PEDAGOGICAL DESIGN IN STEM EDUCATION BRIDGING EDUCATIONAL ROBOTICS, GAME-BASED LEARNING AND INQUIRY-BASED LEARNING: INSIGHTS FROM A BUNDLE OF LESSON PLANS BUILDING ON THE INCLINED PLANE

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Abstract

We present a bundle of four lesson plans focusing on a robotic kit of ENGINO (www.engino.com), which builds on an inclined plane model. The lesson plans target upper elementary students and can be implemented as an interdisciplinary STEM project. Our pedagogical design has two main pillars. First, it uses as its organizing principle physical or digital artefacts created by students themselves, while undertaking learning activities, termed "learning products". These can be stored in student portfolios and can be reused or reworked in forthcoming learning activities. In this regard, learning products can serve for purposes of formative assessment, self-assessment and peer assessment during the lessons. The second pillar of our approach is an integration of educational robotics, game-based learning and inquiry-based learning. We planned iterations of inquiry cycles with the robotic kit and programming based on a concrete working scenario providing the goal and narrative of the game as well as the rules to be followed (sorting recycling material by using the inclined plane). The feedback gained through the iterations guide the optimization of the major learning artefact (inclined plane). Namely, the operation of the inclined plane is optimized to meet the goal of the game through the iterations by means of add-ons and programming.

Keywords: STEM education, educational robotics, game-based learning, inquiry-based learning.

1 INTRODUCTION

Previous research underlined several beneficial effects of game-based learning in student performance and motivation [1, 2] including conceptual understanding in science and science process skills [3]. Although educational robotics have been frequently used to gamify STEM initiatives delivering a set of encouraging learning outcomes [4], more research will be needed in that latter field to consolidate its learning effects [5, 6]. It should be highlighted that the lack of definite findings and trends are not due to the number of studies, which has been impressive and is still growing, but mostly due to the nature of the field of educational robotics itself and the assessment instruments employed.

Specifically, the inconclusiveness of learning effects of educational robotics should be attributed, at least up to an extent, to gaps or inconsistencies in assessment methodologies implemented so far [5, 6]. A main consideration, in this direction, has been that usual assessment methodologies, such as pre-post study designs, cannot fully capture the richness, diversity and context-dependency of open-ended student learning paths [7, 8]. Another concern is that the confined duration of most interventions building on educational robotics may not suffice for students to interact with the learning material and artefacts in a comprehensive manner [9], before learning effects can be detected in the first place. This usually results in superficial and fragmented educational experiences, which cannot even secure a proper familiarization of students with robotic kits.

Our rationale in the present contribution is to present an example of how to integrate game-based learning, educational robotics, and inquiry-based learning in order to address the challenges outlined above. Inquiry-based learning contributes a structured sequence of learning activities to be followed to conclude an inquiry cycle [10], which is a coherent and complete in terms of pedagogical design, and furthermore, provides the opportunity of iterations, in the form of a succession of inquiry cycles the one after the other, segmenting a student mission into a set of tasks to be processed serially. This scheme can accommodate a considerable degree of flexibility, which is to be expected in interdisciplinary STEM projects, but it can still offer proper scaffolding to student work along their divergent routes.

We will exemplify our perspective by means of a bundle of four lesson plans, which can be implemented as an interdisciplinary STEM project. Specifically, we will showcase how we can use basic building blocks of learning scenarios for pedagogical design and how we can exploit one of these building blocks, namely, learning products, for assessment purposes, including formative assessment, self-assessment and peer assessment. Student inquiry can be planned to progress through the construction of these learning products, which can feed in forthcoming learning activities, and which can offer fruitful ground for optimizing student deliverables through subsequent rounds of testing and re-testing. The lesson plans to be presented have been developed within the frame of the project GINOBOT, which is funded by the Cypriot Research & Innovation Foundation.

2 METHODOLOGY

2.1 Building blocks of pedagogical design

Table 1 depicts our detailed approach to pedagogical design, which has been based on phases and subphases of the inquiry cycle [10], learning activities and learning products tried out and refined during implementations in computer supported and web-based learning environments [11], as well as reference material and support/feedback needed to undertake these activities (for a detailed presentation of Table 1 see [12]). A main focus in our pedagogical design is learning products, which are defined as physical or digital artefacts constructed by students themselves when enacting learning activities. Student inquiry is organized around some core learning artefacts of ENGINO (www.engino.com), which are optimized in iterations of gaming with educational robotics to fulfill a mission.

