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The Effect of Robotics Activities on Learning the Engineering Design Process

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Abstract. This paper describes a study of students' meaningful learning of the engineering design process during their participation in robotics activities. The population consisted of middle-school students (ages 13–15 years) who participated in the FIRST® LEGO® League competition. The methodology used was qualitative, including observations and interviews. The analysis was based on the Revised Bloom Taxonomy. Almost all the groups demonstrated meaningful learning, although some reached higher levels than others. Most of the groups demonstrated the understanding/applying level during each of the design process phases (searching and decision making, construction and testing, diagnosing and debugging), some demonstrated the analyzing/evaluating level, but only a few demonstrated the higher level of creating. Factors that seemed to play a role in the students' learning include: (a) the teaching or mentoring style; (b) the absence of a robotics textbook; (c) the extra-curricular competition-oriented nature of the activities; and (d) the unstable nature of the design of the robot.

Keywords: Robotics, engineering design process, middle school, meaningful learning, Revised Bloom Taxonomy, representational model.

1. Introduction

Educators have suggested incorporating technology such as robotics into schools at many levels from kindergarten (Elkin, Sullivan and Bers, 2014), through middle school to college (Anderson *et al.*, 2011). Experience in designing, building, and operating robots promotes development of problem solving skills and teamwork (Verner and Ahlgren, 2004). Competitions like the FIRST® LEGO® League (FLL) are popular robotics activities in schools. Most of the existing literature (e.g., Verner and Ahlgren, 2004; Lauwers *et al.*, 2009; Kaloti-Hallak, Armoni, and Ben-Ari, 2015a) shows that students can be motivated and enthusiastic about participation in robotics activities. However, there are few empirical studies that demonstrate improvement in students' learning of

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science, technology, engineering and mathematics (STEM) in general, and engineering in particular. This paper focuses on the engineering discipline, with emphasis on the design process, as a part of a larger research project that investigated students' learning, attitudes and motivation in the context of robotics activities (Kaloti-Hallak, Armoni, and Ben-Ari, 2015a; 2015b).

The research questions are:

a. What knowledge on the engineering design process do students acquire through the robotics activities?
b. To what extent is the students' learning of the engineering design process meaningful?

A survey of previous work (Section 2) is followed by the presentation of the methodology in Section 3. Section 4 describes data analysis and is followed by the findings in Section 5. Sections 6 and 7 contain the discussion and conclusions.

2. Background

2.1. *Robotics in Education*

Robots have been used in both community outreach programs and academic institutions at all educational levels (Anderson *et al.*, 2011). Robots, as tangible computing devices, inherently show students how the programs that they write can impact the real world. They facilitate hands-on activities and improve the quality of instruction (Virnes, Sutinen and Kärnä-Lin, 2008). Such activities foster interdisciplinary explorations and personal interaction (Bers, 2008). Robots are used to motivate students' interest in STEM (Lauwers, Nourbakhsh, and Hamner, 2009). This was demonstrated by Ben-Bassat Levy and Ben-Ari (2017) who compared participants in two programs intended for middle-school students, one program that included robotics and a second program that did not. Students in the first program tended to continue studying STEM more than the students in the second program.

Jung and Won's systematic review of research on robotics education (2018) pointed at a second approach, which aims at learning per se. It takes advantage of the interdisciplinary nature of robotics and the common teaching contents and objectivities shared by robotics education and STEM education, and thus aims at teaching robotics to enhance students' knowledge, particularly STEM knowledge.

As noted in the introduction, our work is consistent with this perspective, building on the interdisciplinary nature of robotics as a bridge to STEM education.

However, the success of this approach can also depend on the teaching strategy. Hynes (2008) investigated the engineering knowledge and pedagogical content of middle-school math and science teachers who used LEGO robots to teach the design process. They showed that teachers rarely used math or science knowledge explicitly to make connections to engineering.

2.2. *Robotics Activities*

One of the most widely used educational robots is the LEGO® Mindstorms® kit, which contains LEGO® bricks and an onboard computer, as well as motors, gears and sensors. Programs are written on a personal computer using a visual programming environment called LabView and downloaded to the onboard computer, so that the robot can run untethered.

Even though the LEGO® company is primarily a designer and manufacturer of toys, LEGO®-based robotics activities were shown to be more than just playing with toys. Chetty's views regarding LEGO®-based robotics as an educational tool that enables learners to engage with "real-world problems" (2015), led her to incorporate LEGO®-based robotics activities in her educational robotics research project. The aims of the project were: "Firstly, to further reinforce fundamental computer programming concepts that had been partially developed. Secondly, to increase interaction between learners and generate higher motivation and interest in computer programming" (Chetty, 2015, p. 111). Her aims were somewhat similar to ours: to achieve meaningful learning, as well as to induce positive affective effects. Her findings indicated some improvement in problem solving and algorithmic skills, a significant increase in collaboration, a high level of excitement and motivation, and an increase in learners' confidence.

Most robotics activities are competitions, such as the yearly FIRST LEGO League (FLL) competition (`http://firstlegoleague.org`) for children aged 9–14, although some schools have integrated robotics into their curriculum. Each year the FLL competition has a different theme, such as assisting senior citizens, helping people deal with natural disasters; all the missions relate to the theme. The competition consists of three parts: 1) The design and construction of a robot that fulfills missions in a given scenario; 2) A scientific project where students solve a problem related to the scenario; 3) The development of core values that emphasize teamwork. Our research focuses on the design and construction of the robots.

Tougaw and Will (2005) showed that competitions promote teamwork. Melchior *et al.* (2005; 2015) evaluated the affective aspects of the FLL competition. The participants reported increased interest in and understanding of the role of STEM, improved attitudes towards school, and had a more positive outlook on their capabilities and future prospects. Most participants reported gains in their ability to work with others, finding information, managing time, using trial and error to solve problems, and giving presentations.

Breuch and Fislake (2018) report on a large-scale project in Germany where LEGO® robot sets and support for participating the FLL competition were given to 108 secondary and vocational schools. Although schools were encouraged to participate in the FLL competition, the robots were also used extensively in the classrooms and in other educational contexts. The results showed that 42.9% of the participating schools think that regular use of robotics in classes fosters the development of professional competence. They found that the sponsorship of the large-scale project by the Ministry of Education contributed to the project's success. Finally, they found that the robotics activities enriched lessons in STEM subjects.

We chose to work within the context of the FLL competition for several reasons: (1) the theme that it offers each year is related to STEM and to real world problems; (2) it requires the students to prepare a presentation; (3) it targets young students; and (4) we had access to schools that participated in the competition.

