A Systems Approach to Analyzing Design-Based Research in Robotics-Focused Middle School STEM Lessons through Cognitive Apprenticeship

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1. Introduction

Under the design-based research (DBR)[1-6] process, the design and implementation of a lesson undergoes several iterations, the outcomes of each iteration are analyzed, and the necessary changes and refinement in the design are proposed for implementation and adaptation in the next iterations.[7-9] The DBR process can promote partnership and relationship among education researchers, subject matter experts, teachers, and students for learning concepts, design, theories, etc. Moreover, DBR can be combined with the concepts of project-based learning (PBL)[10] and it can evolve constructionism theories, in which learners may create their own knowledge through the process of designing and developing objects and artifacts.[7,10,11] The DBR approach seeks linkages with existing learning theories,[1] produces new theories,[1] and is usually contextually situated.[1,7] Such a strategy may ultimately improve learning outcomes and help yield novel learning theories and artifacts.[6-8]

As evidenced from the literature, DBR has been frequently employed in teacher professional development (PD) programs and in higher education, wherein, as adult learners partake in learning activities, facilitators and researchers can carefully observe them and analyze their learning.[8-10,12] Incorporating the DBR process when conducting classroom instruction and hands-on learning activities in K-12 environment may require special considerations due to the young age and still developing maturity level of students. Illustrative examples of implementation of DBR in K-12 classrooms include Refs. 7, 13-15. Recent years have witnessed increasing incorporation of technologies such as robotics with pedagogies.[16,17] Adoption of appropriate technologies for pedagogy can provide alternative and accessible representations of lesson contents and enhance learning outcomes.[18] The DBR methodology implemented in connection with robotics components to rigorously analyze design phenomena for middle school students has received limited attention.[7,10] The DBR approach is especially important to design science and math lessons with robotics because the flexibility and uncertainty of robotics applications require investigations on various alternative approaches to identify the most appropriate, feasible, reliable, and cognitively appealing approach for using robotics in the lesson design that promotes students' intrinsic and extrinsic motivation to engage in the lesson.[19,20] Moreover, application of DBR in science, technology, engineering, and math (STEM) education with robotics provides numerous opportunities to examine the feasibility and benefits of incorporating constructs of various learning theories such as: cognitive apprenticeship,[21] situated cognition,[22] problem-based learning,[23,24] and inquiry-based learning, among others. However, application of DBR in robotics-based STEM education has not received significant attention yet.

From the review of available literature, it is evidenced that while rich observations and descriptive analyses of outcomes guide DBR iterations,[5] rendering DBR as a "form of qualitative research,"[25] it is lacking of a systematic, quantitatively-guided approach that can guarantee objectivity. With its focus on curricula and instruction refinement by performing observations, analyzing videos, collecting learning artifacts, conducting interviews and focus groups, etc., and qualitatively interpreting[26] the resulting data, the DBR process generally does not quantify the significance of results and is deemed lacking to support large-scale implementation.[27] It is possible that the prevailing DBR strategy may not fully capture true scenario of an iteration and may fail to suggest appropriate modifications for the next iteration. This may limit the effectiveness of DBR as currently practiced. To remedy this situation, we believe that a suitable set of systems engineering tools and approaches[28,29] can be adapted to help analyze the true scenario of each iteration and suggest appropriate modifications for next iterations, which may enhance the effectiveness of the DBR process and learning outcomes.

The objective of this paper is to employ systems engineering tools and techniques in conjunction with the DBR process for middle school STEM lesson design using robotics. This paper is based on our (researchers') collaboration with a school teacher who is designing and implementing 7th grade math lessons using robotics. First, students build robots based on the instructions of the teacher and then the teacher designs math lessons using robotics and implements them in class. The learning activities are sequentially performed in several sessions, which we treat as 'iterations.' In each iteration of robot building, the students discuss among themselves and with the teacher and researcher under a student-teacher-researcher co-design approach, which fosters collaborative learning[30] and co-generation.[31] The students receive researcher's expert opinion, which provides the benefits of cognitive apprenticeship.[21]

In each iteration, two separate groups of students work toward building two identical robots. For one group, the teacher and researcher use traditional qualitative observation, brainstorming, discussion, questionnaire, and feedback methods to analyze the outcomes of the iteration.[7,8] For the second group, in addition to the traditional methods, the teacher and researcher follow some advanced systems engineering approaches under the cognitive apprenticeship of the expert researcher. The DBR is treated as a continuous improvement (CI) method,[32] and resembles as the Deming or Plan-Do-Check-Act (PDCA) cycle.[33] The teacher and researcher observe the outcomes in each iteration and analyze them using cause-effect diagrams.[34] Then, they apply the Pareto principle (80:20 rule) to identify the vital few causes that contribute to the major outcomes.[35] At the end of iterations, outcomes for the systems approach are compared to that for the traditional approach. The results show that the system approach is more effective. The results are novel that enrich the DBR method and improve its efficacy in designing STEM lessons using robotics for middle school classrooms.

The remainder of this paper is organized as follows. Section 2 introduces the robotics-focused lesson and the targeted lesson design that needs to be performed through the collaboration among the students, teacher, and researcher. Section 3 introduces the classroom environment consisting of the teacher, researcher, and student teams. Section 4 reviews the systems engineering tools and techniques that are to be used in conjunction with the DBR process. Section 5 describes the iterations and analyses conducted following the systems engineering approaches. Section 6 contrasts the outcomes between the traditional and systems engineering approaches. Section 7 includes a general discussion. Finally, Section 8 provides concluding remarks and suggests directions for future research.

2. The Robotics-Focused Targeted STEM Lesson

To implement various robotics-focused STEM lessons, we created a base robot, shown in Figure 1, using the LEGO Mindstorms EV3 robotics kit.[36] The kit includes (i) a programmable brick serving as the control center and power station for the robot, (ii) two large motors to render precise and powerful action by and motion of the robot under program control, (iii) sensors, such as color, touch, ultrasonic, wheel rotation, and gyroscope, and (iv) two wheels, miscellaneous gears, cables, buttons, an LCD screen, and various construction parts and accessories to build the robot structure. The aforementioned robot kit was used for its relatively affordable cost and easy programming and the base robot of Figure 1 was used for its flexibility in assembly and configuration, easy operation, and suitability of its functions in explaining the middle school science and math content.

Figure 1: LEGO Mindstorms EV3 base robot.

In summer 2016, the project team held a three week long PD workshop for 20 teachers. The PD sessions were conducted five days a week for eight hours each day, providing 40 contact hours per week for a total of 120 contact hours during the summer. The PD workshop team (i.e., the project team) consisted of 10 persons (engineering and education faculty, post-doctoral researchers, and graduate students) who helped in various aspects of the summer program (e.g., plan, design, implementation, observation, iterative redesign, etc.). Ten teams were formed with one math and one science teacher from the same school. Each team had a large bench to work on, all teams were housed in a large room, and they operated their robots on the unoccupied floor space in the same room or outside the room in a large corridor. Through the PD workshop, using the robotics kit, the teachers learned myriad robot-related tasks, such as assembly, programming, actuation, motion planning, sensor integration, operations, and troubleshooting. To plan and develop robotics-based lessons, the project team began by asking workshop participants to identify middle school relevant, standards aligned,[37,38] science and math concepts that they deemed pedagogically challenging. For a subset of the identified topics, the project team and teachers collaboratively developed robotics-based teaching and learning strategies, hands-on activities, and corresponding assessment materials. Specifically, supported by the project team, the teachers designed and constructed the base robots including the needed attachments for the base robot, created the corresponding computer programs, and developed the appropriate activity sheets. During this initial lesson development stage, group discussions, brainstorming sessions, and co-generation meetings offered opportunities to iteratively adapt, modify, and improve the lessons. Using the aforementioned process, we have created several lessons for math topics (e.g., number line, least common multiplier, ratio and proportion, function, analyzing and interpreting data, expressions and equations, statistics, etc.) and science topics (e.g., force, displacement, velocity, acceleration, gravity, mass, friction, energy, environment, design optimization, biological adaptation, etc.) for implementing them in the classroom setting with students. This paper is based on the collaboration between one teacher and one researcher. For classroom implementation, to save time and to generate technical skills in students, the teacher began by guiding students to assemble the base robot that is used in all lessons. The teacher then guided the students to implement the activities using the robots during the actual class period and the students recorded the observations in activity sheets. A representative math lesson is introduced in Table 1 and is illustrated in Figure 2.