2.2 Inclined plane

We developed four lesson plans for upper elementary students in the form of an interdisciplinary STEM project concentrating on the inclined plane, which has been manufactured as a blend of two ENGINO artefacts: (1) The launching platform; and (2) Galileo's experimental inclined plane. We have also added to the inclined plane the PRO controller developed by ENGINO to allow us to include programming in the lesson plans. In the example to be presented in the next sections, the inclined plane is used as a machine that sorts recycling materials. The final artefact that emerged offers opportunities for students' engagement in experimentation and optimization, both in terms of construction as well as in terms of programming, and thereby, it offers the opportunity for gamification. The adaptation of the inclined plane as described above has resulted in increasing the possibilities for anchoring the lesson plans on multiple learning objectives of the curriculum for the upper primary level. Details on curriculum mapping for Cyprus and the New York State can be provided upon request by the authors.

3 RESULTS

3.1 Overall rationale of the bundle of four lesson plans that comprise an interdisciplinary STEM project

The working scenario of the project is to design and construct a prototype of a machine that sorts recycling materials. This machine is termed "inclined plane" and consists of an elevating slope, a landing platform, a detection system and a pushing system (Fig. 1). The recycling materials (ENGINO medium rods wrapped in paper or aluminum) roll down the elevating slope, land on the platform on different positions and are pushed through an automated system to the next recycling stage (detection system performed by an infrared sensor placed at the end of the slope; pushing system comprised of a rack and pinion connected to a motor). The slope can be elevated turning a crank, which is connected through a rope with the slope; the game challenge is to configure the machine so that recycling materials with different coefficient of friction (e.g. paper of different texture, glossy surfaces) will land on different positions on the landing platform to be sorted. Students explore variables that may affect the endpoint an object reaches after descending the slope and they define operationally the concept of friction (Science). Before conducting their experiments, they measure angles using the protractor (Mathematics) to vary the slope elevation angle in their experiments. During their experiments they gather data and, then, they draw conclusions based on these data (Science and Mathematics). Students also incorporate programming using the ENGINO PRO controller and the KEIRO software to program the detection system and pushing system so that the machine can sort automatically the two types of recycling materials (paper and aluminium) (Engineering Design). Whenever a recycling material is detected by the infrared sensor, when it has rolled down the slope, then the motor rotates the pinion and the latter moves a rack front and back to push the recycling material to the next recycling stage. Further details on the construction of the inclined plane can be provided upon request by the authors.

Table 1. Phases, subphases, learning activities, reference material, support/feedback, and learning products in learning scenarios.

Phase and subphase	Learning activities	Reference material	Support/feedback	Learning products
Orientation	Watch a video	Video		Notes taken; quiz responses
	Read a text in a weblink	Weblink		Notes taken; quiz responses
Conceptualization	Identify variables	Operational definition guidelines	Partially worked example: Operational definition	List of variables; decision tree
Conceptualization	Construct a concept map	Guidelines for constructing a concept map	Partially worked example: Concept map	Concept map
Conceptualization; Questioning	Formulate questions			Questions
Conceptualization; Hypothesis generation	Formulate hypotheses	Guidelines for formulating a valid hypothesis	Partially worked example: Hypothesis	Hypotheses
Investigation; Design	Design a product/procedure	Blueprint	Highlight different forms/functionalities of the product/procedure	Drawing (paper-and-pencil or digital); specifications
Investigation; Build	Build an artefact	Construction guidelines	Highlight key construction aspects	Artefact (physical or digital)
Investigation; Model	Build a model	Construction guidelines	Highlight key construction aspects	Model (physical or digital)
Investigation; Program	Create a program	Conditional statement		Flow diagram
Investigation; Explore	Interrelate variables and identify trends	Operational definition guidelines	Partially worked example: Operational definition	Data collected
Investigation; Experiment	Design an experiment	VOTAT (vary-one-variable-at-a-time) heuristic	Partially worked example: Classification of variables; experimental trials	Experimental design
	Execute an experiment	VOTAT heuristic		Data collected
Investigation; Data interpretation	Process and interpret data		Partially worked example: Tables; graphs; figures	Tables; graphs; figures
Conclusion; Evaluate	Assess learning products	Reference object (e.g., own, peer or expert learning product)	Rubric with assessment criteria	Assessment rubric completed
Conclusion; Report	Prepare a report		Prompts to refer to learning products	Report
Discussion; Reflect	Reflect upon learning products/routes		Prompts to refer to learning products; visualization of learning routes	Goal accomplishment; mind map
Discussion, Communicate	Present learning products/routes		Prompts to refer to learning products; visualization of learning routes	Presentation; documentary; press release; article