2.3. *The Engineering Design Process*

Engineering is about designing useful artifacts. The *engineering design process* (Katehi, Pearson, and Feder, 2009) is the process of creating an economic solution to satisfy a customer's demand (Kolberg, 2006). In education, it is also defined as the process by which the students use resources available to them to construct a product (Schunn, 2009). The students' first solution is rarely their best. Instead, they try different ideas, learn from mistakes and try again. Similarly, the design process performed by engineers is an iterative process that progresses from an incomplete design to a complete and coherent solution. Engineering design relies on the knowledge of scientific concepts and the ability to contextualize this knowledge (Katehi, Pearson, and Feder, 2009).

An activity guide (PBS n.d.; Katehi, Pearson and Feder, 2009) for engaging students (9–12 years old) in engineering defines the design process to include: identify the problem, brainstorm, design, build, test and evaluate, redesign, and share the solution. These steps are repeated as necessary until the engineer is satisfied with the results.

Beginners demonstrate common habits during their engineering design activities (Crismond, 2013): (1) Treating design challenges as a well-defined problem that they assume has a clear answer and for which they have the skills to solve it. (2) Sketching design ideas that would not work. (3) Evaluating their product by running a few isolated tests on their prototype, sometimes changing a few variables in the same test, instead of methodical testing. (4) Lacking focus when monitoring the tests they run on their prototype, and lacking a structured method of analyzing the data obtained from the tests. (5) Demonstrating reluctance to generate more than one solution, especially when working in an unfamiliar domain, instead of brainstorming many different ideas; (6) Being unaware of reasons for their design decisions and start the building phase too early. (7) Skipping the stage of conducting research before they start designing and tend not to communicate what they learn from doing design work.

The literature recommends focusing on these steps to teach engineering and computer science to young students (PBS n.d.; Verner and Ahlgren, 2004; Martin, 2006; Crismond, 2013). Robotics activities are usually the only educational activities through which most students can engage with engineering design.

Pack, Avanzato, Ahlgren and Verner (2004) used a fire-fighting robot design competition to achieve a wide range of educational goals, including K-12 outreach, robot design, advanced design projects, and undergraduate research. Their study showed that this project is an effective educational tool to encourage and motivate undergraduate engineering students as well as K-12 students. The students combined knowledge and concepts in an innovative manner, and were motivated to learn the fundamentals of engineering knowledge and skills.

In order to evaluate the influence of robotics activities on students' learning, our research investigated the engineering designed process as reflected through three iterative phases: (1) searching and decision making, (2) construction, and (3) testing, diagnosing and debugging. The definitions of these phases were based on robotics learning materials such as Trobaugh (2010), Kumar (2009) and Martin (2001). In more detail:

a. Searching and decision making: The students need to identify the environment in order to decide which solution to pursue.
b. Construction: The students use LEGO pieces to assemble a robot that will accomplish the missions.
c. Testing, diagnosing and debugging: The students evaluate the robot's behavior to establish whether it accomplishes the required tasks.

2.4. *The Bloom Taxonomy and Meaningful Learning*

The *Bloom Taxonomy* is a hierarchical model that organizes the cognitive aspects of learning into six hierarchical levels: knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom *et al.*, 1956). The taxonomy has been condensed, expanded and reinterpreted in a variety of ways (Forehand, 2010; Johnson and Fuller, 2006) and revised by Anderson *et al.* (2001): the *Revised Bloom Taxonomy (RBT).*

The RBT has two dimensions: the cognitive process dimension with the six categories of remembering, understanding, applying, analyzing, evaluating, and creating, and the knowledge dimension with the three categories of factual, conceptual, procedural and meta-cognitive. Our study investigated meaningful learning of the engineering design process based on the RBT dimension of cognitive process. In this context the knowledge dimension is about acquiring and using meta-cognitive skills for engineering, which deserves a separate study.

Ausubel (1963; 2000) defined meaningful learning as the subsumption or incorporation of new learned material into the student's cognitive structures. The goal of meaningful learning is to teach students concepts that will be recalled and used in multiple contexts. Meaningful learning is consistent with the view of learning as knowledge construction in which students seek to make sense of their experience and go beyond recalling factual knowledge.

The RBT is closely related to meaningful learning. The five higher categories of RBT (understanding, applying, analyzing, evaluating and creating) are increasingly related to transfer where students go beyond factual knowledge, while the RBT remembering category is related to retention of subject matter content (Mayer, 2002).

Technology can make learning more meaningful. Howland, Jonassen and Marra (2012) present five characteristics of technology that are necessary to achieve meaningful learning: active, constructive, intentional, authentic and cooperative.

In line with this, the FLL competition is conjectured to facilitate meaningful learning (Miller, Nourbakhsh and Siegwart, 2008), because the activities require students collaborate in solving problems, by intentionally constructing artifacts in authentic contexts.

3. Methodology

3.1. *Research Instruments*

The following data were collected: (a) Non-participating observations during the school year. Each group was observed at least once a month for 3–4 hours each time; (b) Semi-structured interviews conducted by the first author with 2–3 students from each group at the end of the robotics activities; (c) Group interviews conducted by the judges during the FLL competition day.[2] The observations and the interviews were recorded on video.

The interview used a descriptive tool which we called a *representational model*, defined as an inscription, image, analogy, physical construction or computer simulation that facilitates the externalization of students' knowledge and understanding. We based this tool on studies that identified representations that students may use to clarify their thoughts, feeling and experiences when learning English language and art (Atlantic Canada, 1998) and biology (Anderson, Ellis and Jones, 2014). The representational model was used by the students to express the design of their robots (mechanics, electronics and software), graphically or in writing. They were provided with aids to express their thoughts, such as paper, pencils, rulers, as well as LEGO® components.

During the interviews, the students were asked about the engineering design of the robots that is the focus of this paper. They were asked to draw the design of a robot that can perform the FLL missions. The design could be similar to the robot they had used in the competition. In follow-up questions, the students were asked to explain the drawing and the purpose of the various parts of the robot. If a student could not draw the design, pictures of the robot they had used in the competition were presented and the students were asked to explain.

3.2. *Research Setting*

The FLL robotics activities were extracurricular: after school, on weekends and during vacations. Most of the teachers had no background in robotics and received several months of training from the FLL organizers. The activities began at the start of the school year and continued until the competition day near the end of the school year.

We collected data during two consecutive years from eight schools. In each year, a group of middle-school students (aged 13–15 years) from each school were supervised by one or two teachers. The students were chosen by the principals or the teachers based on their interest in robotics, LEGO, or computer science, or prior high academic achievements. Their teachers' background was varied including physics, mathematics, business, technology, and computer science. Some of the students and some of the teachers participated in both years.

In the first year, the FLL theme was "Senior Solutions" and contained missions that simulated assisting senior citizens in areas that they might find difficult. In the second

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[2] The first researcher was asked by the judges to participate in these interviews.

year of our study, the FLL theme was “Nature’s Fury”, containing missions that simulated helping people prepare, stay safe and rebuild in case of natural disasters.

