Video camera and C-Laser alarm.

Performance scale: 5=best; 4=good; 3=ok; 2=fair; 1=poor; 0=not at all

	Solutions / Requirements	A chip	B video Camra	C taser alarm
1.	induvival sensors	4	4	3
2.	mini chip	5	4	2
3.	The alarm	5	5	5
4.	remote control	5	4	2
5.	energy	5	5	5
6.	Ability to test	5	5	5
7.				
8.				
9.				
10.				
Sum	TOTAl:	29	27	22

FIGURE 6.2 Using a performance scale to evaluate the performance of alternative solutions on a scale of 1–5

Figure 6.2 shows how the pupils ranked the performance of each alternative (on a scale of 1–5) on six requirements that they considered to be important for their alarm such as 'innovative sensor' or 'mini chip'. In the present case, the total scores seen in Figure 6.2 indicated that alternative design A is the best one.

One should pay attention that in the two points described above, the pupils received empty tables to fill in. This approach is desirable for first-time pupils in the design process.

3.4 *Fostering System Thinking*

In the literature review, we have seen that one of the important objectives of technology education is fostering pupils' system thinking, especially in the era of rapid technological development affecting almost every aspect of our lives. In the case of systems design-based learning discussed in the present work, the pupils learned to describe their alarm design system as being comprised of sub-systems, as seen in Figure 6.3.

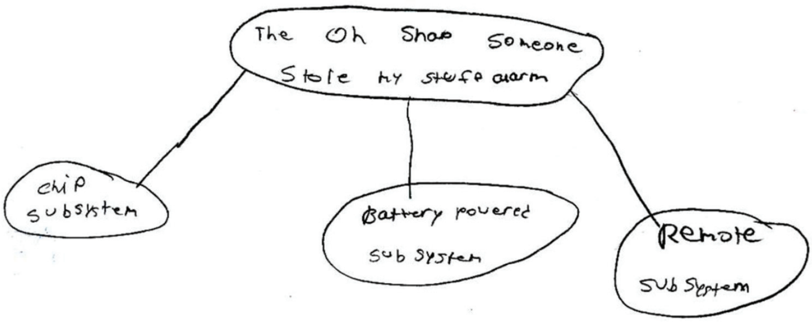


FIGURE 6.3 An example of system thinking: the pupils describe their "The Oh Snap Someone Stole My Stuff Alarm" alarm systems as being composed of three sub-systems: Chip, Battery power and Remote

3.5 *Constructing and Testing*

All pupils constructed the electronics circuit they designed on a springboard, as seen in Figure 6.4, which was part of the standard materials available in the science lab.

From the viewpoint of learning science, it is enough to assemble the circuit as illustrated in Figure 6.4 and there is no need to build a technological product.

3.6 *Reflecting on the Project Design*

The pupils were required to create a portfolio documentation of their alarm system according to the following guiding questions, as seen in Figure 6.5.

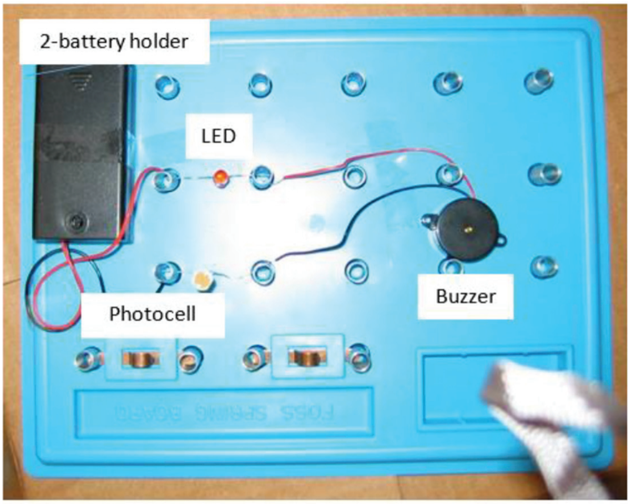


FIGURE 6.4 An example of constructing an alarm system on a springboard

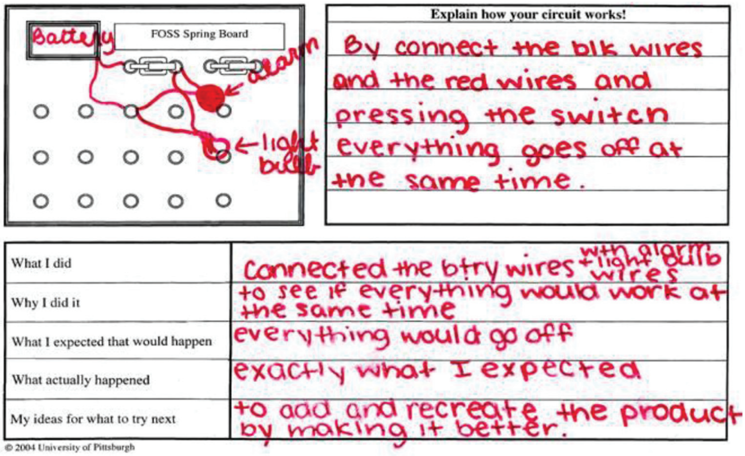


FIGURE 6.5 An example of how pupils reflected on their design through guiding questions

– What I did.
– Why I did it.
– What I expected that would happen.
– What actually happened?
– My ideas for what to try next.