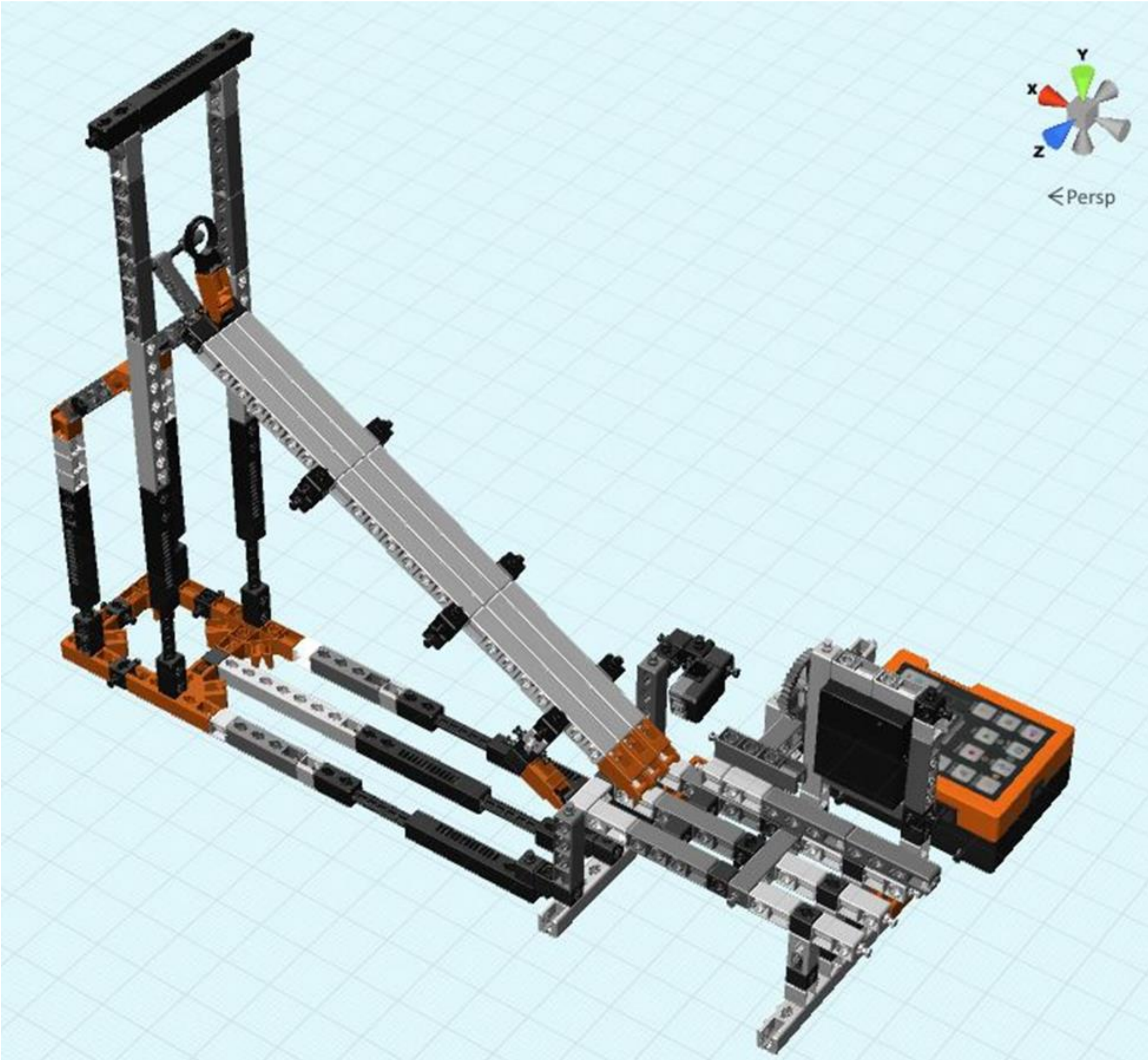

Figure 1. The inclined plane.