Table 1: A representative robotics-based math lesson.

Lesson topic	Lesson description
Ratio and proportion	The teacher verbally teaches the theoretical concepts of ratio and proportion. Then, the teacher explains the applications of the ratio and proportion concepts in daily life. To illustrate the concepts and applications of ratio and proportion, the teacher asks the students to change the gears between the motor (driver) and wheel (driven) shafts of the base robot. The students change the gears to yield different gear ratio between the driver and driven shafts. The students command the robot wheels to turn a fixed number of rotations for different gear ratios. The students observe the distance travelled by the base robot for different gear ratios and write the observations on the activity sheets. The students also compare the traveled distance measured manually using a measurement tape and by an ultrasonic sensor attached with the base robot. The students try to explain reasons for differences in travelled distance for different gear ratios. In this way, the students learn the fundamental concepts of ratio and proportion, and also see its applications in meaningful activities. Figure 2 shows an example of how a student observes the impacts of changes in gear ratios on the distance travelled by the robot.

Figure 2: A student observes the distance travelled by the base robot for different gear ratios and writes the observations on the activity sheet. The student also compares the measurements of the travelled distance using a measurement tape and an ultrasonic sensor attached to the base robot.

3. The Research Team and the DBR Process

To implement the robotics-focused science or math lessons, the teacher first needs a couple of properly assembled base robots. The teachers are usually busy, and the teachers also think that the students should gain the technical skills of building the base robots. Such experience of building the robots may enrich the students with technical expertise and they may also feel better while using the robots in their robotics-based lessons. Thus, as indicated previously, the teacher planned to get the base robots assembled by the students under her guidance.

The teacher randomly selected 10 7^{th} grade students from a math class of 30 students. The teacher then randomly divided the 10 students into 2 groups, each comprising of 5 students. The objective of the teacher was to get 2 base robots assembled by 2 student groups so that the teacher could implement a robotics-based math lesson with the students. For this purpose, each group assembles the robot during several 45-minute class sessions. The two participant groups assemble in the same classroom, they work in parallel, but separately in separate spaces, under teacher's guidance. The researcher observes the assembly activities performed by the students. The teacher planned to finish the assembly tasks in four 45-minute classes over four consecutive days, and then, having completed the robot building, conduct the math lesson in the fifth class period. We consider each class period as an iteration of the DBR process. So, there were four iterations to finish the design/assembly process and a fifth iteration to conduct the math lesson. For each iteration, pedagogical effectiveness and student learning were assessed and documented to inform the following iteration, which is the basic concept of the DBR process.

We call one group of students as the *traditional* DBR group. With this group, we use traditional qualitative observation, brainstorming, discussion, questionnaire, and feedback methods to analyze the outcomes of each iteration. We call the second group as the *systems* engineering DBR group. With this group, in addition to the traditional methods, we follow some advanced systems engineering approaches under the cognitive apprenticeship of the expert researcher to analyze the outcomes of each iteration. The DBR process is treated as a CI method and resembles the PDCA cycle. We observe the outcomes in each iteration and analyze them using cause-effect diagrams. Then, we apply the Pareto principle to identify the vital few causes that contribute to the major outcomes. At the end of an iteration, outcomes for the systems approach are compared to that for the traditional approach. A variety of criteria are used for comparing outcome in the two groups, including: timely completion of robot assembly, amount of help required, number of assembly mistakes, level of understanding of robot function, level of understanding of engineering vocabulary, mistakes in the final product, engagement and enthusiasm, classroom environment, timely completion of math lesson, ease in classroom management, correctness in completed activity sheets, overall learning effectiveness, etc. As detailed below, for this comparative study, the researcher uses appropriate observation and questionnaire techniques, data collection approaches, and recording methods and materials. Table 2 presents detailed statistics of the research team (teacher, students, and researcher).

Table 2: Detailed statistics of the research team and the class

Number of teachers	1
Number of researchers	1
Number of students	10
Number of male students	4
Number of female students	6
Number of students in the traditional group	5
Number of male students in the traditional group	2
Number of female students in the traditional group	3
Number of students in the systems group	5
Number of male students in the systems group	2
Number of female students in the systems group	3
Number of planned classes (iterations)	5
Planned duration of each class/iteration	45 minutes
Students' grade levels	7th
Targeted subject to teach	Math

4. Familiarizing with the Advanced Systems Engineering Approaches

4.1. Continual Improvement Process[32,39,40]

A continual improvement process (CIP) refers to a culture of relentless enhancement in the performance of products, services, or businesses through gradual efforts or breakthrough advancements. Under the CIP paradigm, customer-focused processes must be subject to ongoing evaluation for improvements *vis-à-vis* requirements such as efficiency, effectiveness, and flexibility. Many management system (e.g., business strategy, organization relationship, product quality, etc.) rely on the CIP to help accomplish goals of diverse business organizations. Specifically, the CIP becomes part of the process or system under consideration wherein the performance of the process and feedback from customers are evaluated against the organizational goals to identify areas for improvement. Although identified as a management process, CIP's execution is not limited to management, instead simply that the CIP makes decisions about the implementation of the delivery process and the design of the delivery process itself.

4.2. The PDCA Cycle[33,39,41]

Plan-do-check–act (PDCA) is an iterative technique to perform a CIP. A typical PDCA cycle is drawn in Figure 3 with its components elaborated below. In the PLAN phase, we identify the desired outputs (targets or goals), which can serve as complete and accurate specifications for expected improvement, and enumerate tasks to follow for achieving those outputs. When feasible, it is advisable to begin on a small scale and test possible effects. In the DO phase, we implement the tasks by following the plan to produce an instantiation of the system, process, or product aiming for the goals specified in the PLAN phase. Moreover, we measure and collect actual performance data for graphing and analyses in the CHECK and ACT phases. In the CHECK phase, we contrast the actual performance with the desired performance to ascertain any differences. Moreover, we examine the implementation of tasks *vis-à-vis* the PLAN to establish the appropriateness and completeness of execution and to reveal any deviations. We utilize appropriate graphing techniques to represent data, making it easier to uncover trends over iterative PDCA cycles and transforming the collected data into information, which is needed for the next phase ACT. In the last phase ACT, we draw lessons, uncover any unresolved problems, and trigger the next iterative cycle. Specifically, if in the CHECK phase, we deem the PLAN implemented in the DO phase to be an improvement over the prior performance standard (baseline), then we make the achieved performance outcome the new performance standard (baseline) for how the system, process, or organization should ACT going forward (i.e., we enACT new standards). If in the CHECK phase, we deem the PLAN implemented in the DO phase not to yield any improvement, then we retain the prevailing performance standard (baseline) in effect for the next iteration. If in either case, in the CHECK phase, we uncover something better or worse than expected, then additional learning is recommended, which suggests potential future PDCA cycles. Some practitioners of PDCA assert that in the ACT phase the system under consideration must be subjected to adjustments or corrective action. However, it is counter to the PDCA paradigm to propose and implement process adjustment without performing the formal PLAN phase, or to make the new performance standard (baseline) without going through the DO and CHECK stages.