Observing pupils' activities and portfolios in 30 classes demonstrated that they followed the design process quite well. Many of the pupils documented their work individually and then integrated the work of the group members into a summative documentation for presentation in the class.

3.7 *Teachers' Professional Development*

Development of the DBL program included a Professional Developed (PD) program for teachers comprised of five four-hour workshop sessions (Doppelt et al., 2009). One PD session took place before the teachers implemented the new program in their classes. Three sessions were conducted during class implementation of the experimental program, and the last after completing the implementation in the classes. The study involved three groups of teachers: 13 teachers who implemented the reformed design-based curriculum and attended the PD program; five teachers who implemented the reform curriculum without participating in the PD program; and five teachers who continued to teach the chapter of electricity according to the conventional inquiry-oriented curriculum mainly through class lessons and pre-designed lab experiments. All PD sessions (total of 20 hours) were videotaped.

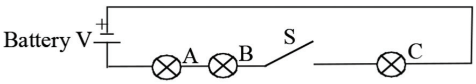
Analysis of the workshops' videos shows that the teachers devoted about 39% of the course to learning content knowledge in electronics, 20% to teamwork, 12% to reflection, and the remainder to discussions, presentations and administrative issues. Having the workshop distributed during the implementation of the reform curriculum gave teachers the opportunity to bring challenging examples from their classrooms. Teachers received help with electronics content, alternative instructional strategies, and decisions about when and where each strategy is appropriate. In this community, the teachers felt safe to admit their limited content knowledge, were open to learning pedagogical interventions and were able to address their pupils' questions with confidence. As a result of these experiences, the teachers changed their practice in ways that were more consistent with the reform curriculum. Furthermore, according to observations of 440 lessons across 26 classes, the researchers reported that the teachers implemented in their actual classes the same modes of learning as demonstrated during the workshops (Doppelt et al., 2008, 2009).

3.8 *The Effect of Design-Based Learning on Understanding Science Concepts*

The researchers explained how pupils in the design-oriented class learned the scientific concepts of electrical circuits. Through their attempt to use the various components available to them in order to embody their design plans in working devices, they tried to understand how each of the components works and how their performance could be improved. This is a process of discovery and inquiry, and it takes place within the context of creative design thinking to which pupils relate because they are creating from their needs and interests. The teachers were encouraged to explain a science concept to a pupil only after the pupils had attempted to explore the concept and tried different ideas and configurations during the circuit construction. This is in major contrast with the conventional scripted inquiry approach that provides step-by-step instructions by the teacher for most aspects of an investigation. Scripted inquiry is mainly organized according to the presentation of science concepts in a way chosen by curriculum designers instead of by modes of thinking.

3.9 *The Science Knowledge Exam*

After completing the learning of the system design program in the experimental classes and the inquiry-oriented conventional program in the control group, the pupils in both groups answered a final exam on understanding science concepts such as voltage, current, resistance, parallel circuits, series circuits, batteries, lamps, resistors and conceptual relationships in Ohm's Law. The knowledge assessment included 20 items. The internal reliability of the test was high (Cronbach Alpha = 0.80). An example of a question on scientific concepts is illustrated in Figure 6.6.



Which bulb(s) are lit in this circuit?
A
B
C
A & B but not C
None of the above.

FIGURE 6.6 An example of a question in electricity concepts from the knowledge exam

Pupils in the experimental and control classes answered the exam pre- and post- learning the course, and the results suggest that pupils in the experimental design class showed superior performance over pupils in the control classes in terms of knowledge gained in core science concepts, engagement and retention. For example, the design group showed a mean gain of 18% between the post- and pre-course exams, versus a gain of 7% in the inquiry (control) group gain ($t = 2.02$; $p < 0.01$).

3.10 *The Design Knowledge Exam*

The knowledge test also included four questions related to the design process, as illustrated in Figure 6.7.

Because you often play music in your room, sometimes you do not hear the phone ring. You have decided to add to your phone a light that will flash in your room when the phone rings. You sat down and wrote what your design for a phone light needed to be able to do.

You decided that your design must have:
– a bright light;
– a light that blinks when the phone rings; and
– a light that runs on 12 Volts because that is what the phone has available.

Things that would be nice to have in your design include:
– a light that is easy to connect to your phone;
– the light to be red in color; and
– a light that will last as long as the phone still works.