3.2 Lesson plans

Fig. 2-5 depict learning activities and learning products for each one of the four lessons. In the first lesson (80min; Environmental Science and Engineering Design), students are initially introduced to the concept of recycling and create drawings to represent their ideas regarding the recycling process of a magazine (Fig. 2). Then, they watch a relevant video in order to compare their drawings to the actual recycling process. Afterwards, students are introduced to the working scenario of the project, which is to design and build a prototype of a machine that will sort recycling materials (paper; aluminium). Based on this challenge, they create the specifications for their machine and draw ideas emphasizing on the slope's characteristics (e.g., shape; dimensions).

In the second lesson (80min; Engineering Design and Science), students create, test and evaluate a machine for the recycling industry that will sort paper and aluminium to address the engineering challenge (Fig. 3). They first build the ENGINO inclined plane model with given construction guidelines, as well as their first slope based on the specifications they had formulated during the first lesson. Then, they test and evaluate their slope based on several criteria. The same process is followed for the second slope as well. During testing, they explore variables that may affect the endpoint an object reaches after descending the slope and they formulate operational definitions of the concept of friction. At the end of the lesson, students choose two variables that might affect their construction and formulate relevant research questions to be investigated in the next lesson.

In the third lesson (120min; Science and Mathematics), students formulate hypotheses and design experiments to investigate whether the variables they have selected in the previous lesson affect the endpoint an object reaches after descending the slope (Fig. 4). In order to be able to take accurate measurements of their slope during their experiments, students use a protractor to figure out how they can measure angles and create a relevant operational definition. During this process, they also classify angles to obtuse and acute based on their measurements and relevant criteria. Then, they test their definition on their inclined plane model with the use of a paper protractor and make final adjustments if needed. Finally, students conduct their experiments and draw conclusions based on the data collected in order to answer their research questions and discuss possible optimizations of their inclined plane model.

In the fourth lesson (120min; Engineering Design), students optimize and program their machine to address the engineering challenge (Fig. 5). They initially discuss how the machine could be automatized by also taking into consideration the scientific knowledge gained in the previous lesson. Students are then introduced to the rack and pinion gears, they learn how to convert rotational motion to linear and follow the construction guidelines to build their automatized system for sorting paper and aluminium and integrate it to their inclined planes. In order for their machine to sort automatically the two types of recycling material, they need to create a program for their system. Thus, students are introduced to the ENGINO PRO controller and the KEIRO software. They first follow instructions to learn how to create a program with the use of the infrared sensor and the "repeat forever" and "if" conditional statements, and then, they create their programs and test the effectiveness of their machine in addressing the game challenge. Students refine their programs and/or systems, if needed, or help other groups to do so. Finally, students reflect upon the final learning product (i.e. the sorting machine), the learning process and their group work based on questions that prompt reflection. This last set of reflection activities may be converted to a peer assessment procedure, provided that students are trained to use pre-specified assessment criteria or to formulate and use their own assessment criteria.

4 CONCLUSIONS

Our approach to pedagogical design builds on educational robotics and exploits inquiry-based learning for implementing iterations of inquiry cycles in order to optimize a core learning artefact and address a game challenge. The concentration on learning products can structure student work in educational robotics [13], as has been recommended by previous research, and at the same time, it can satisfy the need for open-ended learning settings [14]. Learning products can offer multiple opportunities for formative assessment, without the need for additional assessment instruments. Teachers can rely on certain aspects of learning products, which reflect student knowledge and skills, to diagnose student performance and provide on-the-fly feedback to students [15]. Learning products can further enable self-assessment and peer assessment so that student interaction and reflection upon peer work is catalyzed.

Based on the building blocks of learning scenarios of Table 1, teachers can design learning activity sequences or prepare interventions of larger scale, in the form of interdisciplinary STEM projects, which would integrate educational robotics, game-based learning and inquiry-based learning in a productive manner. These synergies may also be insightful for addressing recent calls for integrated STEM, where robotics and engineering have been outlined as a basic strength for pedagogical design and implementation [16]. Moreover, our perspective and the focus on learning products may facilitate a dialogue between stakeholders, enabling communication between educators, policy makers and industry partners, for streamlining discussion on STEM standards, educational evaluation and certification of student skills.