The data collected changed from the first year to the second year. In Year 1 class observations took place in all eight groups, whereas in Year 2 class observations took place only in Group 7 due to procedural reasons. In Year 1 individual interviews were conducted with a few students from each group, except for Group 4 whose teachers did not cooperate because of scheduling constraints. In Year 2, individual interviews were conducted only with two students from Group 7 who had no previous experience in competitions. In addition, group interviews with the rest of the groups (1, 2, 5, and 6) were conducted by the competition judges and the first author during the competition day.

Table 1 summarizes the characteristics of the groups. We use FO, MG, and MO to denote female-only, mixed-gender, and male-only schools, respectively. For Year 2, x/y means that x is the number of students who participated in Year 1, and y is the number of students who joined in Year 2.

In Year 2, a robotics class was offered as a regular class at Group 7’s school, in addition to the FLL activities. The six new students who joined this group in Year 2 participated in both the robotics class and the competition.

The resources available to all the groups were the LEGO® Mindstorms® kit, its manual, online tutorials and books, and handouts provided by the organizers.

Table 1

Research participants

Group	School type	School’s former participation in FLL	Year	Students – number and gender	Students with experience in robotics	Interviewed students
1	FO	-	1	9F	-	3F
			2	3F/7F	3F	Group Interview
2	MG	-	1	6F	-	2F
			2	2F/2M+3F	2F	Group Interview
3	FO	√	1	8F	4F	2F
			2	Did not participate in FLL		
4	FO	√	1	7F	6F	-
			2	No data		
5	MO	-	1	7M	-	2M
			2	-/6M	-	Group Interview
6	FO	-	1	10F	-	2F
			2	-/7F	-	Group Interview
7	FO	-	1	7F	-	2F
			2	4F/6F	4F	2F
8	MG	√	1	6M, 2F	-	2M
			2	No data		
Total			1	62 (49F, 13M)	10F	15 (11F, 4M)
			2	40 (32F, 8M)	9F	2F+Group Interviews

3.3. *The Operationalization of Meaningful Learning of the Engineering Design Process*

We used the levels[3] of the cognitive process dimension of the revised RBT (remembering, understanding, applying, analyzing, evaluating, and creating) to analyze the meaningful learning of the engineering design process during the robotics activities. We modified the definition of the first level, **remembering**. Originally, it corresponds only to retention, while the five higher levels correspond to deeper levels of learning, which foster increasing levels of transfer (Mayer 2002). Here, the first level is defined to be superficial learning that does not reflect independent knowledge construction. Therefore, we name this level **rote execution** rather than **remembering**.

In the context of the robotics activities, for the first two phases of the engineering design process, searching and decision making, and construction, we merged the consecutive levels **understanding** and **applying**, because the students had to *realize* (understand) the knowledge needed to accomplish the missions, while at the same time they *implemented* (applied) the design. For example, the students *added* a manipulator to their design when they *realized* that one requirement is to drag an object. We did not merge these levels for the phases of testing, diagnosing and debugging, because there the students had to *realize* the problem before finding or *implementing* a solution for it.

For all the phases of the engineering design process, we merged the consecutive levels of **analyzing** and **evaluating**, because when the students *integrated* (analyzed) knowledge they also *compared* and *criticized* (evaluated) their design.

We defined the following operationalization of the learning levels for each of the phases:

1. **Rote execution:** The students demonstrated this level if they
   a. (Searching and decision making) *Limited* the search and the decision making to the available resources.
   b. (Product construction) Constructed the product by *meticulously following* the resources' instructions step by step.
   c. (Testing, diagnosing and debugging) *Tested* the design by checking whether the product's behavior matches the desired output without a meaningful grasp of the design, and debugged it by checking if they followed the design instructions. Or, they quickly began another design *without investigating the problem*.
2. **Understanding/applying**: The students demonstrated this level if they:
   a. (Searching and decision making) *Realized* the requirements of a mission, searched the available resources and decided on *implementing* a design accordingly.
   b. (Product construction) *Constructed* the product by *using* an existing design, making changes in the *implementation* based on their *interpretation* of the

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[3] We use the term levels instead of categories. Words in **bold** refer to the categories of the RBT. *Italic* is used for the operational definitions of each category in the dimension of the cognitive process (Anderson *et al.* 2001).

   needs. Or, they constructed a basic product based on limited familiarity with the design components.

   c. (Testing, diagnosing and debugging) The students demonstrated this level if they:
      i. **Understanding:** Tested the design by checking whether the robot's behavior matched the desired output, or if they *recognized* a problem in the design but blamed it on external agents such the LEGO® manufacturer, or *called for assistance* without making an attempt to diagnose the problem.
      ii. **Applying:** Tested the design by checking whether the product's behavior matched the desired output, or if they *diagnosed* the problem by *making* changes without realizing which of the changes were relevant, or if they *debugged* their design by *making* changes to the design through trial and error.

3. **Analyzing/evaluating**: The students demonstrated this level if they:
   a. (Searching and decision making) Searched several resources, made decisions based on *analyzing* the relevant knowledge, and *criticized* the performance of their design, or *compared* it with other designs.
   b. (Product construction) *Compared* the techniques or ideas presented in resources and *identified* the relevant ideas for modifying their design.
   c. (Testing, diagnosing and debugging) *Tested* the design by *checking* and *detecting* whether the product's behavior matched the desired output, and *criticized* each component of the design, or if they *identified* the part that caused the problem, and realized and debugged the cause of the problem.
4. **Creating:** The students demonstrated this level if they:
   a. (Searching and decision making) *Planned* an original design by discussing or drawing sketches or prototypes that represented the design and its components, based on the requirements of the competition and the functionality of each component.
   b. (Product construction) *Generated* and *constructed* an alternative or original design, based on relevant knowledge and insights gained during the design process.
   c. (Testing, diagnosing and debugging) Checked each component of the design, modified and debugged the design to *produce* a more successful and reliable design.

4. Data Analysis

The students of each of the eight groups worked as teams on the FLL activities. Some worked more on the scientific project part, but during the observations, the students worked together as a group. In addition, during the individual as well as the competition-day group interviews, students used the plural pronoun 'we', thus expressing the group's mutual responsibility. Since learning was not evaluated using written tests or other means of individual evaluation, our findings refer to the groups.

Following Year 1 we analyzed the interviews with 15 students that took place after the end of the activities, as well as the observations of the students during the activities. We divided the observations into three parts, corresponding to the beginning, middle and end of Year 1. The data analyzed following Year 2 included the group interviews held during the competition day only, except for Group 7 for which richer data were collected, including observations conducted during Year 2 and interviews held with two students from the group at the end of the year.

The data were analyzed qualitatively by examining the video tapes of the observations and interviews, and their transcripts. The transcripts were analyzed according to the RBT as operationalized above. The analysis of the students' verbalization during the observations and their interaction with the representational models was inspired by Chi's (1997) verbal analysis for quantifying qualitative data, as well as by Miles, Huberman, and Saldana (2014):

1. Segmenting each group's data according to the timing: the beginning, the middle and the end of the year (the competition).
2. Further segmenting the data according to the phases: searching and decision making, construction, and the testing, diagnosing and debugging.
3. For each group, for each time segment and for each phase, each fragment of speech or action was classified according to the operational definitions of the RBT levels.
4. Patterns and themes were noted to draw, test and verify meanings and conclusions.