You researched four possible options for the light. Here is what you found:

Light A	**Light B**	**Light C**	**Light D**
Bright yellow	Medium bright red	Bright red	Bright green
Lasts a short time	Long-lasting	Long-lasting	Long-lasting
Difficult to connect	Easy to connect	Easy to connect	Easy to connect
Does not blink	Blinks when phone rings	Does not blink blink when phone rings	Blinks when phone rings
12 Volts	24 Volts	12 Volts	24 Volts

3. Which light does the best job of meeting the necessary requirements of your design?
a) Light A
b) Light B
c) Light C
d) Light D
e) Both Light C and Light D work

4. Explain your answer to Question 3:

____

____

____

Pupil ID: ___________ Date: ___________

FIGURE 6.7 An example of a question in design from the knowledge exam

Analysis of pupils' scores in pre- and post-knowledge tests showed two interesting results, as described in Figure 6.8.

Figure 6.8 shows the gain (difference) in scores between the post-course test versus the pre-course test regarding pupils whose teachers participated in PD or did not (NPD). Scores on science questions show an improvement of 18% in

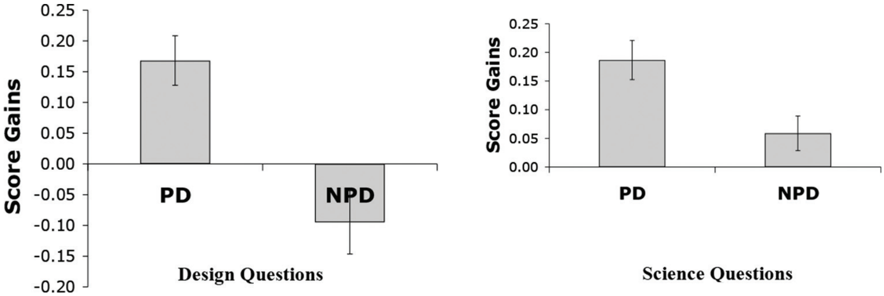


FIGURE 6.8 Pre- and post-gains in pupils' scores in science questions and design questions according to teachers' participation in the Professional Development (PD) program

PD and 6% in NPD classes. In the scores on design, however, the average score increased by 16% in PD classes but decreased by 9% in NPD classes. These results indicate the importance of providing a professional development program for teaching design, perhaps more than for teaching science by science teachers. Furthermore, the researchers also showed that both pupils' engagement and achievements were significantly higher for low-achieving pupils (Doppelt et al., 2008).

3.11 *Summary of Case Study 1: Design-Based Learning in Electronics in Junior High Schools*

As previously mentioned, the main objective of this chapter is to closely examine specific examples of applying DBL in school. In the first example, we focused on a program for teaching design in an electronics environment. The program was designed and accompanied by a professional team from academia, and included close monitoring of pupils' activities and achievements, with a focus on science teachers' integration in teaching engineering design. The DBL program under discussion puts into practice several concepts the educational literature stresses for promoting meaningful learning in school, such as contextual learning, collaborative learning, project-based learning, active and reflective learning, and fostering analytic and creative thinking.

Following the observations in the current study, we present in Figure 6.9 the 'real' model of the design process the pupils went through, including the approximate time the learners spent on each step.

1. *Identifying needs*: presenting the system purpose, needs and requirements; describing the model by means of pictures and sketches (two hours).
2. *Generating alternatives and creative solutions*: describing the system structure and the subsystems; documentation of various solutions (four hours).

3. *Analyzing solutions and selecting a design*: comparing several solutions and choosing the optimal design (six hours).
4. *Planning and constructing*: building a working model of the system; troubleshooting and solving problems (10 hours).
5. *Evaluating and reflecting*: examining the final product's features compared to the set goals; reflecting on the design process; identifying successes or difficulties in the product development and suggesting improvements (two hours).

Figure 6.9 illustrates that the pupils did not work in a linear process as steps 1–5 seem to be; they moved iteratively back and forth through the five stages, depending on the success or difficulties they experienced in doing the work.

The "forward" arrows in Figure 6.9 indicate the core of the process, and the "backward" arrows are optional and flexible.