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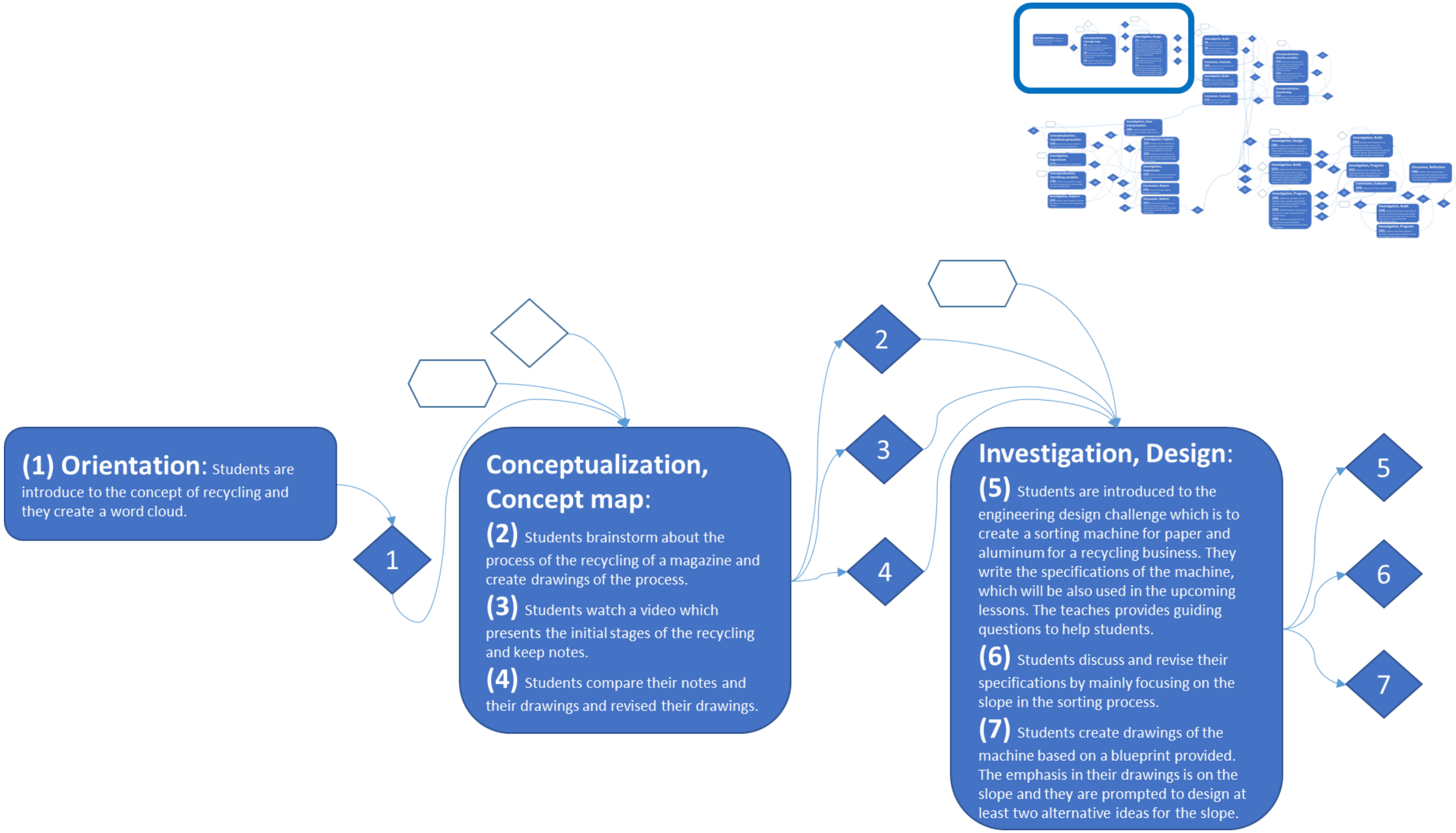

Figure 2. Description of the first lesson of the project. Learning activities are depicted as blue rectangles, support/feedback as hexagons, reference material as white rhombuses, and learning products as blue rhombuses. List of learning products: 1: Word cloud; 2 Brainstorm map consisting of drawings about the process of recycling a magazine; 3: Notes; 4: Revised drawings about the process of recycling a magazine; 5: Written specifications of the machine; 6: Revised specifications; 7: Drawings (paper-and-pencil or digital) of the slope of the sorting machine. The first lesson plan is shown in the frame on the top-right corner of the figure in the sequence of the four lesson plans that comprise the project.