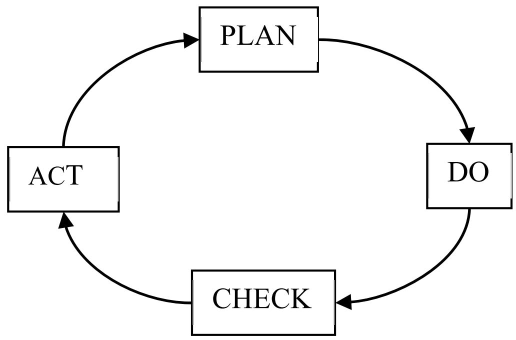

Figure 3: A typical PDCA cycle.

4.3. The Cause-and-Effect Diagram[34,39,42]

The Ishikawa diagrams are causal diagrams that are created to clearly depict many possible root causes affecting a process or the various root causes of a specific event. Since the Ishikawa diagram resembles the side view of a fish skeleton, it is also known as the fishbone diagram. The Ishikawa diagram can be used in a variety of scenarios, e.g., to structure a brainstorming session to categorize ideas; to prevent quality defects by identifying potential factors causing an overall effect; etc. For each effect (i.e., imperfection, variation, etc.), it is likely that there are various categorizes of causes, for example:[42]

- People refers to individuals who are involved in any aspect of the process.
- Methods refer to the way the process is performed and the specific requirements for performing it, e.g., policies, procedures, rules, regulations, and laws.
- Machines refer to any equipment, computers, tools, etc., needed to accomplish the process.
- Materials refer to raw materials, supplies, parts, pens, paper, etc., used to produce the final product.
- Measurements refer to data generated from the process that is used for assessing the process quality
- Environment refers to the conditions, e.g., location, time, temperature, and culture in which the process operates.

4.4. *The Pareto Principle*[35,43]

In 1896, an Italian economist Vilfredo Pareto published a paper "*Cours d'économie politique*," showing that approximately 80% of the land in Italy was owned by 20% of the population. In the late 1940s, a management consultant Joseph M. Juran noted that for many situations, a large number of effects come from a small number of causes, suggesting the 80:20 rule, and he named it as the Pareto principle. The Pareto principle is also referred to as the law of the vital few, the principle of factor sparsity, etc. The 80:20 rule is widely employed in business, e.g., effectiveness of advertisement campaigns (80% of results are produced by 20% of messages); strategizing about product mix (80% of a company's sales is produced by 20% of its products); examining defects in design (80% of design flaws may be due to 20% reasons); etc. The 80:20 rule is known to approximately follow a power law distribution (or a Pareto distribution) for a given set of parameters. Thus, it follows from the 80:20 rule that the input-output or cause-effort distribution for most events or things is unequal (i.e., not one-to-one).

5. The Iterations in the DBR Process with Analyses for Designing the Base Robots and the Robotics-Focused Math Lesson

5.1. *The First Iteration*

The objective of the first iteration was to sort out parts of the robotics kit, keep the parts in different categories, and put the parts of different categories inside different Ziploc clear plastic bags. The targeted/planned outcomes were that, within a single class period, the students would be able to sort out the parts and keep them inside the bags properly without any mistake. The two groups of students started to sort out the parts in parallel.

For the systems group, the teacher and researcher independently recorded their planned outcomes of the iteration using the data sheet shown in Appendix A. First, they wrote the planned outcomes in response to Q1, which we considered as the PLAN phase of the PDCA cycle. The teacher provided sorting instruction sheets to the student groups. The teacher and the researcher guided the students sorting the parts. Figure 4 shows the actual classroom environment where the two student groups were sorting out the robotics parts. Second, the teacher and researcher independently recorded their activities with the students in response to Appendix A, Q2, which we considered as the DO phase of the PDCA cycle. Third, following the completion of this iteration, the teacher and researcher independently recorded their analyses based on their observations in response to Appendix A, Q3 and Q4, which we considered as the CHECK phase of the PDCA cycle. Fourth, the teacher and researcher independently made their decisions about the outcomes using the information on the data sheet shown in Appendix A, i.e., they recorded the proposed corrective actions in response to Q5, which we considered as the ACT phase of the PDCA cycle. For the traditional group, the teacher and researcher did not record their observations and analyses using Appendix A or any similar tool. Instead, they used traditional methods to observe, analyze, and make decision about the outcomes of student activities in the traditional group.

Figure 4: Actual classroom environment where student groups sort out robotics parts and keep them inside plastic bags.

We analyzed the teacher and researcher responses to Q3 of Appendix A and determined the outcomes of the first iteration for the systems group students as follows: 2 students could not find (identify) a few parts, 2 students could not categorize the parts and they put the parts into wrong bags, 1 student lost a few parts, 2 students could not finish sorting the parts timely, etc. We note that that this finding is different from our planned outcomes, and we see some deficits in the actual outcomes. We analyzed the deficits in the actual outcomes based on the responses gathered for Q4 in Appendix A. In addition to identifying the probable reasons for the deficits in the actual outcomes, we also estimated the average of the relative contribution/importance (%) of each reason for causing the total (entire) deficits. The results outlined in Table 3 show that $\approx$80% (actually 72.5%) contributions to the total deficits in the targeted outcomes were due to only 20% of the reasons, *viz.*, (i) lack of introductory remarks and (ii) lack of proper instruction sheets. Such comparison is better explained in Figure 5. In this manner, the Pareto principle helped us identify the few critical factors over many other trivial factors and pinpoint the main factors that may affect the lesson outcomes the most.

Figure 6 shows the cause-and-effect diagram that specifies various factors that are responsible for the unwanted effects (deficits in the planned lesson outcomes). This diagram helps pinpoint the sources (reasons) that may be responsible for the unwanted outcomes, and also helps identify necessary corrective actions to be implemented in the next iteration. Based on the analysis and results obtained for Q3 and Q4 (as provided in Table 3 and Figures 5 and 6), the teacher and researcher suggested a set of corrective actions to be implemented in the next iteration, which is articulated as the response of Q5 in Appendix A. We consider such corrective actions as the ACT activity of the PDCA cycle. The teacher and researcher collectively adopted the following corrective actions to implement in the next iteration.

i. The teacher would explicitly explain the objectives of the class in a better way at the start of the class period.
ii. The teacher would organize appropriate instruction materials for students.
iii. The teacher would motivate the students to grow their interest, attention, discipline, etc.
iv. The teacher would be relaxed to reduce time pressure on students and help them individually.
v. The teacher would motivate the students to arrive on time, maintain good interpersonal relationship, and team spirit.
vi. The researcher would go closer to students and help them when they seek her help. The researcher would show a visual model of the finished product (robot) to the students so that the students have better understanding of what they were expected to achieve.
vii. The teacher would request the school management to provide classroom environment with less or no noise.
viii. The teacher would check that all accessories were readily available so that the students could get those easily for sorting out.