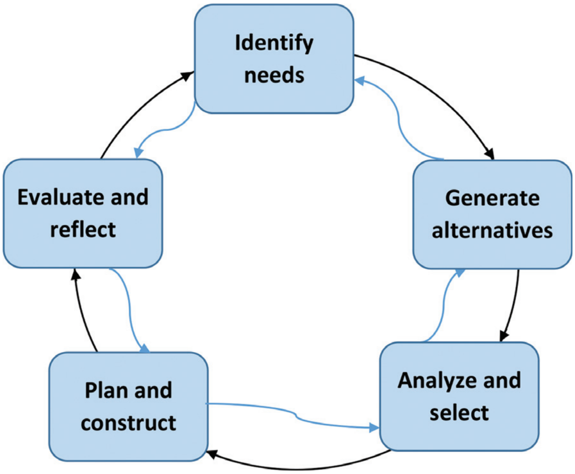


FIGURE 6.9 Main stages of the design process, including step-by-step progress and return to previous steps as needed

4 Case Study 2 – Design-Based Learning in Mechatronics Engineering Studies in High School

4.1 *Engineering Studies in Israeli High Schools*

The second case study we address in this paper relates to the application of DBL in mechatronics engineering studies in Israeli high schools (10th, 11th and 12th grades; 16–18 years old). At the beginning of high school, pupils choose to major in a specific area in science or technology such as biology, physics, biotechnology, computer engineering, electronics engineering, or mechatronics engineering. All the pupils take general compulsory subjects such as math, Hebrew, English, history and citizenship. Towards graduation from high school, all pupils in the engineering tracks are required to submit a final project for the *Bagrut* (high school matriculation exams). While in areas such as computer engineering or electronics engineering, pupils are engaged in project-based learning (Barak, 2002; Barak & Shachar, 2008), the mechatronics program adopted the DBL approach, on which we focus in the present paper (Doppelt, 2009). Doppelt (2005) described DBL's implementation in school with a previous version of a formative assessment scale that schools were using (Barak & Doppelt, 2000).

4.2 *Design-Based Learning in Mechatronics Engineering in High School*

As noted above, pupils study mechatronics engineering for three years (10th–12th grades), including courses such as physics, control systems, mechanics and programming. The mechatronics courses take place for 15 hours a week, which is about one third of the high school hours. Design-based learning takes place for two hours a week every year during 10th & 11th grades. During the last year in high-school (12th grade) students are engaged in DBL towards their final graduation project. Similar to the model described in Figure 6.9, the design process has been implemented in mechatronics studies for over 20 years in about 240 classes, involving 4,500 pupils each year.

In the 10th grade, pupils study subjects such as force and motion, statics, logic, basic programming in Lab-VIEW or C, control systems and computer-aided design (CAD). They select the general framework or subject of their project, investigate the subject, select materials and prepare a mini project. In the 11th grade, the pupils continue to study the theory of mechanical systems, advanced control systems, electronics, pneumatic and hydraulic systems, and programming. They work in pairs or small teams to prepare initial parts of their project, for example, mechanical construction, electronics and programming. In the 12th grade, the pupils continue learning the theoretical subjects mentioned above and additional subjects such as advanced programming and control systems. They prepare a final version of their project within the requirements of the national *Bagrut* matriculation exams. Following are some examples of pupils' projects on mechatronics:

– Mechatronics fitness room;
– Theo Jansen's walking mechanism;
– Various parking systems;
– Systems for learning basic arithmetic;

- Systems for learning Johannes Kepler laws;
- Fire-fighting home robot;
- Basketball robot;
- Guided look robot;
- Window cleaning robot;
- Mechatronics shirt printer.

4.3 *An Example of a Pupils' Project: Underwater Glider*

The following example illustrates the complexity of projects pupils are designing (2019–2020). In one of the schools, a group of five pupils designed and constructed an underwater glider aimed at exploring seas and lakes. Figure 6.10 shows the final glider as the pupils documented in their project booklet.

FIGURE 6.10 The glider's inner sub-systems (left) and the final product on exhibition (right)

Table 6.2 shows part of the user requirements and engineering requirements the pupils defined.

The pupils created a similar requirements table for each of the glider's sub-systems.

Figures 6.11 and 6.12 show parts of the glider's mechanical and control design.

Figure 6.11 presents the calculations the pupils performed for controlling the glider's motion. They asked for the teacher's help, and he changed his role from being a mentor to a lecturer to explain engineering concepts towards achieving this goal.

Figure 6.12 shows a classical block diagram of a feedback control system that the pupils adopted from a control systems book. The text under the block diagram the pupils wrote says: "This is a closed loop control system that measures the pressure and activates the piston accordingly in order to change the water volume in the glider. This causes the glider to rise or sink".