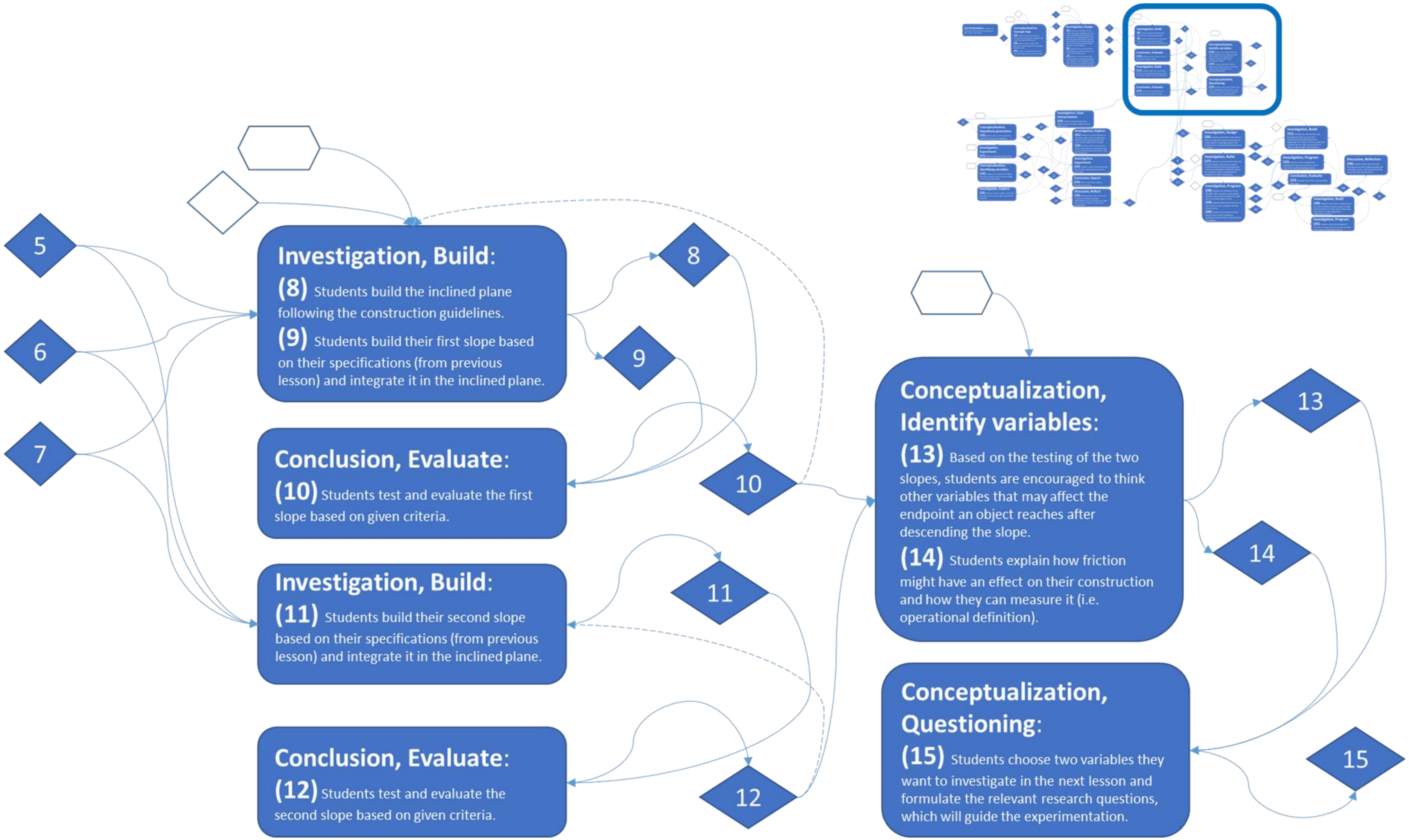

Figure 3. Description of the second lesson of the project. Learning activities are depicted as blue rectangles, support/feedback as hexagons, reference material as white rhombuses, and learning products as blue rhombuses. List of learning products: 8: ENGINO's inclined plane; 9: Slope with the ENGINO construction bricks; 10: Assessment rubric completed; 11: Slope with the ENGINO construction bricks; 12: Assessment rubric completed; 13: List of variables; 14: Operational definition; 15: Research questions. Dashed lines depict iterations. The second lesson plan is shown in the frame on the top-right corner of the figure in the sequence of the four lesson plans that comprise the project.