Table 3: Analysis of deficits in the actual outcomes for the first iteration

No.	Probable reason	Mean (*n*=2, teacher, researcher) relative contribution (%) to the total deficits
1.	An introductory speech about the objective of the class and the functions of different parts was not given to the students.	37.5%
2.	Brief instructions about what to do or how to do were not given to the students or were given but were improper and insufficient. There was no appropriate instruction materials provided to the students.	35%
3.	Assembling the parts requires students to pay attention, but the students were not very attentive, there was lack of interest by some students, students were not well-disciplined.	5%
4.	Teacher could not take care of each student/group properly due to shortage of time. Time pressure (pressure to finish within a short period of time) was severe for students.	7.5%
5.	Grouping of the students was not appropriate. Two students arrived late that did not help form the team properly.	3.5%
6.	Poor interpersonal relationships and team sprit among the students and lack of coordination among the students within group were observed.	3.5%
7.	The students did not show interest to receive cognitive apprenticeship from the expert researcher.	2%
8.	There was noise and the classroom environment was unsuitable.	2%
9.	Students did not have a visual model of the finished product.	2%
10.	Some accessories such as plastic bags, scissors, marker pen, loose papers were not readily available.	2%

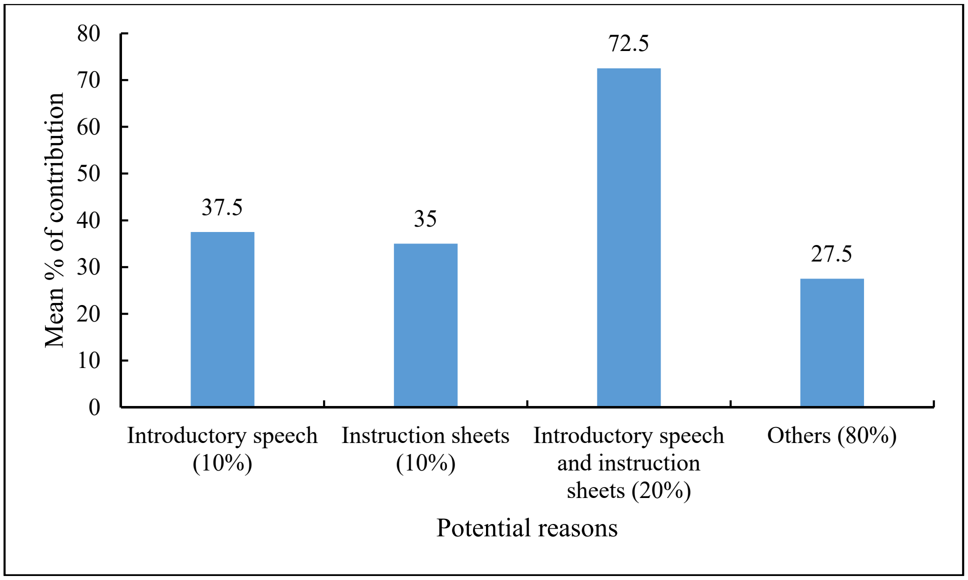

Figure 5: The Pareto principle helps identify few critical factors over many trivial factors to pinpoint the main reasons affecting the outcomes of the lesson.

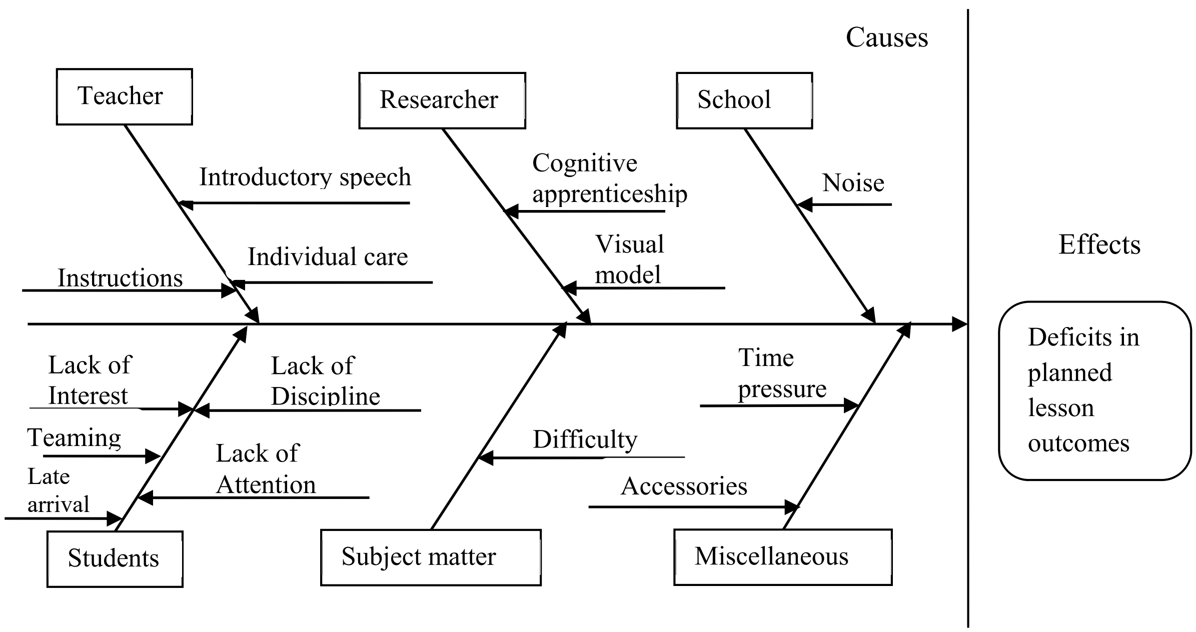

Figure 6: The cause-and-effect diagram showing the various factors responsible for the unwanted learning effects (deficits in the planned lesson outcomes).

5.2. The Second Iteration

In the second iteration, for the systems group students, the teacher implemented the aforementioned corrective actions. The students finished the remaining portion of sorting task. The researcher helped the students when they were about to make mistake. In addition, the researcher explained the functions of different LEGO parts so that the students could gain better understanding of them. The researcher asked the students to cut and paste on their note book the instruction sheets that showed various LEGO parts and their functions, as illustrated in Figure 7. It was thought that such an effort would help the students have a better understanding of the LEGO parts and would be useful during the actual assembly in the next iteration. The researcher explained the interconnection among various parts and, under the cognitive apprenticeship model, built various subassemblies and demonstrated and explained those to the students for practice. The researcher also responded to various questions raised by the students regarding the functionality and assembly of the LEGO parts and the applications of the instruction sheets. As in first iteration, the teacher and researcher followed the systems approach using the data collection sheet in Appendix A for the systems group of students and the traditional approach for the traditional group of students.

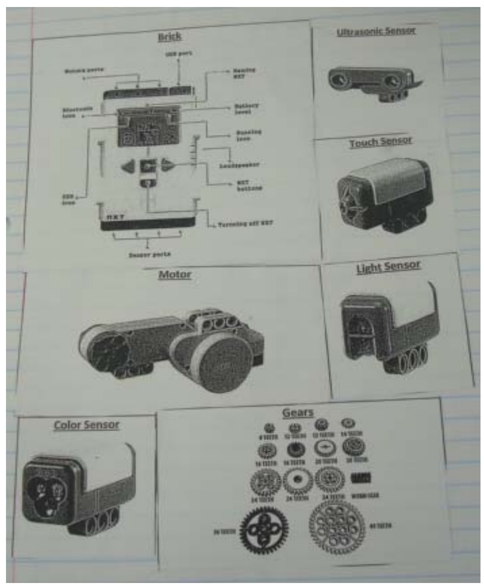

Figure 7: The students cut the instruction sheets containing different LEGO parts and their functions and paste on their notebook to be familiar with them.