The researchers were not involved in the teaching and learning process, but only in preparing the research instruments, collecting data, and performing the data analysis. Triangulation among the instruments (observations and interviews) was used to ensure the accuracy of the results (Miles, Huberman, and Saldana, 2014). In addition, an independent analysis of four of the interviews was performed by a colleague to ensure the consistency of the operationalization. The few disagreements that occurred were negotiated until a consensus was reached.

5. Findings

The findings are summarized in tables, one table for each of the three phases of the engineering design process. The evolvement of learning for each of the groups is presented in terms of the RBT. For groups that were investigated in both Years 1 and 2, the table contains two rows per group: the first row refers to Year 1, and the second row to Year 2.

The students' learning is depicted by arrows that start at the RBT level achieved by the group at the beginning of the activities, and continue to the RBT level that they achieved at the end of the activities. This is the case for all groups in Year 1 and for Group 7 in Year 2. The findings for Year 2 for all groups except Group 7 are shown as undirected lines, each one belonging to a single cognitive level and for the competition day only. The dashed lines for Group 7 in Year 2 indicate the starting level of the six students in the group.

For each phase we present qualitative insights to illuminate the students' learning. In group n, the notation Gn-Sm is used for student m (from 1 to 10) who participated in Year 1. Students who participated in both years retained their names from one year to another. Students who joined a group n in Year 2 were denoted by Gn-Sm for student m (from 11 to 20).

5.1. *Searching and Decision Making*

Table 2 displays the results for the phase of searching and decision making.

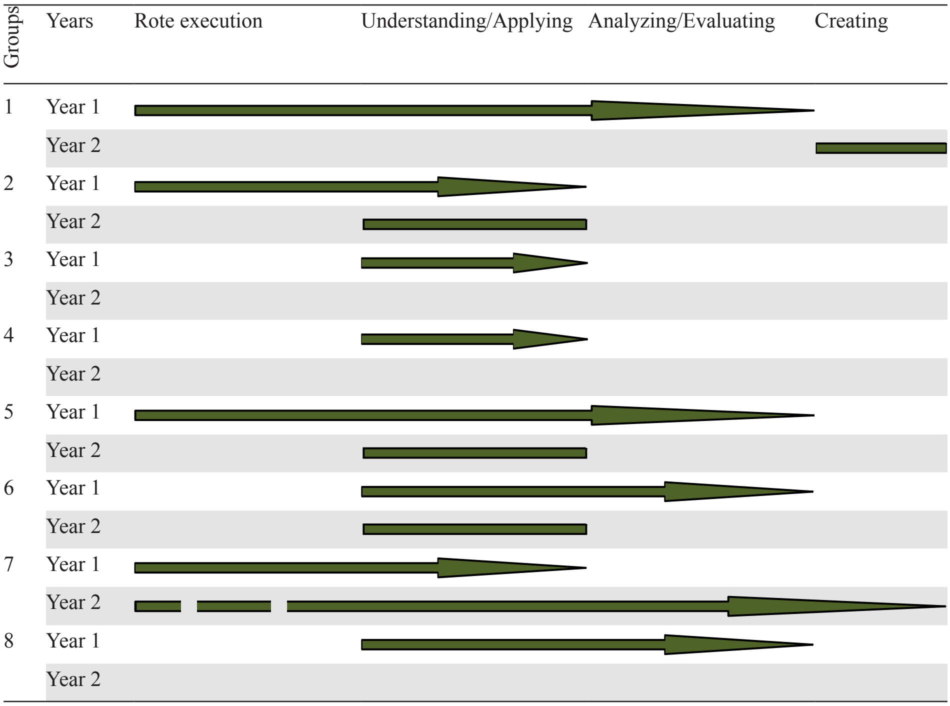
The analysis yielded the following observations.

Limited search: In the first year of participation in the FLL competition, all the groups treated the resources as sufficient resources for completing the project without considering the requirements of the missions. Thus, they demonstrated the **rote execution** level. For example:

> G5-S5: The first thing we used was the LEGO® booklet. We thought that if we do all the robots [robot designs] in the booklet, we would be ready and finish

Table 2

Results for the searching and decision making phase



> learning [required for the robot construction]. But we discovered that we needed to reassemble a new [different] robot.

The group treated the LEGO® Kit booklet as a textbook. They chose one of the designs and assembled it without determining if the design was relevant to the competition.

Searching and randomly choosing a design: Some of the groups chose a design from resources other than the booklet; however, this choice was not based on any reasoning, but rather on irrelevant impressions ("this design looks nice"), on their mentor's recommendations, or on guesswork. Thus, they demonstrated the **rote execution** level. This phenomenon was occasionally observed during most of the activities of the groups. For example:

> G2-S5: We chose a design from the internet, we looked at several [designs] and liked one shape [robot] […]. We used to look at the instructions and choose what was best for us […] by its [the chosen design's] size. It would move faster.

G2-S5 and her group's design was based on trying out one design. The students knew that they needed a small and fast robot, but they did not identify the needs of the competition nor did they check whether the size of the robot would fall within the constraints of the competition. Indeed, the robot they chose did not behave as expected.

Searching upon requirements' identification: Some groups chose from the available resources a design they thought would meet the requirements. They did not compare it to other designs and analyze it. Therefore, they demonstrated the **understanding/applying** level. For example, in the middle of the activities of Year 2, Group 7 realized that they needed an additional motor in order to accomplish one of the missions, where the robot had to go over some obstacles. Student G7-S16 explained their work:

> G7-S16: At the beginning of the activities, we used two motors [in the main design] and that was just fine. Then we discovered that in addition to the three motors in the main design, having two on the obstacle design [the additional design] would be too much [according to the competition's rules]. That means we were only left with one motor for the obstacle design.

G7-S16 and her group noted the constraint on the number of motors, so they searched several resources and gathered ideas to create a design with only one motor.

Relating the design to authentic examples: In some cases, the students connected the design with real-life entities, such as cars or humans. They demonstrated the **analyzing/evaluating** level. For example, in Year 2, Groups 1and 7 were inspired by real cars driving on rough roads. Student G1-S2 said:

> G1-S2: We made the obstacle design long [in shape], to behave as the car's spring. The longer the robot the better it performs.

G1-S2 described the assembly of the second design that had springs attached to the wheels, as in real cars, in order to move up and down.