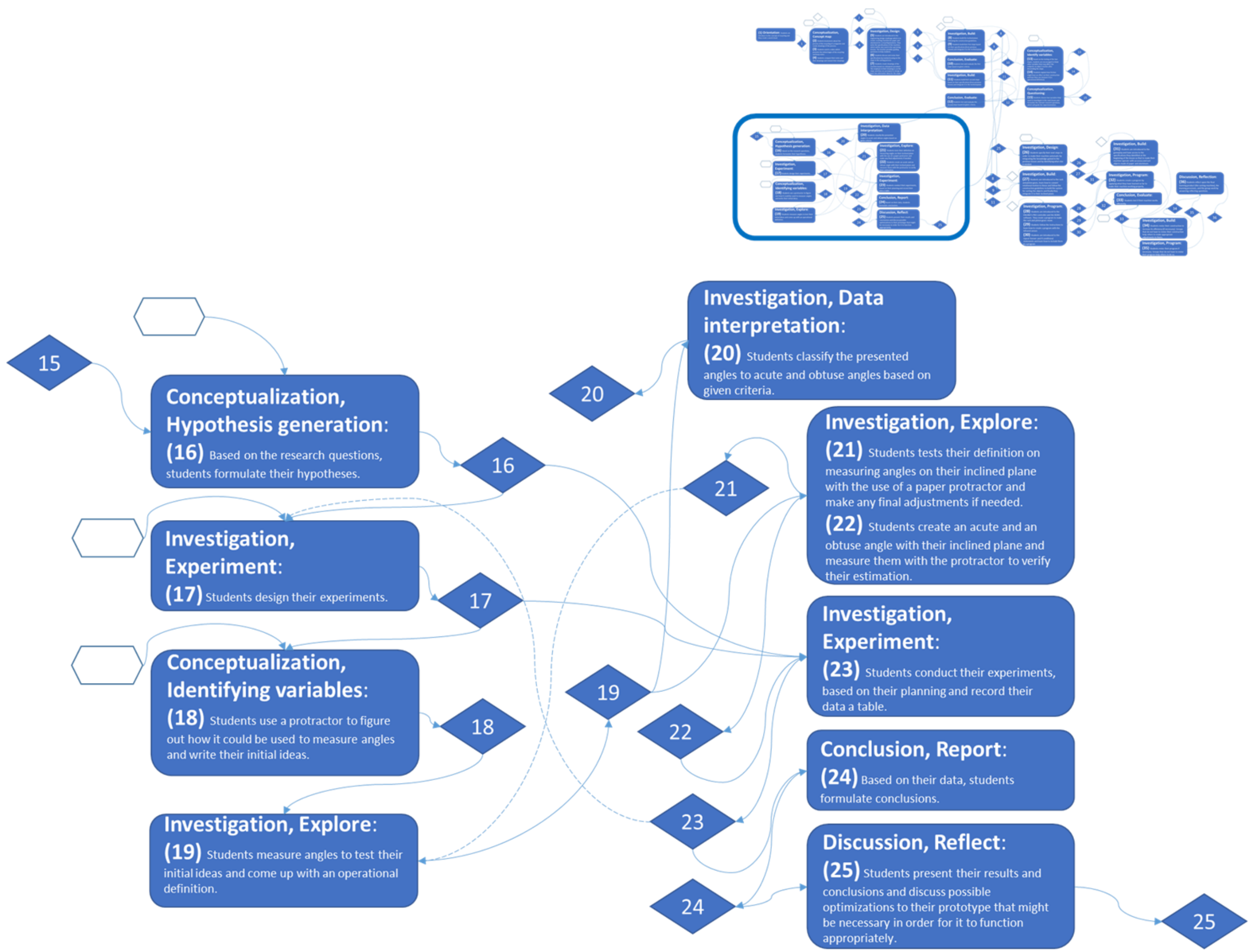

Figure 4. Description of the third lesson of the project. Learning activities are depicted as blue rectangles, support/feedback as hexagons, reference material as white rhombuses, and learning products as blue rhombuses. List of learning products: 16: Hypotheses; 17: Experiment design; 18: notes (initial ideas); 19: Measurement of angles and operational definition; 20: Classification of the angles to acute and obtuse; 21: Measurement of the angle of the slope and changes to the definition; 22: Measurement of the angles of the slope; 23: Collected data; 24: Conclusion; 25: Ideas for optimizing the slope. Dashed lines depict iterations. The third lesson plan is shown in the frame on the top-right corner of the figure in the sequence of the four lesson plans that comprise the project.