For the systems group, in the second iteration, the researcher tested the knowledge of students randomly regarding the functions of various LEGO parts. Two students failed to explain the functions of all the LEGO parts shown in the instruction sheets pasted on their note books. The researcher also tested students' skills about doing a few subassemblies that had been demonstrated by him. The researcher observed that 3 out of 5 students failed to perform the subassemblies properly. Following challenges and limitations were observed in the second iteration: teamwork, indiscipline, noise, etc. Analysis of results using the systems approaches revealed that $\approx 80\%$ (actually 77.5%) contributions to the total deficits in the targeted outcomes were due to only 20% of the reasons, *viz.*, (i) improper instruction sheets with incomplete instructions and the sheets printed with black and white ink instead of colored ink and (ii) the students exhibited lack of attention while the researcher demonstrated the subassemblies under the cognitive apprenticeship model. As previously, the results were analyzed to suggest corrective actions to be implemented in the next iteration.

5.3. The Third Iteration

The objective of the third iteration was for students to follow the instruction sheets, assemble the LEGO parts, and build the robot partially. The teacher guided the students and the researcher helped the students. The teacher also implemented the corrective actions decided in the previous iteration. The teacher and researcher continued to follow the systems and traditional approaches as previously. The students attempted to assemble the robot, however, students in both the traditional and systems groups made some mistakes during the assemblies and could not progress as much as expected. Some previously observed challenges and limitations persisted in this iteration. For example, the teacher distributed the robot assembly instruction sheets printed in black ink and provided additional instruction sheets that were incorrect and irrelevant. Hence, the students were confused about the instruction sheets, could not proceed far, and completed only a portion of the assembly task. Furthermore, the class time was short (only 30 minutes were used for assembly, 15 minutes were used for wrap up). Analysis of results using the systems approaches revealed that $\approx$80% (actually 82.5%) of contributions to the total deficits in the targeted outcomes were due to only 20% of the reasons, *viz*., (i) improper and incorrect instruction sheets and (ii) time limitation. As previously, the results were analyzed to determine corrective actions to be implemented in the next iteration. For example, the teacher decided to consult with the researcher to examine the relevance of instruction sheets in advance of the next iteration and print and distribute instruction sheets in color ink to every student. Moreover, the teacher planned to increase the class period to a double period for the next iteration.

5.4 The Fourth Iteration

As previously, the teacher and researcher followed the systems and traditional approaches. The students were working towards finishing the assembly of the robots. The teacher implemented the corrective actions that were deemed necessary in the previous iteration. The outcomes showed that the students attempted to assemble the robot parts and the students completed assembling two robots. A fully developed base robot is illustrated in Figure 8. However, the students faced some problems or made some mistakes during this iteration, as follows.

i. A few students placed the programmable brick in a wrong location.
ii. Some students needed additional time as they were slow.
iii. A few parts were missing and it took time to find them and use in the assembly.
iv. Some parts were attached in wrong locations.

v. Stability of the robot structure was not good as some pins were missing or were not attached properly.
vi. The students were confused about the front and back side of the robot.
vii. The gears were attached loosely and caused motion problem.
viii. The students faced problems to attach the sensors, etc.

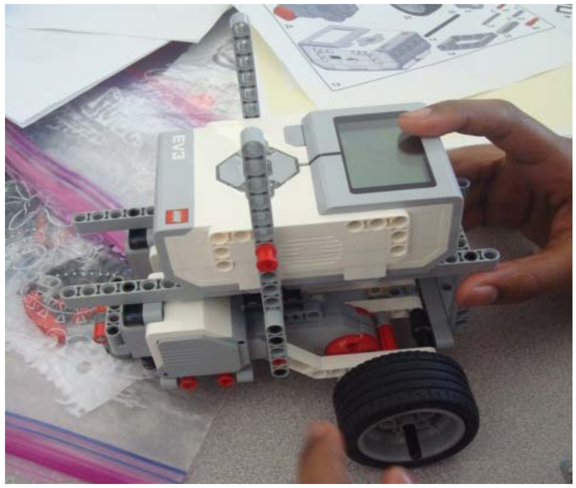

Figure 8: A base robot assembled by the students with the guidance and help of the teacher and researcher after several iterations.

Analysis of results using the systems approaches revealed that 80% contributions to the total deficits in the targeted outcomes were due to 20% of the reasons, *viz.*, (i) lack of previous experience of the students (the instruction sheets were not enough to enable the students assemble independently) and (ii) lack of sufficient number of experienced adults to help students during the assembly under the cognitive apprenticeship model. As previously, the results were analyzed to determine corrective actions to be implemented in the next iteration. Specifically, the teacher and researcher decided to proactively help the students as follows. The researcher, under the cognitive apprenticeship model, demonstrated the correct assembly. The students who finished their assigned tasks early were tasked to help other students who could not finish. The teacher and researcher used additional time after the class to check the assemblies and finish the small incomplete portions of the assembly tasks. As a first robotics-based math lesson, these 10 students were to be taught the ratio/proportion topic using the assembled robots in the next class.

5.5 The Fifth Iteration

The teacher implemented the lesson outlined in Table 1 and illustrated in Figure 2 in the classroom settings. Based on the corrective actions decided previously, the researcher made the students aware of some of the limitations (e.g., stability of the robot structure, identification of front and back of the robot, etc.). After the implementation of the lesson using robotics, outcomes were analyzed. It was observed that the teacher could not finish the entire lesson with all students on time. The students found mismatch between the activity sheets and the robots' behaviors. They faced problem in changing the gears timely and properly since the necessary gears were also not readily found. Analysis of results using the systems approaches revealed that 80% contributions to the total deficits in the targeted outcomes were due to 20% of the reasons, *viz.*, (i) teacher's lack of prior experience and inability to perceive the time needed by students to complete the activity and (ii) lack of mock practice trials using the activity sheets and the robots including changes in gears before lesson implementation in the classroom. Following corrective actions were considered. First, the teacher and researcher helped students who could not finish the gear change and robot operation activities properly. The teacher gave a correction note to students regarding the mismatch between the activity sheets and the actual behaviors of the robots. The teacher learned from this first robotics-based math lesson about the need for time and material management to obviate these problems in future classes. The researcher, under the cognitive apprenticeship model, demonstrated the correct activities including gear changing. The students who finished the activities early were tasked to help other students who could not finish. The teacher and researcher used additional time after the class to work with students who could not finish the activities on time.

6. Overall Outcomes of the Systems Approach in the DBR Process

The assembly of the robots performed by students is treated as an engineering experience within the STEM scope in the middle school. In addition to gaining engineering experience, students learned various engineering vocabulary terms such as control, sensor, gear, power, wheel, shaft, motion, measurement, etc. Based on our observations, students in both the traditional and systems groups learned such engineering skills and vocabulary. This outcome indicates the effectiveness and benefits of the DBR process to help students learn and evolve their understanding through an iterative process. The results provide a successful illustration of the effectiveness of the DBR process for the young, middle school age students. The differences between the systems group and traditional group in the teaching effectiveness and learning outcomes, observed in and analyzed after the fourth and fifth iterations, are summarized in Table 4.