The pupils worked on the glider project over a period of three years (10th–12th grades) in the following process:

TABLE 6.2 Examples of user's and engineering requirements for the Glider

User requirements	Engineering requirements	Must have	Nice to have
Water sealed	Water sealed under pressure of 5 bar (50 m depth)	Yes	
Automatic system	Autonomous system	Yes	
Easy to handle and manipulate	Sub-systems will be designed in a symmetrical approach in order to keep the center of gravity at the center of the glider and leave space between the components to make it easy to reach for maintenance and malfunction diagnostics		Yes
Easy to convey	Glider weight will not exceed 50 kg	Yes	
Ability to monitor several parameters	Ability to identify required parameters in high resolution	Yes	

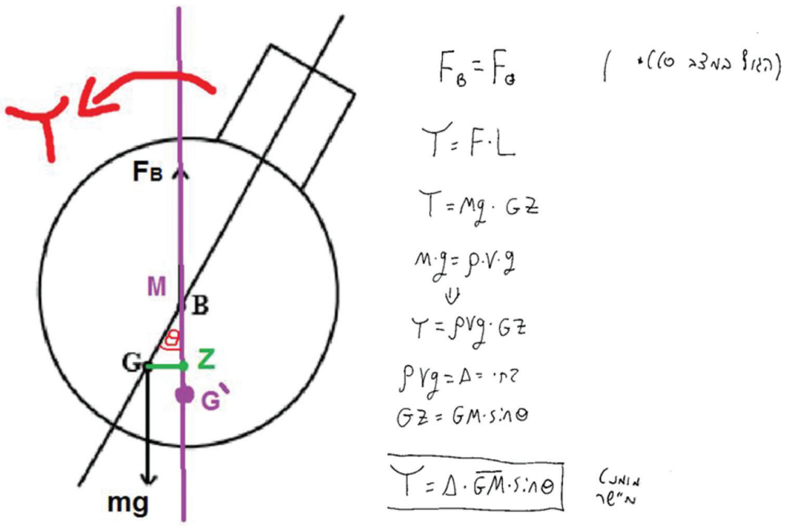


FIGURE 6.11 Calculation of the torque T (moment) (N·m) required for glider navigation

– During the first year, they initiated the first stage of the DBL, collected information, explored ideas, and discovered that they needed to learn about hydrostatics, hydraulics and aerodynamics.

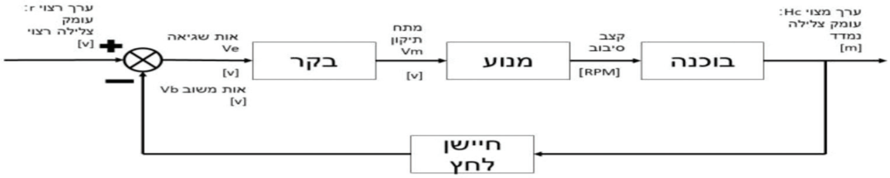


FIGURE 6.12 Block diagram of close-loop control of diving depth

– In the second year, they continued the stages of DBL by suggesting a number of solutions and choosing the optimal one, justifying their selection by engineering calculations based on the theory they had learned, selecting components for their project, for example, motors and mechanical transmission, and prepared initial parts of their programming.
– Throughout their last year in high school, the pupils coped with final design details, mechanical construction, electronics construction, programming and troubleshooting. In parallel, they learned on their own further theories of mechanical engineering, electronics and computing, and prepared a printed booklet on their project. At the end of the 12th grade, the pupils submitted their projects and underwent an oral exam given by an external examiner sent by the Ministry of Education to the school.

The main tool that guided the pupils in the design process revealed above was the Formative Assessment Scale described in the following section.

4.4 *Using the Formative Assessment Scale (FAS) for Systems Design and Evaluation*

The Formative Assessment Scale (FAS) shown in Appendix A is a tool for evaluating project work by pupils' self-evaluation, teachers and external examiners sent by the Ministry of Education. FAS consists of 54 items in the following six categories:

1. *Problem definition* (items 1–7).
2. *Gathered information* (items 8–15).
3. *Alternative solutions* (items 16–26).
4. *Choosing a solution* (items 27–33).
5. *Implementing the solution: manufacturing, assembling, controlling* (items 34–48).
6. *Summative assessment* (items 49–54).

Table 6.3 shows examples of two items from the FAS. A full version of the scale is attached in Appendix A. The evaluation by FAS takes place by marking one of the levels Not True/Mostly True/True/Very True beside each item in the scale.

TABLE 6.3 The two first items from the Formative Assessment Scale (FAS) for evaluation of the design process

	Main criteria	What is expected of the pupils and the teachers to assess during the learning process while pupils are using the design-process throughout the school year	Not true	Mostly true	True	Very true	Calculated grade
1	Problem definition	The problem is authentic or relevant to one of the pupils on the team and is worth solving.					
2	Problem definition	The problem is clearly defined and written in a simple and understandable language with references to the needs for solving the problem					
3	...						

The pupils carry out a team self-evaluation with FAS about five times during each school year; the teacher and the external examiner use the FAS for evaluating pupils' work, including in the final *Bagrut* matriculation exam. In the past decade, about 80 high schools throughout the country successfully adapted FAS, and it became the major tool for preparing about 1,500 pupils a year for the official *Bagrut* exam in mechatronics.

It is worth noting that during the years 2010 and 2020, the number of pupils taking mechatronics class in Israeli high schools almost doubled. Part of the explanation for this phenomenon could be attributed to introducing design-based learning, the rich and attractive projects the pupils prepare, and the systematic use of FAS in the mechatronics class.