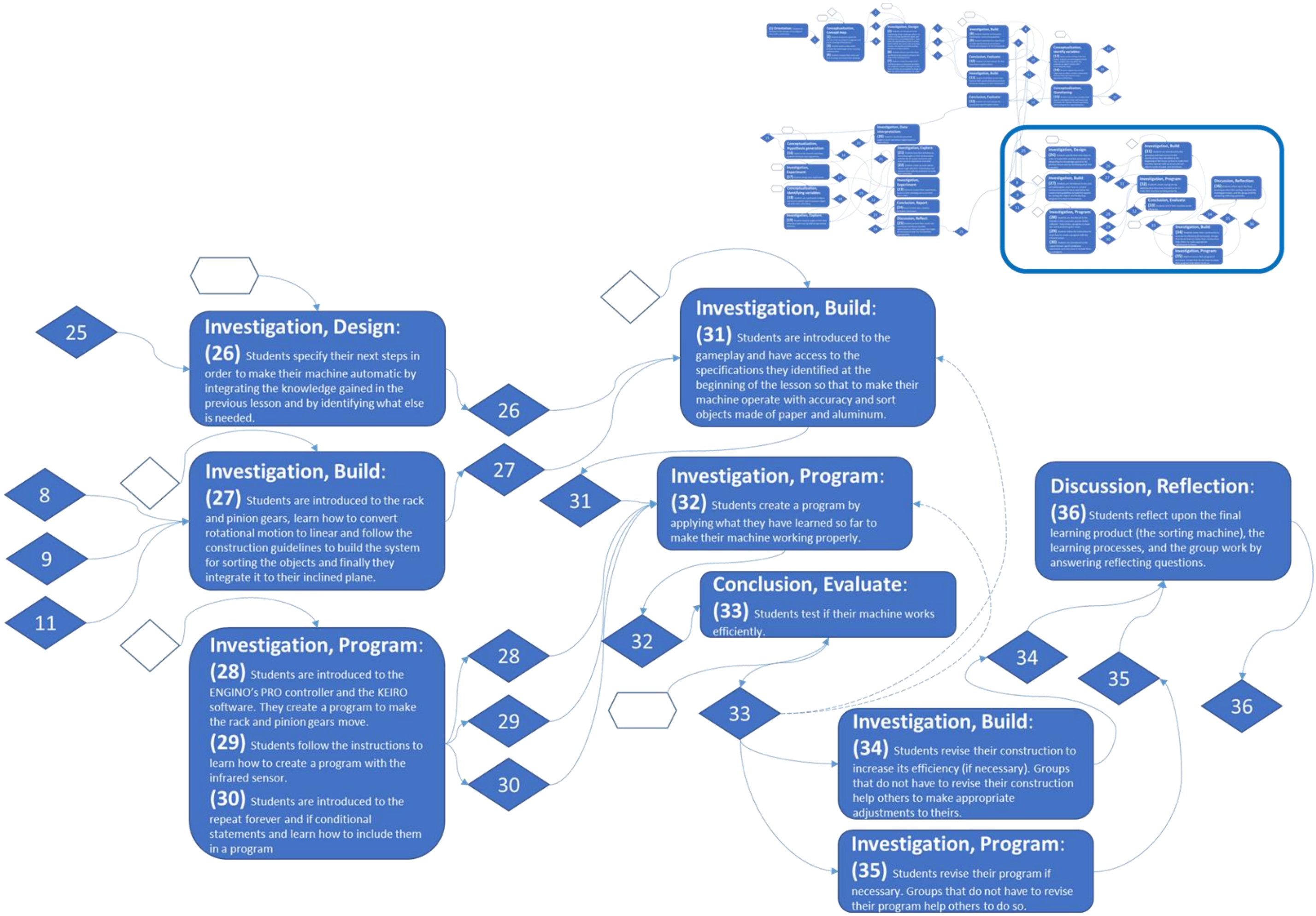

Figure 5. Description of the fourth lesson of the project. Learning activities are depicted as blue rectangles, support/feedback as hexagons, reference material as white rhombuses, and learning products as blue rhombuses. List of learning products: 26: Specifications; 27: ENGINO's inclined plane with an integrated system for sorting objects by pushing them; 28: KEIRO flow diagram; 29: KEIRO flow diagram; 30: KEIRO flow diagram; 31: Revised inclined plane; 32: KEIRO flow diagram; 33: Evaluation form completed; 34: Revised inclined plane; 35: Revised KEIRO flow diagram; 36: Reflection report. Dashed lines depict iterations. The fourth lesson plan is shown in the frame on the top-right corner of the figure in the sequence of the four lesson plans that comprise the project.

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