7. Discussion

In the study reported in paper, middle school students took part in designing and developing a robotic device that was used to implement a math lesson in the later phase. Performing robotic design and robotics-based math lesson can impart new learning to students: (i) they gain basic engineering knowledge, skills, and vocabulary terms in addition to the math content of lesson and (ii) familiarization with engineering and technology may enhance their interest, awareness, and engagement in STEM disciplines and may improve their STEM learning outcomes. The engineering design and engineering practices entailed in the lesson of this study are not beyond

Table 4: Differences in outcomes between the systems and traditional approaches observed after the fourth and fifth iterations of the DBR process

Evaluation parameter	Systems approach	Traditional approach
Timely completion of the LEGO assembly	Took ≈ 5 minutes more to complete the assembly process	Took ≈ 15 minutes more to complete the assembly process
Timely completion of the robotics-focused math lesson	Took ≈ 10 minutes more to complete the lesson activities	Took ≈ 25 minutes more to complete the lesson activities
Amount of help provided by the teacher and the researcher	The students needed less help from the teacher and researcher during the assembly procedures	The students needed more help from the teacher and researcher during the assembly procedures
Mistake in the assembly procedures	The students made less mistake in assembly steps during the assembly procedures	The students made more mistake in assembly steps during the assembly procedures
Level of understanding about the configuration and functions of the robots	Based on the questionnaires of the researcher, it was evident that the students gained more understanding about the configuration and functions of the robots	Based on the questionnaires of the researcher, it was evident that the students gained comparatively less understanding about the configuration and functions of the robots
Level of understanding about the engineering vocabulary	Based on the questionnaires of the researcher, it was evident that the students gained more understanding about the engineering vocabulary	Based on the questionnaires of the researcher, it was evident that the students gained comparatively less understanding about the engineering vocabulary.
Mistakes in the finished assembly product (robot)	It was observed that there were less mistakes in the finished product when the researcher checked such product	It was observed that there were more mistakes in the finished product when the researcher checked such product
Student engagement and enthusiasm	It was observed that the students were comparatively more engaged and enthusiastic during the assembly processes	It was observed that the students were comparatively less engaged and enthusiastic during the assembly processes
Classroom environment	It was observed that the classroom environment was comparatively more professional and calm	It was observed that the classroom environment was comparatively less professional and calm
Ease is classroom management by the teacher	It was observed that the teacher experienced more ease in classroom management	It was observed that the teacher experienced less ease in classroom management
Correctness in activity sheets	It was observed that the systems team performed all the activities correctly and recorded on the activity sheets properly without any mistake	It was observed that the traditional team performed 3 activities out of 4, but 1 activity was not correct and the activities were not recorded properly on the activity sheets.
Learning effectiveness	The researcher asked 5 questions to judge the level of understanding of the students about the subject matter (ratio and proportion). The systems group could give correct answers to all the 5 questions	The researcher asked the same 5 questions to judge the level of understanding of the students about the subject matter (ratio and proportion). The traditional group could give correct answers to 3 out of 5 questions

the educational preparation and general maturity level of middle school students. In fact, the robotic design and robotics-based math lesson are inspired by prior literature in which engineering design projects and high-tech engineering concepts have been utilized to engage middle and high school students, e.g., embedded systems design and development with high school students,[44] ocean observing systems data explored by K-12 students,[45] engineering design projects to improve K-12 math understanding,[46] microelectronic systems design conducted with K-12 students,[47] etc. Moreover, the inclusion of engineering design and engineering practices in the Next Generation Science Standards (NGSS)[37] necessitates the integration of engineering in K-12 STEM education. Therefore, the approach of this paper is applicable to teaching and learning in middle school.

Successful application of system engineering-based DBR iterations in middle school classroom requires formal training of teachers in its methodology. This paper is based on a collaboration between a teacher, who received a three-week PD in the use of robotics to teach middle school science and math and experienced traditional DBR iterations during the summer PD, and a researcher, who is experienced in robotics, DBR, and systems engineering. The researcher sensitized the teacher to systems engineering concepts and was present in the classroom to assist the teacher under the cognitive apprenticeship model.[21] The trained teacher and expert researcher both helped the students from the start of the DBR iterations verbally and with appropriate instructional materials. The structure, organization, and content of the PD workshop and follow-up support allowed the project team to overcome any perceived lack of teacher's expertise in implementing systems engineering based DBR iterations with students in the classroom.

The design and development of the base robot and its use in the math lesson were divided into several iterations under the DBR approach and the iterations were performed in a regular class within the specified class duration (45 minutes or 90 minutes). That is, the proposed approach was implemented considering the time constraints of the middle school classroom management systems. Therefore, this paper's approach can be implemented, under time constraints, by well-trained and motivated teachers, who value the integration of robotics in regular classroom environment. In our study, during different iterations of DBR, the teacher involved students in varied robotics activities so that they had opportunities to enhance their engineering skills and become familiar with technological components behind the lesson. Repeat offerings of robotics-based STEM lessons do not need to undergo extensive DBR iterations. Having conducted DBR iterations for such lessons a few times, a teacher will acquire intimate familiarity with frictionless organization of classroom, student teams, lessons and activity sheets, robotics kits, observation protocols, etc. Dissemination of iteratively refined principles for designing robotics-based STEM lessons, and corresponding classroom practices, can facilitate their broad adoption and adaptation by other teachers in the context of middle school environment with tight schedule.

The central idea of this paper is to examine whether the systems approach of analyzing the outcomes of DBR iterations can enhance the effectiveness of the DBR itself. Our objective is not to justify whether all the activities and analyses for the DBR process be performed (i) during the class period; (ii) after the class period; (iii) by the teacher; or (iv) by the researcher and teacher in collaboration. Nonetheless, as evidenced above, the DBR process with the systems approach was deemed practical by the researcher-teacher team for implementation during actual class period with students. Further research and continual improvement[40,48] will enhance the practicality and usability of DBR approach with systems engineering in the middle school classrooms.

As stated in Section 1, the young age and maturity level of students may necessitate *special consideration* for incorporating the DBR process in K-12 environment. However, this does not mean that middle school students cannot pursue robotics-based STEM learning and that such learning is not amenable for examination under the lens of DBR. In fact, implementation of DBR in classrooms has been considered in Refs. 7, 13-15. Although a tangible robotic platform, enabling kinesthetic learning, may help young middle school students to learn the content in a better way, special considerations may be required, e.g., guidance from the teacher, easy to follow instructional material, well-paced and appropriately sequenced activities, etc. In fact, throughout this study, our systems engineering based implementation of the DBR process carefully examined and uncovered such considerations. Students simply pursued the assigned design and learning activities guided by ample support from the researcher and teacher, who utilized the systems approach to analyze the outcomes of the DBR iterations. Of course, to gainfully utilize such approaches, various obstacles must be overcome, e.g., classroom time constraints, students' lack of robotics experience, lack of motivation of teachers and students, lack of school support, lack of sufficient number of robotics kits and appropriate instruction materials, etc. During this study's DBR process, such obstacles were observed and the results presented herein were obtained despite such obstacles. We submit that removal of such obstacles, through continuous improvement,[39-40,48] can ease the implementation of the DBR process.

The DBR process documented in this paper is the study of a teacher actually implementing such process while providing instruction to a regular class of middle school students in an actual classroom setting. For examining the robotics-focused lesson with the systems engineering DBR process, the teacher randomly selected a subset of students. Nonetheless, the teacher was responsible to complete the school year curriculum requirements in a timely manner. Even as this implementation of the DBR process was conducted on a pilot basis, its success can facilitate integration of robotics-based lessons more widely.