4.5 *Teachers' Professional Development*

The Ministry of Education provides a regional professional development course of 30–60 hours for mechatronics teachers every year. About half of the course time is devoted to learning updated content knowledge in mechanical and mechatronics engineering, for example, using LabVIEW for Arduino, concepts of mechanical design, computer-aided design (CAD), control systems, hydraulic systems and pneumatics systems. About half the time in the course is dedicated to learning pedagogical knowledge, for example, project-based learning, design-based learning, using the Formative Assessment Scale (FAS) by the pupils and the teacher, and fostering pupils' 'soft skills' such as critical thinking, creativity, reflection and collaboration in class.

4.6 *Renewing Design-Based Learning in Israeli High Schools*

The Ministry of Education and academic experts in technology education are encouraging schools to extend, deepen and refresh DBL in line with today's technological and cultural changes. Following are directions for updating DBL in mechatronics and other technology education areas.

- In the future, pupils will document all stages of project design online only, instead of preparing the traditional printed booklet on the project. This change will also enable pupils to share knowledge, collaborate with their peers, and reflect on the project development online. Online documentation will take place using a personal webpage the Ministry of Education provides to each pupil, a project website the pupils can prepare, or other professional tools for data storage and sharing.
- Schools labs, and particularly DBL, will address state-of-the-art technologies, for example, Raspberry-Pi technology, image-processing technologies, autonomous robots and aviation technologies such as drones.
- Future DBL will strive to cope with interdisciplinary projects suitable for pupils and teachers majoring in different areas, such as mechanical engineering, electronics, computer science, physics and industrial design arts. This may be a significant change compared to today's situation, in which pupils in a class have little opportunity to interact with other pupils majoring in different technological areas.
- An important expected change in DBL is to require all schools to start project design from the first year in high school, as in the example discussed in the present paper. In this method, project work will spread over three years of high school (10th, 11th and 12th grades), which will enable pupils to gain more theoretical knowledge, technical skills and design competences.

5 Discussion

In the literature review section at the beginning of this chapter, we have seen that DBL is derived from the constructivist view of learning. Burghardt and Hacker (2004) described the advantages of design as an instructional strategy as follows (Soloway, 1994; Papert, 1993; Resnick, 1998):

> In recent years, there has been a growing recognition of the educational value of design activities in which pupils create external artifacts that they share and discuss with others. A synthesis of the literature reveals that pedagogically solid design projects involve authentic, hands-on

tasks; use familiar and easy-to-work materials; possess clearly defined outcomes that allow for multiple solutions; promote pupil-centered, collaborative work and higher order thinking; allow for multiple design iterations to improve the product; and have clear links to a limited number of science and engineering concepts.

In the present chapter, we have seen how the above-mentioned pedagogical advantages of DBL took place in two quite different learning frameworks. One example relates to the implementation of DBL in a short course of about five weeks within 26 science classes in American middle schools. The pupils' task was to design (plan, construct and evaluate) an electronic alarm system based on conventional school electronics kits, plus special components such as buzzers, thermistors and photo resistors. Since this course was relatively short and the learning environment was quite limited, this case serves as an example of applying a small-task DBL course in school. Still, the pupils coped successfully with all the design stages by using ready-made tables for documenting their design work (as seen in Figures 6.1–6.3), and a given scale for self- and teacher evaluation.

The second example this work addressed is the case of implementing DBL in mechatronics engineering studies in Israeli high schools. This implementation began 20 years ago with five schools and has expanded today to about 80 schools involving 1,500 pupils a year. The pupils cope with a design-based project during their final year (12th grade) or over three years (10th–12th grades) of high school. Pupils prepare projects such as robotics and computer-controlled systems and attend an oral exam on their project given by an external examiner from the Ministry of Education. This case is obviously an example of applying a broad DBL program in schools. In this example, the major tool that guides pupils', teachers' and official examiners' work is the Formative Assessment Scale (FAS) for design-based learning, documentation and evaluation. We have seen that the scale includes 54 items in six categories: *defining the problem, gathering information, preparing alternative solutions, choosing a solution, implementing the solution,* and *summative assessment*. Pupils, teachers and examiners have been using this scale successfully for about 15 years, and it is updated from time to time according to feedback obtained from the field. We believe that the widespread application of DBL in mechatronics studies in Israeli comprehensive high schools is unique, and we could not find similar examples in other countries. In Israel, there is a long tradition of project-based learning in technological areas such as electronic and mechanical engineering (Barak & Doppelt, 2000; Doppelt, 2005; Mioduser & Bezer, 2008), but only mechatronics studies clearly apply the design-based learning model as discussed in the current article.