Mapping and comparing ideas: Some groups were able to specify the needs and check whether they were met by a given design, and they were also able to compare ideas from several resources. For example, Group 5's search of the resources was not limited to the existing designs, but extended to watching videos that displayed different kinds of robots or LEGO® pieces. Student G5-S5 said:

> G5-S5: We found a good idea from a video [they watched], we did our [design], not exactly as the one in the video […] we got ideas from it. The video showed a different [type of] robot from the one we used, so we tried to assemble our own robot [accordingly] […]. We had several ideas to accomplish each mission.

G5-S5 and his group used ideas that they had gathered after mapping and comparing them to the requirements. They demonstrated the **analyzing/evaluating** level.

Generating an original solution: During Year 2, the final designs of Groups 1 and 7 integrated previous designs into a new design. For example, Group 1 designed two skeletons of robots for accomplishing the different missions and the controller was to be moved from one design to another, depending on the mission at hand (see Fig. 1). By this, Group 1 increased the number of the missions that they could accomplish. Therefore, the students demonstrated the **creating** level.

The importance of excelling in the competition: Some groups were so focused on the competition that they did not use the activities to increase their knowledge. Other groups realized that they needed to investigate the robot's components and behavior, and work accordingly to achieve more points during the competition. This triggered learning. For example, Student G5-S4 said:

> G5-S4: Only one month before the competition, we discovered that we were wasting our time. We caused the robot to move [without using the sensors]. It used

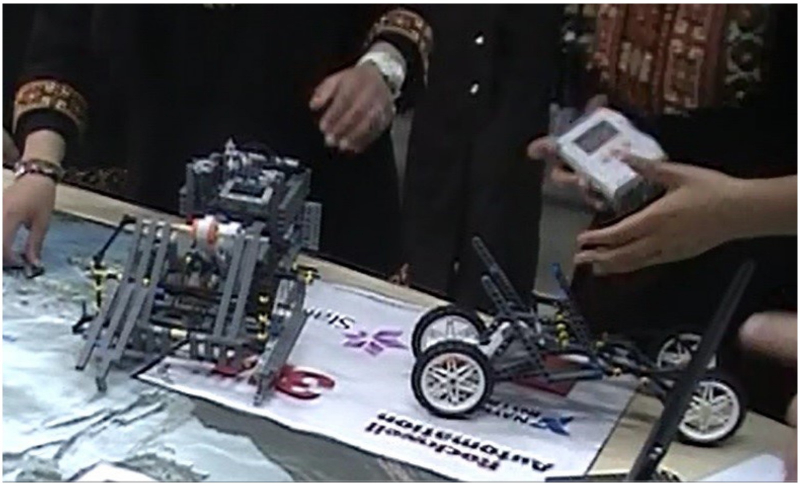


Fig. 1. Group 1, Year 2 – moving the controller from one skeleton to another.

> to move in one direction or another and did not reach the target. But when we used the sensors, we caused the robot to move straight without zigzag. […] Anyway, we were able to learn how to program and cause the robot to move on a line without zigzagging.

G5-S4 and his group were not satisfied with the robot's behavior because it zigzagged and did not reach the target. This failure triggered further learning, until they came up with a way to cause the robot to move in a straight line and reach its destination. Thus, these students demonstrated the **analyzing/evaluating** level.

5.2. *Construction*

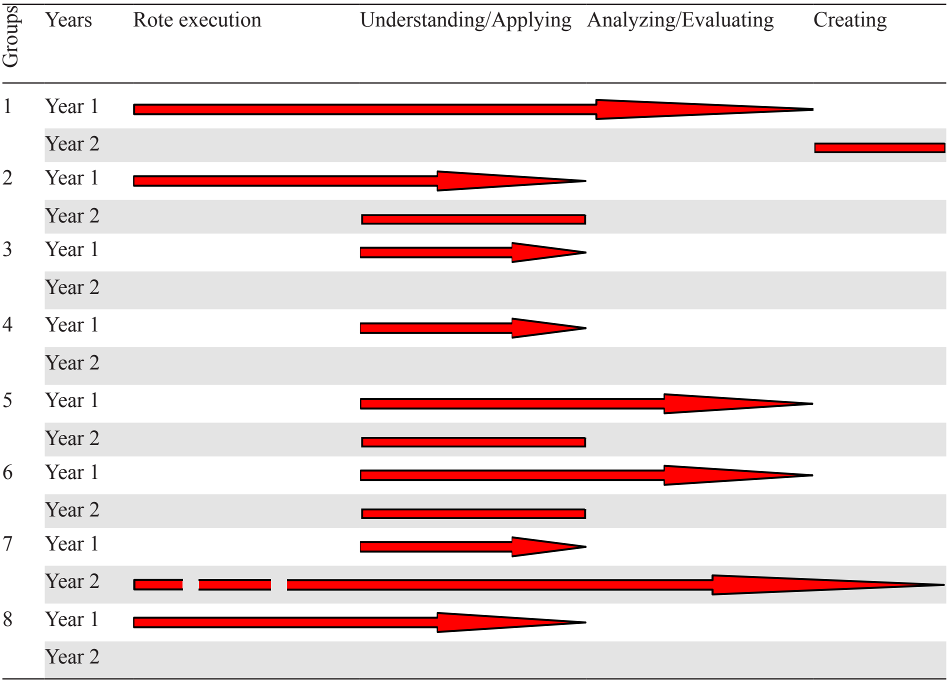
Table 3 displays the results of the construction phase.

The analysis yielded the following observations.

Following the instructions step by step: Some groups meticulously followed the graphical assembly instructions of LEGO® robots without understanding the functionality component of the construction. For example, Group 1 (Year 1) pointed out the importance of repeating the assembly of the same design several times, in order to become

Table 3

Results for the construction phase



Groups	Years	Rote execution	Understanding/Applying	Analyzing/Evaluating	Creating
1	Year 1	━━━━	━━━━	━━━▶	
	Year 2				━━━━
2	Year 1	━━━━	━━━▶		
	Year 2		━━━━		
3	Year 1		━━━▶		
	Year 2				
4	Year 1		━━━▶		
	Year 2				
5	Year 1		━━━━	━━━▶	
	Year 2		━━━━		
6	Year 1		━━━━	━━━▶	
	Year 2		━━━━		
7	Year 1		━━━▶		
	Year 2	━ ━ ━	━━━━	━━━━	━━━▶
8	Year 1	━━━━	━━━▶		
	Year 2				

familiar with LEGO$^{®}$ constructions and to correctly construct a design to accomplish the missions. Student G1-S2 said:

> G1-S2: I think if we keep practicing [the assembly of the booklet's design] we can do it without the booklet.

G1-S2 and his group believed that repeating and memorizing a construction they could improve their skills although they gave no consideration to the requirements of the missions. They demonstrated the **rote execution** level.

Discarding parts of the design: Some groups decided to include or exclude a part based superficially on the robot's behavior, such as when a sensor appeared to negatively affect the behavior of the robot. They demonstrated some understanding of the functionality of the design, but not at a level that enabled them to make more sophisticated modifications. These groups demonstrated the **understanding/applying** level. Student G8-S5 said:

> G8-S5: In the beginning we used sensors, but then we found that the robot was not behaving the way we expected so we decided to take them all off […] We found that we did not have enough time to work on it [interfacing with sensors]; it was too complicated. Also, there were not many points to collect by accomplishing this mission.