The CIP[39-40] is a systems engineering tool that is used under the systems engineering concept called Quality Management System (QMS). Such systems engineering tools have been specifically used in college level programs and courses[48] and are adaptable for educational innovation in general. As evidenced in this paper, system engineering concepts were applied by a researcher and teacher to analyze the outcomes observed in each iteration of the DBR process to support the students and inform the modifications for the next iteration. As noted in Section 1 and as seen in Section 5, such an incorporation of system engineering principles in the DBR process helps enhance the effectiveness of the DBR process and learning outcomes. Throughout our implementation, middle school students were engaged in performing activities that were aligned with their education and maturity level, without posing any hindrance to the analysis performed by the researcher and teacher. In a similar vein as CIP, the Pareto principle[43] is not for analyzing business scenarios only. The key objective of the Pareto principle is to identify major reasons that may cause an undesirable outcome.[35,43] We employed the Pareto principle to identify major reasons that caused undesirable outcomes in each DBR iteration. The cause and effect diagrams[42] were used to relate the potential causes to the observed effects (i.e., undesirable outcomes). As seen in Section 5, application of various systems engineering tools for refining DBR iterations, to facilitate systematic integration of robotics in education, was meaningful, useful, and beneficial. Our objective has not been to establish the applicability of or to introduce these systems engineering tools for education, instead our objective has been to examine how DBR iterations can be systematized by using established systems engineering tools. In fact, examples abound in literature showing the use of systems engineering tools to enhance education, e.g., a Kansei-based interface design analysis of open source e-Learning system,[49] use of systems engineering methods in the study of higher education structure optimization,[50] analysis of course implementation performance using a PDCA cycle,[51] use of PDCA cycle to improve teaching quality,[33] applications of continual quality improvement and process improvement to improve engineering education,[51-52] etc. Evidence from such prior works on the use of systems engineering for improving education provides ample justification for examining and refining DBR iterations using systems engineering in the context of designing and implementing robotics-based STEM lessons and activities in middle school classrooms.

8. Conclusions and Future Works

We observed two small groups of middle school students as they assembled LEGO robots and conducted a math lesson with the robot in a classroom environment. Their teacher helped the students perform the tasks. A researcher employed the cognitive apprenticeship model to help the students learn tasks. All instructional and hands-on learning activities were performed under the DBR process. That is, the robot assembly and math lesson tasks were performed in a few iterations and the experiences and mistakes in one iteration were used to improve the pedagogy and learning outcomes in the next iterations. The outcomes were assessed after the iterations. The researcher pursued two distinct approaches in performing the DBR iterations. Specifically, one group of students was observed using the traditional DBR approach consisting of qualitative observation, brainstorming, discussion, questionnaire, and feedback methods. For the second group of students, some advanced systems engineering approaches were employed to analyze the outcomes of each DBR iteration and to formulate iterative modifications. The overall outcomes of the two approaches were observed and compared. The results showed that both traditional and systems approaches were effective to teach the students the assembly of the LEGO robots successfully. The results also show that the systems approach was more effectiveness than the traditional approach. The results thus prove the effectiveness of the DBR process in STEM education for middle school environment. The results show that engagement of students in pilot testing of instructions design, lesson planning, and lesson implementation can be helpful to teachers.

In future work, we will design and develop instruments and rubrics to assess the outcomes of each DBR iteration more formally and evaluate the differences in outcomes between the two approaches quantitatively. Specifically, we will conduct a study with teachers implementing the DBR process in classroom environment with students (25 to 30 students) within the usual single and double class periods allocated for instruction. For comparison purposes, we will consider two teachers, each with one class of students. To address the observed challenges related to students' lack of interest, lack of attention, and lack of discipline, we will restrict number of students in each team to three and assign each student in the team a specific role to keep them engaged. While one teacher will follow the traditional DBR methodology, the other teacher will follow the systems engineering based DBR methodology. Such an approach will ensure that observations and learnings of the teacher from the systems engineering based DBR iterations do not influence the teacher following the traditional DBR methodology. The DBR outcomes of each iteration in each DBR approach (systems engineering versus traditional) will be observed, evaluated, and analyzed by at least two researchers independently to obtain reliable and generalizable results.

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References

1. Barab, S., and Squire, K. "Design-based research: Putting a stake in the ground." *The Journal of the Learning Sciences* 13.1 (2004): 1-14.
2. Brown, A.L. "Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings." *The Journal of the Learning Sciences* 2.2 (1992): 141-178.
3. Cobb, P., *et al*. "Design experiments in educational research." *Educational Researcher* 32.1 (2003): 9-13.
4. Fishman, B.J., *et al.* "Design-based implementation research: An emerging model for transforming the relationship of research and practice." *Design-based Implementation Research: Theories, Methods, and Exemplars. National Society for the Study of Education Yearbook* 112.2 (2013): 136-156.
5. Kelly, A. "Design research in education: Yes, but is it methodological?" *The Journal of the Learning Sciences* 13.1 (2004): 115-128.
6. The Design-Based Research Collective. "Design-based research: An emerging paradigm for educational inquiry." *Educational Researcher* 32.1 (2003): 5-8.
7. Moorhead, M., Listman, J., and Kapila, V. "A robotics-focused instructional framework for design-based research in middle school classrooms." *Proc. ASEE Annual Conference and Exposition* (2015): 10.18260/p.23444.

8. Moorhead, M., *et al.* “Professional development through situated learning techniques adapted with design-based research.” *Proc. ASEE Annual Conference and Exposition* (2016): 10.18260/p.25967.

9. Sztajn, P., *et al.* “Using design experiments to conduct research on mathematics professional development.” *ALEXANDRIA Revista de Educação em Ciência e Tecnologia* 6 (2013): 9—34.

10. Ganesh, T.G., and Fulton, I.A. “Design-based research: A framework for designing novel teaching and learning experiences in middle school engineering education.” *Proc. 2011 Frontiers in Education Conf.* (*FIE*) (2011): T2F-1-T2F-7

11. Papert, S., and Harel, I. “Situating constructionism.” In I. Harel and S. Papert (Eds.), *Constructionism*. Norwood, NJ: Ablex Publishing Corporation. (1991): 1–9.

12. Singh, O.B. *Development and Validation of a Web-based Module to Teach Metacognitive Learning Strategies to Students in Higher Education*. Ph.D. Dissertation, University of South Florida, (2009).

13. Reiser, B., *et al.* “BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms.” *Cognition and Instruction: Twenty-five Years of Progress* (2001): 263–305.

14. Cobb, P. “Conducting teaching experiments in collaboration with teachers.” In A.E. Kelly and R.A. Lesh (eds.), *Handbook of Research Design in Mathematics and Science Education* Mahwah, NJ: Erlbaum (2000): 307–333.

15. Stephan, M., and Cobb, P. “Teachers engaging in mathematics design research.” In T. Plomp and N. Nieveen (eds.), *Educational Design Research – Part B: Illustrative Cases* Enschede, the Netherlands: SLO (2013): 277-298.

16. Lawhead, P., *et al.* “A road map for teaching introductory programming using LEGO Mindstorms robots.” *ACM SIGCSE Bulletin* 35.2 (2003):191-201.

17. Cruz-Martín, A., *et al.* “A LEGO Mindstorms NXT approach for teaching at data acquisition, control systems engineering and real-time systems undergraduate courses.” *Computers & Education* 59.3 (2012): 974988.

18. Whitman, L., and Witherspoon, T. “Using LEGOs to interest high school students and improve K12 STEM education.” *Proc. ASEE/IEEE Frontiers in Education Conf.* (2003): F3A6-10.