6 Conclusions

In this article, we have seen two cases of applying design-based learning in school. First, a small-task program of 20–25 hours implemented in 26 science classes; and second, a three-year program in mechatronics engineering studies implemented in about 100 classes involving 1,000 pupils. The findings from this study may contribute to the literature on DBL, and technology and engineering education in general, in five points:

Firstly, in the two examples under discussion, the design process consisted of the 'classical' stages (in various versions): *identifying needs; generating alternative solutions; analyzing solutions and selecting the optimal design; planning and constructing; evaluating and reflecting*. However, in both examples we have seen, pupils worked through an iterative process in which they could move forward or backward from/to any stage of the product development, rather than an obligatory linear process. This is an essential route in case the pupils encounter difficulties, the results are unsatisfactory or new ideas arise.

Secondly, the two examples of design-based learning discussed in this article indicated that a key element in the design process is presenting several alternative solutions and systematically selecting the optimal solutions, given the strength and weakness of each option. This is the opportunity for pupils to learn that engineering has to do with optimization and tradeoff. Engineers often face a situational decision that involves diminishing or losing one quality of a design in return for gains in other aspects. It is worth noting that although project-based learning is very close to DBL, project-based learning frequently places less emphasis on the engineering process of presenting several solutions and systematically choosing the optimal solution. In fact, PBL differs from DBL merely in that point.

Thirdly, the curriculum developers of the two programs we have seen prepared detailed instructional materials for pupils and teachers for application of the design process. That includes, for example, a performance scale table for presenting alternative solutions and selecting the optimal one, and the Formative Assessment Scale (FAS) in mechatronics studies that directs pupils and teachers throughout the design process. These instructional materials are critical in the application of DBL among a variety of pupil populations and achieving the goal of developing pupils' skills related to problem solving, creativity and self-directed learning.

Fourthly, we have seen that providing professional development courses for teachers is a vital component of introducing DBL into the classroom. Teachers need to update their technological content knowledge, for example, in electronics, mechanics and computing. In parallel, professional development courses must address teachers' pedagogical knowledge related to the application of design-based learning and project-based learning in school. A PD course needs to deal with questions such as the teacher's role in the DBL classroom, providing feedback to pupils, or using digital technologies for teaching and learning. Teachers' technological and pedagogical knowledge is the most important factor that might encourage or hinder the integration of DBL in traditional schooling.

Fifthly, DBL which was presented in both case-studies, was implemented in three pedagogical lenses:

- A learning material development platform for engaging teachers in design-based learning
- Teachers use the same platform to engage pupils in DBL.
- Creating FAS that assisted both teachers and pupils to implement DBL as a method to improve learning, thinking skills and presentation and teamwork.

These three lenses assisted teachers to engage pupils in concept learning of design, for example teamwork, iterative cycle of design and optimization to improve creation. In addition, the pupils gained conceptual knowledge in Mechatronics and Electronics such as: Electronic circuits, sensors, closed-loop control, and mechanisms which pupils implemented in their project-design.

Finally, we have raised some thoughts about introducing innovation to DBL, for example, encouraging pupils to deal with interdisciplinary projects and promoting collaboration of pupils who major in mechatronics, electronics, computer science and industrial design arts. In addition, the traditional method for implementing DBL could greatly benefit from using digital technologies throughout the project work. For example, pupils create a website on their project on which they save design details, drawings, calculations, test findings, as well as pictures and videos about the system operation. The digital environment might also promote online sharing of information and collaborative work between pupils on a team. These innovations may take DBL together with technological and social changes occurring today.

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Appendix A: Formative Assessment Scale (FAS)