G8-S5 and other groups that acted similarly gave several explanations: (a) they cannot predict the robot's behavior all the time; (b) the sensors' input values in the competition place might not be the same as in the classroom; (c) interfacing with sensors was complicated; (d) the students needed more time; and (e) collecting just a few points was not worth the work.

Realizing the relevant knowledge related to the design: Even though some groups discarded parts of the design, some of them observed and analyzed the robot's behavior in accomplishing the missions and tried to explain the behavior before finding solutions to problems. They demonstrated the **analyzing/evaluating** level.

Assembling different designs during the entire activities: Some groups used similar designs for all the activities. For example, the final designs of Groups 3 and 4 were similar to their initial designs. Interestingly, these groups demonstrated no higher level than **understanding/applying** in this phase, as can be seen from Table 3.

Other groups changed their design several times during the activities. In Year 2 Group 7 initially proposed a design that used gears (Fig. 2). Then they realized that with gears the robot was stable, but it could not overcome all the obstacles for accomplishing one of the missions. They changed the design so that the robot had large spring-like front wheels. Their final design used windmill-shaped front wheels, but the students could detach it and then assemble the right wheels or manipulator according to the mission to be performed (see Fig. 5).

Student G7-S17 said:

> G7-S17: For the obstacles, we first thought that the same robot can do all the missions including the obstacles. It [the robot, Fig. 2] used to pass or climb over

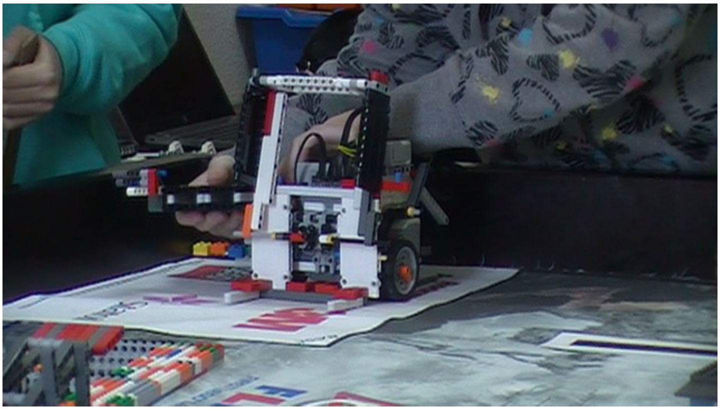


Fig. 2. Group 7, Year 2 – an early design for accomplishing most of the missions except for the obstacle mission.

> the first two and then got stuck, moved to the right or flipped. So we decided to do two designs [main robot and obstacle robot] […] We did several designs [e.g., Fig. 3 and Fig. 4], some worked and others did not […] Finally, we decided to have a robot that has two front wheels and then we thought of separating the whole front section of the robot [resulting in two sections, see Fig. 5].

G7-S17 and her group constructed several designs, and explained the purpose of each of them. Their final robot demonstrated originality; it was constructed in two parts, which could be assembled according to the mission at hand. They demonstrated the **creating** level.

Learning from experience: Some groups were aware of the knowledge gained from experience, from the previous year's activities or from pervious designs for the current missions. Group 3's initial robot in the second year was almost the same as their final robot from the previous year. They also rejected an idea that had failed during the previous year. Student G3-S2 was observed explaining why the robot's ability to turn was insufficient:

> G3-S2: The problem was not the turning [the method they used to cause the robot to turn]. We increased the power of one of the [front] wheels and decreased it [the power] on the other wheel. Last year, we used the steering wheel [in the back of the robot], it [the steering wheel] gave us a hard time and we were always fixing it [the steering wheel's direction]. The robot can turn normally without the steering [the use of steering wheel].

Eventually, they used the steering wheel to achieve positive results, although they did not investigate why this was so. Since they considered the work of other groups and the need to change their design, they were above the **rote execution** level, but were no higher than the **understanding/applying** level.

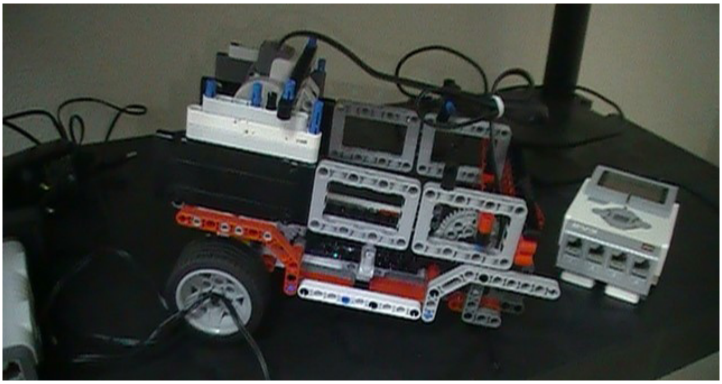


Fig. 3. Group 7, Year 2 – a subsequent design constructed to accomplish the obstacle mission, which relies on the use of gears and operates with one motor.

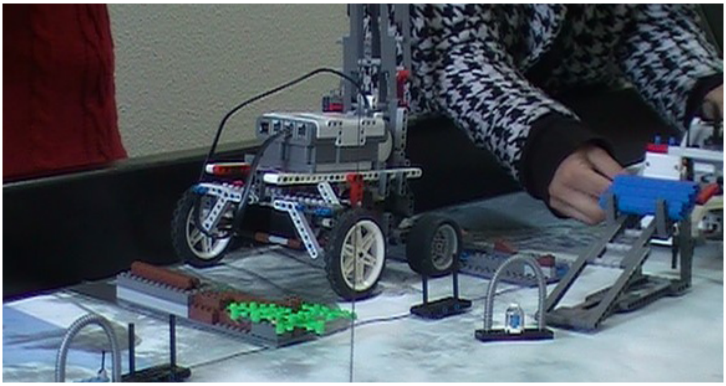


Fig. 4. Group 7, Year 2 – the 3rd design, constructed for the obstacle mission, with wheels that go up and down over the obstacles.

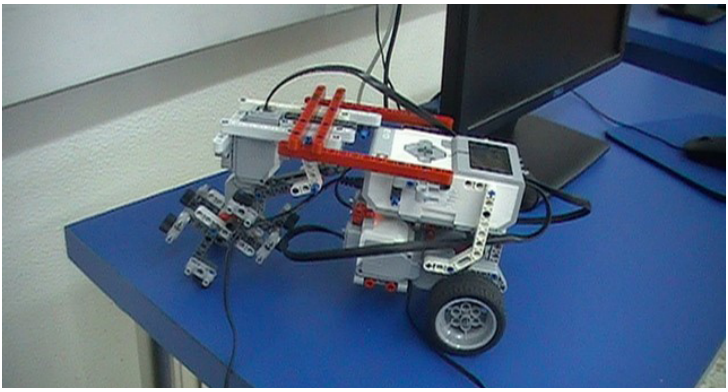


Fig. 5. Group 7, Year 2 – final design, in which the front part (with the windmill-shaped front wheels) could be detached.