19. Ryan, R.M., and Deci, E.L. “Intrinsic and extrinsic motivations: Classic definitions and new directions.” *Contemporary Educational Psychology* 25.1 (2000): 54-67.

20. Subramaniam, P.R. “Motivational effects of interest on student engagement and learning in physical education: A review.” *International Journal of Physical Education* 46.2 (2009): 11-19.

21. Collins, A. “Cognitive apprenticeship and instructional technology.” *Educational Values and Cognitive Instruction: Implications for Reform*, (1991): 121-138.

22. Brown, J.S., Collins, A., and Duguid, P. “Situated cognition and the culture of learning.” *Educational Researcher* 18.1(1989): 32-42.

23. Savery, J.R., and Duffy, T.M. “Problem based learning: An instructional model and its constructivist framework.” *Educational Technology* 35.5 (1995): 31-38.

24. Blumenfeld, P.C., *et al.* “Motivating project-based learning: Sustaining the doing, supporting the learning.” *Educational Psychologist* 26.3-4 (1991): 369-398.

25. Easterday, M.W, Lewis, D.R., and Gerber, E.M. “Design-based research process: Problems, phases, and applications.” *Proc. of Int. Conf. of Learning Sciences* 1 (2014): 317-324.

26. Gravemeijer, K., and Cobb, P. “Design research from a learning design perspective.” In J. van den Akker, K. Gravemeijer, S. McKenney, and N. Nieveen (eds.) *Educational Design Research* (2006): 45-85, London: Routledge.

27. McKenney, S., Nieveen, N., and van den Akker, J. “Design research from a curriculum perspective.” In J. van den Akker, K. Gravemeijer, S. McKenney, and N. Nieveen (eds.) *Educational Design Research* (2006): 110-143, London: Routledge.

28. Savino, M.M., and Mazza, A. “Toward environmental and quality sustainability: an integrated approach for continuous improvement.” *IEEE Transactions on Engineering Management* 60.1 (2014): 171-181.

29. Blumenfeld, M., Schmid. F., and Roberts, C. “A systems approach to developing future urban systems: creating a metro that fits the megalopolis.” *Proc. the Int. Conf. on Railway Engineering* (2016): 1-8.

30. Willey, K. “Combining a collaborative learning framework with an e-learning tool to improve learning and professional development in blended learning environments.” *Proc. 2016 Future Technologies Conf.* (*FTC*) (2016): 1303-1304.

31. Tobin, K., and Roth, W.-M. “Implementing coteaching and cogenerative dialoguing in urban science education.” *School Science and Mathematics* 105 (2005): 313–322.
32. Fryer, K.J., Antony, J., and Douglas, A. “Critical success factors of continuous improvement in the public sector: A literature review and some key findings.” *Total Quality Management* 19.5 (2007): 497–517.
33. Li, Y., Li, X., and Li, J. “Exploring the underlying mechanism of PDCA cycle to improve teaching quality: A motivation theory perspective.” *Proc. of PICMET '14 Conf.: Portland Int. Center for Management of Engineering and Technology; Infrastructure and Service Integration* (2014): 2693-2698.
34. Liu, Z.J., *et al.* “A method for improving service reliability of bank counter.” *Proc. IEEE Int. Conf. on Management of Innovation and Technology* (*ICMIT*) (2016): 177-181.
35. Gittens, M., Yong, K., and Godwin, D. “The vital few versus the trivial many: examining the Pareto principle for software.” *Proc. 29th Annual Int. Computer Software and Applications Conf.* (*COMPSAC*), (2005): 179-185.
36. https://education.lego.com/en-us.
37. NGSS. *Next Generation Science Standards (NGSS): For Sates, by States*. Washington, DC: The National Academies Press. Online: http://www.nextgenscience.org/, (2013).
38. CCSSM. *Common Core State Standards for Mathematics. Common Core Standards Initiative*. Online: http://www.corestandards.org/assets/CCSSI_Math%20Standards.pdf, (2010).
39. Kuznetsova, E.S. “Continuous improvement process as a way to increase effectiveness.” *KORUS 2004. Proc. of The 8th IEEE Russian-Korean Int. Symp. on Science and Technology*, 3 (2004): 244—246.
40. https://en.wikipedia.org/wiki/Continual_improvement_process.
41. https://en.wikipedia.org/wiki/PDCA,
42. https://en.wikipedia.org/wiki/Ishikawa_diagram.
43. https://en.wikipedia.org/wiki/Pareto_principle.
44. Bobbie, P.O., Uboh, J., and Davis, B. “A project in embedded systems design and development: a partnership with area high school scholars.” *Proc. ASEE/IEEE Annual Frontiers in Education Conf.* (2004): F4D-14-17.
45. McDonnell, J., *et al.* “Using ocean observing systems data in K-12 classrooms: Proceedings from a workshop exploring the merit and feasibility of developing a National Ocean Observing Systems (NOOS) education product.” *Proc. MTS/IEEE OCEANS* 3 (2005): 2590-2596.
46. Akins, L., and Burghardt, D. “Work in progress: Improving K-12 mathematics understanding with engineering design projects.” *Proc. ASEE/IEEE Annual Frontiers in Education Conf.* (2006): 13-14.
47. Mazzoni, V., and Bertozzi, D. “Interdisciplinary design of a research experience on microelectronic systems for K-12 students.” *Proc. 10th European Workshop on Microelectronics Education (EWME)* (2014): 64-69.
48. Takriff, M. S., *et al.* “Students’ feedback in the continuous quality improvement cycle of engineering education.” *Proc. IEEE Global Engineering Education Conf.* (*EDUCON*) (2011): 374-377.
49. Hadiana, A. “Kansei based interface design analysis of open source e-Learning system for high education.” *Proc. Int. Conf. on Computer, Control, Informatics and its Applications* (*IC3INA*) (2016): 89-92.
50. Shaorong, S. and Liyong, Z. “Systems engineering methods in the study of higher education structure optimization.” *Proc. 4th Int. Conf. on Computer Science & Education* (2009): 484-487.
51. Esa, M., *et al.* “Performance of continual quality improvement for learning process in a microwave engineering based core subject.” *Proc. Int. RF and Microwave Conf.* (2006): 238-242.
52. Williams, M.W., Litynski, D.M., and Apple, D.K. “Process education and continual process improvement at Western Michigan University (WMU).” *Proc. ASEE/IEEE Annual Frontiers in Education Conf.* (2001): F2A-5-F2A-10.

Appendix A: Design-Based Research (DBR) Data Collection Sheet

Date of the class (iteration):

Students' grade:

Subject:

Q 1: What are the targeted/planned/aimed outcomes of this class/iteration? Please write and be specific. [PLAN]

Q 2: Please briefly write what you have done with the students during this iteration. [DO]

Q 3: What deficits/limitations have you observed in the actual outcomes? Please compare with the planned outcomes [CHECK]

Q 4: What may be the probable reasons for the deficits in the actual outcomes? Please identify as many reasons as you can. Please also estimate the relative contribution/importance (%) of each reason for causing the total (entire) deficits. Please also identify who may be potentially responsible for the deficits, e.g. students, teacher, researcher, school management, subject matter, situation, miscellaneous, etc. [CHECK/ANALYZE]

Probable reason	Relative contribution (%) to the total deficits	Responsible

Q 5: What changes are you planning to reflect in the next class/iteration of similar activities to remove or reduce the above deficits in the targeted outcomes? [ACT]