Put 1 or 0 in one of the ranking cells for each row

	Main criteria	**What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year**	**Not rue**	**Mostly true**	**True**	**Very true**	**Calculated trade**
1	Problem definition	The problem is authentic or relevant to one of the pupils in the team and is worth solving it.					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
2	Problem definition	The problem is clearly defined and written in a simple and understandable language with references to the needs for solving the problem					
3	Problem definition	There is a translation of the verbal problem to a block diagram presenting the problem solving as a function of information which is needed to the system to function properly, energy which is converted to functions of the sub-systems and materials which the system processes or are needed to construct the system.					
4	Problem definition	The problem and its solutions was translated to requirements table which characterize the system by engineering requirements that enable engineering development of the system with regards to physical variables or engineering calculations which are needed in the process of decision making for selecting the system components or sub-systems					
5	Problem definition	The needs that the system solves are defined properly					
6	Problem definition	There are reasonable various solutions to the sub-systems					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
7	Problem definition	The chapter, defining the problem, includes evaluations of the success and efficiency of defining the problem					
8	Gathered information	Inquiry questions which are relevant to the problem were defined					
9	Gathered information	Several references were used to gather information that is needed for solving the problem					
10	Gathered information	The gathered information is directly relevant to the engineering development of the system					
11	Gathered information	Pupils documented a learning process in which they analyzed similar systems or phenomena from which they learned scientific and/or engineering principles which may assist them in developing the system					
12	Gathered information	The alternative solutions or systems used and documented as a source to deep learning via analyzing the system structure and functioning, and control processes					
13	Gathered information	The information processing includes discussion of physical and engineering principles which is required to learning and understanding of the system's development					
14	Gathered information	The gathered information was helpful to continue the development of the design process					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
15	Gathered information	The chapter includes evaluation of success and efficiency of the gathered information					
16	Alternative solutions	At least three different solutions are documented					
17	Alternative solutions	The first solution is applicable and clearly defined and presented					
18	Alternative solutions	The second solution is applicable and clearly defined and presented					
19	Alternative solutions	The third solution is applicable and clearly defined and presented					
20	Alternative solutions	The gathered information assist in shaping and documenting the first solution					
21	Alternative solutions	The gathered information assist in shaping and documenting the second solution					
22	Alternative solutions	The gathered information assist in shaping and documenting the third solution					
23	Alternative solutions	Documenting a team's brain storming supports various alternative solutions					
24	Alternative solutions	The alternative solutions are composed from sub-systems which each of them were examined against alternative sub-systems					
25	Alternative solutions	The alternative solutions describe full system which enables a comprehensive solution of the problem					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
26	Alternative solutions	The chapter includes evaluation of success and efficiency of presenting various alternative solutions					
27	Choosing a solution	There is a thoughtful use of thinking tools and/or decision matrix for choosing a solution for each of the sub-systems					
28	Choosing a solution	Criteria or requirements for choosing a solution were selected					
29	Choosing a solution	The criteria were ranked proportionally to the importance of evaluating the solution					
30	Choosing a solution	The gathered information was helpful for choosing a solution and assisted in determination of the rank of the requirements					
31	Choosing a solution	There is a full and justified documentation for decision making					
32	Choosing a solution	There is a comprehensive description of the selected solution with explanations of the manufacturing and/or assembling and/or controlling of the system					
33	Choosing a solution	The chapter includes evaluation of success and efficiency of choosing the solution					
34	Implementing the solution: Manufacturing, assembling, controlling	There is a clear description of modifications which were made during the construction pf the system					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
35	Implementing the solution: Manufacturing, assembling, controlling	The gathered information was helpful for constructing the system					
36	Implementing the solution: Manufacturing, assembling, controlling	There is detailed documentation about manufacturing and/or assembling and/or controlling of the system via pictures and/or computerized modeling or engineering drawing of several mechanisms and/or important components which their functioning is explained near the picture.					
37	Implementing the solution: Manufacturing, assembling, controlling	Selecting transmission and/or sensors is documented properly					
38	Implementing the solution: Manufacturing, assembling, controlling	There is a documentation of algorithms of the software that was developed for controlling the system					
39	Implementing the solution: Manufacturing, assembling, controlling	there is a description of input/outputs table and components that are connected to the controller					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
40	Implementing the solution: Manufacturing, assembling, controlling	The controlling program and/or algorithm is efficient					
41	Implementing the solution: Manufacturing, assembling, controlling	There is a detailed explanation of the computer program and/or algorithm					
42	Implementing the solution: Manufacturing, assembling, controlling	Friendly human-machine interface is documented					
43	Implementing the solution: Manufacturing, assembling, controlling	There is at least one block diagram of a controlling sub-system					
44	Implementing the solution: Manufacturing, assembling, controlling	A closed-loop control is used for each of the system variables					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
45	Implementing the solution: Manufacturing, assembling, controlling	Engineering Modeling using computer aided design software show system and/or sub-systems design using correct engineering drawings of important sub-systems or schematic drawings of important electrical and/or hydraulic and/or pneumatic and/or mechanical sub-systems are presented					
46	Implementing the solution: Manufacturing, assembling, controlling	The final prototype is close to a solution which is able to practical application					
47	Implementing the solution: Manufacturing, assembling, controlling	The final prototype meets the problem definition and/or function properly					
48	Implementing the solution: Manufacturing, assembling, controlling	The chapter includes evaluation of success and efficiency of the construction and/or manufacturing and/or assembling of the system					
49	Summative assessment	The final documentation was handed to the teacher a week before the external examination					
50	Summative assessment	The documentation is aesthetic					

(*cont.*)

	Main criteria	What is expected from pupils and teachers to assess during the learning process, while pupils are using the design-process along the school year	Not rue	Mostly true	True	Very true	Calculated trade
51	Summative assessment	A digital file is attached to the printed documentation					
52	Summative assessment	Presentation and/or video which are presented in the examination is not a copy-paste of the documentation					
53	Summative assessment	The documentation is written and edited according to the formative assessment scale					
54	Summative assessment	There is a clear and corrected language use in the documentation					