5.3. *Testing, Diagnosing and Debugging*

Table 4 displays the results of the testing, diagnosing and debugging phase.

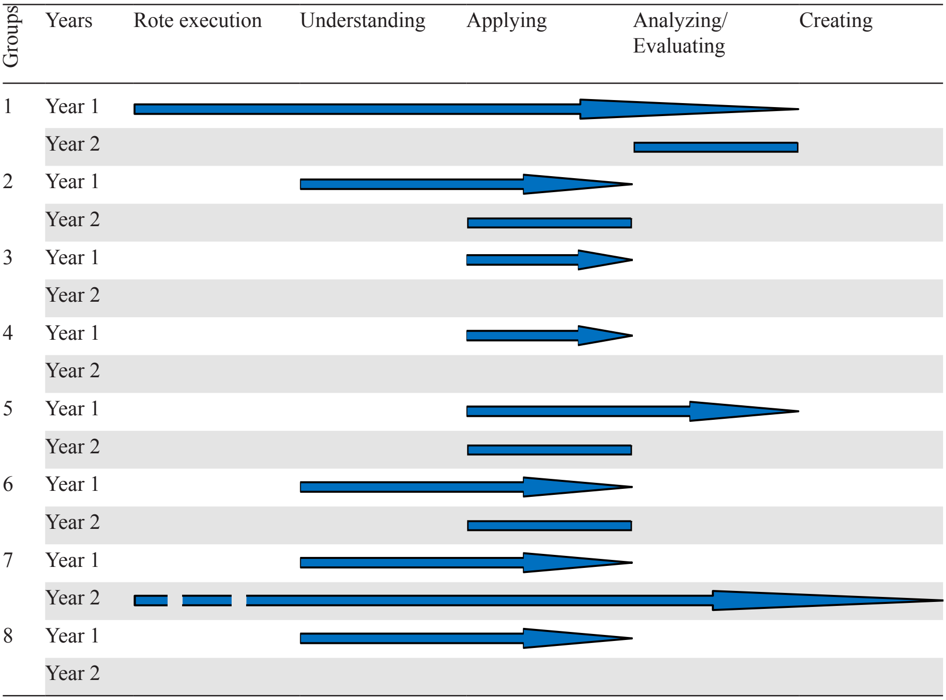
The analysis yielded the following observations.

Abandoning the design without debugging: When the robot did not perform as expected, some groups meticulously checked the LEGO® manual or chose another design. For example, when Group 1's design (Year 1) did not accomplish the missions, they chose another design without debugging the current one, thus demonstrating the **rote execution** level.

Making irrelevant speculations or immediately calling for assistance: Some of the groups made ineffective attempts to diagnose the problem and speculated on the source of the problem. For example, they blamed the manufacturer of the LEGO® kit. In other cases, they called for assistance without trying to debug the problem. The mentor instructed them to carefully reconstruct the design. They were above the rote execution level, since they were able to recognize the problem, but they made no genuine attempt to solve it. Therefore, they demonstrated the **understanding** level.

Table 4

Results for the testing, diagnosing and debugging phase



Groups	Years	Rote execution	Understanding	Applying	Analyzing/ Evaluating	Creating
1	Year 1	▬	▬	▬	►	
	Year 2				▬	
2	Year 1		▬	►		
	Year 2			▬		
3	Year 1			►		
	Year 2					
4	Year 1			►		
	Year 2					
5	Year 1			▬	►	
	Year 2			▬		
6	Year 1		▬	►		
	Year 2			▬		
7	Year 1		▬	►		
	Year 2	‐ ‐	▬	▬	▬	►
8	Year 1		▬	►		
	Year 2					

Relying on trial and error: Most groups occasionally used trial and error when they encountered a problem:

(a) Marking a specific location on the base of the mission table: The students tried to memorize the location of the robot. When the robot did not behave as expected, they kept trying different locations for the robot and did not consider other reasons. However, a few were not convinced that memorizing the location of the robot is a good solution. G7-S2 was observed to say:

> G7-S2: The performance of the robot is different each time. I am sure that there is something else wrong.

In this case, the students did not follow up on this observation and relied on the location marks, instead of looking for a better solution.

(b) Changing the input values: The students tried several times to change the input values in the program until the robot accomplished the expected results. G2-S12 said:

> G2-S12: Trial and error, we tried a lot to define the place of the robot [on the competition table] and for how long [input value] it should move forward.

G2-S13 said:

> G2-S13: We used to estimate the distance, and assign an approximate value; if it did not work we changed it and kept trying.

(c) Modifying the robot's structure without recognizing the reason for the failure: Group 2 tried two alternatives: back wheels with and without tires. The students realized the difference in the robot's behavior for both alternatives, so they were above the **rote execution** level, but they did not explain the reasons for the change in the robot's behavior. Thus, they demonstrated the **applying** level.

Diagnosing the design: Some groups tested the design and tried to diagnose why the robot did not behave as expected. They realized what knowledge was relevant and tried to find a solution, thus demonstrating the **analyzing/evaluating** level. G1-S1 said:

> G1-S1: When it [the robot] stopped working [as expected], we didn't give up, we checked that the battery was full, that the program had no error, and we checked the wires [connections] […] Then we met together, thought more about it [the problem] and decided to reassemble the whole robot again. We tried to make sure that there wasn't any piece that affected the other … the motor is not close to other things such as the wheel … and we tried to minimize the friction. Then it [the robot performing the missions] worked [as expected].

Repeating tests even when the robot accomplished a mission: Several groups insisted on testing the robot at least three times in order to make sure the robot can accomplish the mission successfully. They demonstrated the **applying** level, but not above it; since they did not have sufficient insight into the behavior of the robot, they gave no reasons for multiple tests. G5-S15 said:

> G5-S15: We used to retest the robot several times, and when it accomplished the mission successfully, we repeated the successful operation three times to make sure it accomplished the mission correctly.

G5-S15 and her group chose this strategy because they had already encountered the problem of the inconsistent behavior of the robot.

In contrast, Group 7 (Year 2) was not satisfied with the successful results, but rather tried to look for the reasons behind the success so they produced more reliable results. This group demonstrated the **creating** level. G7-S11 asked her teammate:

> G7-S11: What did you do to make it [the robot] accomplish the [obstacle] mission?

G7-S11 and her group were constantly attempting to fully understand the behavior of the robot, diagnosing even successful results, and if they were not certain they kept on modifying the robot until they achieved more reliable results.

6. Discussion

6.1. *Meaningful Learning in Terms of the Bloom Taxonomy*

In all of the groups meaningful learning was evident. The **rote execution** level occurred only at the beginning of the activities; by the end of the activities all the groups reached at least the **understanding/applying** or **applying** level for all of the engineering design process phases. The students searched available resources for a design that would accomplish the missions. After testing and diagnosing, they changed some parts of the design in order to accomplish the missions.

Some groups, such as Groups 1 and 5 in Year 1, demonstrated the **analyzing/evaluating** level for all phases. The students came up with an unexpected design, based on the information and the ideas they found in the available resources. They tested their robot to check if it accomplished the missions successfully. When it did not behave as expected, they diagnosed and investigated the cause of the problems and tried to debug it.

Only one group (Group 7 in Year 2) achieved the higher **creating** level for all phases. The students in this group came up with an unexpected design for the robot. When they tested their robot, they were not satisfied with just accomplishing the missions, but continued to analyze the successful results.

We saw a progression in learning in most cases. The only exceptions were Groups 3 and 4 who demonstrated no progression in any of the three phases, staying in the **understanding/applying** or the **applying** levels, and Group 7 who in Year 1 demonstrated progression only for the first and third phase, but remained in the **understanding/applying** level of the construction phase.

The results were consistent for all three phases with a few exceptions. Group 8 demonstrated a higher level for searching and decision making. Initially, they relied heavily on the mentor's help, but when they worked alone at the end of the activities, they constructed a familiar robot. They reached the **analyzing/evaluating** level for the phase of searching and decision making but lower levels for the other phases (**understanding/applying and applying**, respectively).

Group 6 in Year 1 reached the **analyzing/evaluating** level for the first two phases and only the **applying** level in the testing, diagnosing and debugging phase. The students searched available resources and constructed their design, but they did not investigate the causes of the robot's problems. Group 1 in Year 2 demonstrated the **creating** level in searching and decision making phase as well as the construction phase, but reached only the **analyzing/evaluating** level in the testing, diagnosing and debugging phase.

Lower levels at the testing, diagnosing and debugging phase may be related to the extensive use of the low problem-solving strategy of trial-and-error. When the **applying** level was achieved at the third phase, this was usually the result of attempting to fix a problem, but relying on trial and error. When higher levels were achieved, this was because the students went beyond trial-and-error.

6.2. *Factors Influencing the Learning of the Engineering Design Process*

Certain factors seemed to play a role in determining the learning levels achieved: (a) the mentoring style; (b) the absence of a textbook; (c) the extra-curricular competition-oriented nature of the activities; and (d) the unstable nature of the design of the robot.

The mentoring style: Students experienced a teacher-centered pedagogy in the beginning of the activities; however, a shift to a student-centered pedagogy occurred in most groups. This caused the students' learning outcomes to shift from rote learning to meaningful learning. We hypothesize that teacher-centered pedagogy may not be effective in the context of robotics competitions. However, involving teachers is important to guide students in gaining sufficient knowledge.

The absence of a textbook: There was no appropriate textbook relevant to the activities, although resources such as online materials were available. The absence of a single textbook caused the students to perform active search, and apparently triggered meaningful learning to varying degrees. In many groups, the students searched for a design and made some changes to fit the competition's requirements and missions. These groups demonstrated the **understanding/applying** level. A few other groups expanded their search for ideas that they could use for accomplishing the missions, and investigated several designs before coming up with their own design. They demonstrated the **analyzing/evaluating** or even the **creating** levels.

The extra-curricular competition-oriented nature of the activities: The activities were extracurricular (except for Group 7, some of whose students participated in an in-school class in Year 2). The students could (and did) devote as much time as they wanted, even at late hours and on weekends. Nevertheless, a frequent comment by students was the limited time that they had before the competition day. This led them to focus on the bottom line of achieving the best results in the competition, usually using trial and error to solve problems. Only a few of the groups attempted to solve problems by diagnosing them and searching for a way of correcting them. For example, Group 7 in Year 2 diagnosed their design, claimed they had enough time to explore, and were exposed to more information. Perhaps the feeling of time pressure was reduced by participation in the structured curricular class. However, Group 5 only participated in the extracurricular competition, but they were able to accomplish most of the missions and solve problems.

The unstable nature of the design of the robot: Robots are concrete artifacts and this can affect students' learning. It can either be treated by the students as interfering with accomplishing missions, or it can become a catalyst for a deeper learning. Some groups tried to minimize the instability of the robot's behavior, while a few groups (Groups 1 and 5 in Year 1, and Group 7 in Year 2) faced up to the challenge and genuinely tried to solve problems.

6.3. *Research Limitations*

This was not a controlled study. In particular, we could not control the composition of the groups (in terms of size, gender, or previous experience), or any aspects concerning the teachers (such as background, experience, or teaching strategy). There were differences among the groups regarding all these factors and we cannot isolate the effects of these differences on students' learning. Nevertheless, since learning did occur in all groups despite the differences, we can safely say that it was the result of the robotics activities. This limitation also prevented us from further investigating the effect of gender on learning, since the females significantly outnumbered the males. Another limitation, referred to in Section 4, concerns the group evaluation. Since the observations were our main research tool, we could only assess the achievements of the groups, rather than of individuals within the groups. While we cannot assume equal contribution of all the members of a group, our observations did not indicate extreme cases in which certain students were especially active while others were especially passive. In Year 2, regular observations took place in only one of the five participating groups, and the other groups were observed only at the end of the year during the competition. Therefore, for these groups, we could not assess learning progression and we were limited in inferring anything other than the final group achievements. In addition, as is the case in any qualitative study, the generalizability of its findings is limited.

7. Conclusions

Our study showed that robotics activities were effective in achieving meaningful learning of the engineering design process. Our first question concerned the knowledge gained by the students. Our findings show that students gained knowledge regarding all three phases of the engineering process: searching and decision making, construction, and testing, diagnosing and debugging. As for the level of learning (the second research question), our findings show that all groups achieved meaningful learning to varying degrees, as detailed in Section 6.1, and that in most cases their level of learning progressed along the school year (when progression could be assessed). In addition, in most cases the level of learning was similar regarding the three levels of the engineering progress.

The most successful learners were those who engaged in exploration of resources in order to learn new concepts and to solve problems they had encountered. Student-centered, discovery-guided activities with robotics, especially when integrated with explicit learning of various concepts, can facilitate a high level of meaningful learning.

We found that, in general, the students did not demonstrate sophisticated problem-solving strategies, and mostly relied on trial-and-error. The competition-oriented nature of the activities may have something to do with it, since the students were focused on accomplishing the tasks and hoped that relatively simple debugging actions would enable them to achieve this goal as fast as possible. The groups were determined to accomplish the missions, but learning opportunities were sometimes pushed aside in order to achieve this goal. Further research is needed to determine the relative advantages and disadvantages of extra-curricular competition activities when compared with curricular classes.

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