Integrating educational robotics, game-based learning and inquiry-based learning: Pedagogical design and implementation

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Abstract: A considerable majority of studies during the last two decades revealed that the use of robotics results in learning gains for the students engaged in educational interventions in K-12. In the present paper we wish to integrate three different topical areas which have remained largely separate up to date, namely, educational robotics, game-based learning and inquiry-based learning. We exemplify this integration by means of a project (bundle of three lesson plans) termed the "Mars Challenge". Students are immersed in the game through a narrative which runs throughout the project and secures its open-ended character, while peer assessment is employed to promote gamification and develop a community of practice around the challenge. Moreover, partially worked examples are recommended as support offered to students for managing cognitive load. Our work has been undertaken within the frame of the GINOBOT project, funded by the Cypriot Research and Innovation Foundation.

Introduction

A considerable majority of studies during the last two decades revealed that the use of robotics results in learning gains for the students engaged in educational interventions in K-12. Prominent examples are programming and scientific inquiry skills (e.g., formulating hypotheses), which featured among the learning outcomes fostered by educational robotics (Benitti, 2012; Sullivan, 2008). Furthermore, game-based interventions show a promising avenue for future research (e.g., Zhong & Xia, 2020). However, there were cases where no significant increase in the measures examined was recorded (Benitti, 2012; Xia & Zhong, 2018; Zhong & Xia, 2020). Indeed, previous research has not shed enough light on the determinants of success or failure of educational interventions (Benitti, 2012), which leaves many areas and aspects of educational robotics inconclusive as far as their learning effects are concerned (Xia & Zhong, 2018; Zhong & Xia, 2020). A related concern is that the studies and learning effects reported do depend on the specific context where each intervention has been implemented, which makes a cross-contextual comparison difficult. And this is also closely related to the need to enrich the assessment toolkit, which has been usually employed to track student performance. A recommendation refers to the analytical methods used to operationalize process evaluation (Xia & Zhong, 2018; Zhong & Xia, 2020). The point here is to depart from common summative pre-post formats or self-designed observation protocols and incorporate measures, which could reflect student progression along their learning routes.

Previous research has converged on a number of pedagogical design and instructional challenges. many papers highlighted the need to provide guidance to structure student work with educational robotics (Mitnik et al., 2008; Nugent et al., 2008; Sullivan, 2008). On the other hand, many authors stressed the need for an open-ended learning environment, harboring difficulty and uncertainty, so that student inquiry can lead to constructive learning paths (e.g., Lindh & Holgersson, 2007). A recommendation for instruction, for example, was that learning tasks and contexts should be designed to entail some degree of difficulty and uncertainty so as to let students develop their skills (Jordan & McDaniel, 2014; Kucuk & Sisman, 2017). This suggestion reflects the core dilemma of striking the best balance between structuring student work, on the one hand, and problematizing student inquiry, on the other (for a detailed account of the structuring vs. problematization controversy see Reiser, 2004; Xenofnotos et al., 2020). Structuring entails decreasing task complexity, e.g., segmenting a complex task in simpler sub-tasks and processing them serially, while problematization involves a local increase in task complexity, where students are encouraged to take initiative and make decisions on their own, e.g., considering and weighing alternatives. Analogous considerations have been frequently voiced in the field of inquiry-based learning, in terms of the level of guidance needed to optimally support student inquiry (to be arranged along a gradient from minimal guidance to full guidance) (Arnold et al., 2014; Koksal & Berberoglou, 2014; Minner et al., 2010).

The controversy between structuring and problematizing student work with educational robotics and games relates to the theory of cognitive load (Mayer, 2009; Brom et al., 2019). Walker et al. (2016) underlined that educational robotics increase students' cognitive load and may detract student attention from problem-solving tasks (see also Sweller et al., 2011). Robotic kits may increase extraneous load, which is due to the instructional material and does not directly contribute to learning. Therefore, Williams et al. (2007) have proposed to add a familiarization period of students with robotic kits, before students will be engaged in the main learning tasks. Moreover, Wei et al. (2011) have suggested that pedagogical design should plan for more than one iteration, where students will be given the opportunity to interact with robotic kits several times. This suggestion is oriented towards securing the construction and activation of cognitive schemes by students to solve the challenges set by the educational material and is linked to the desirable effects of germane load. A last point reflecting the concerns behind cognitive load is a tension which exists in previous studies between the need to design educational interventions in educational robotics of quite long duration, (see Xia & Zhong, 2018), on the one side, and the learning effectiveness of short tasks which has been frequently documented, on the other (Adams & Cook, 2017). In this case, a long duration for the entire educational intervention is meant to incubate all positive influences of the interaction of learners with robotic kits, including the opportunity of multiple iterations, as was mentioned above. Learning tasks, however, need to be planned carefully so as to favour the construction and activation of cognitive schemes. Such an approach seems to be enabled by short learning tasks.

Complexity and context dependency in educational robotics and game-based learning may be held responsible for the many contradictory findings reported in previous research and the difficulty in outlining significant determinants of motivation and learning across educational levels. However, there may be also weaknesses in pedagogical design and assessment instruments which may have presented considerable barriers in previous research. Two major aspects should be carefully considered, here: First, the balancing of different and contrasting instructional principles, and second, the developing and use of valid and reliable assessment instruments. With regard to different or even contrasting instructional perspectives, there are four main areas of concern: (1) The controversy between structuring student work and problematizing their learning tasks; (2) the requirement for decreasing extraneous cognitive load, and the same time, increasing germane cognitive load; (3) the diverging and at times inconsistent specifications for promoting gamification, play and motivation, on the one hand, and maintain students on fruitful learning paths, on the other; (4) the tension between an adequately long duration of educational interventions to facilitate sufficient student interaction with the instructional material, on the one side, and a small-scale pedagogical design of separate but interrelated learning tasks at a finer grain size, on the other side, which will allow for the construction of cognitive schemes by learners.

Concerning assessment instruments, more clarity is needed in methodological frameworks (National Research Council, 2011), especially in terms of compound effects (Brom et al., 2019), while there is also a lack of assessment instruments which would align with the qualities of open-ended learning settings usually encountered in game-based learning environments (National Research Council, 2011). This concern implies that game-based learning cannot be adequately evaluated by means of a black-box assessment strategy, which would be based on uniformity of treatment, and which would make use of conventional psychometric methods. In open-ended learning settings, student trajectories may be quite diverse and heterogeneous, rendering an experimental design obsolete to account for this richness. Such an openness would shift the weight center of assessment on depicting learner routes than comparing an experimental group (e.g., engaged in game-based learning setting) with a control group (e.g., following the "same" instructional material but not within a game-based learning arrangement). Imlig-Iten & Petko (2018) have stressed exactly this difficulty, namely, that game- and non-game treatments differ in so many aspects that they are hardly comparable. The same authors consider this difficulty as a major weakness in the field of serious games. Another weakness has been that assessment methods have not yet profited from the potential offered by technology to embed assessment instruments in game flow (National Research Council, 2011).

In the present paper we wish to integrate three different topical areas which have remained largely separate up to date, namely, educational robotics, game-based learning and inquiry-based learning. Numerous studies have documented the positive outcomes of serious games in terms of both learning and motivation (Clark et al., 2016; Connolly et al., 2012; Dede et al., 2002; Granic et al., 2014; Hwang et al, 2015; Papastergiou, 2009; Sitzmann, 2011; Spires & Lester, 2016; Vogel et al., 2006; Wouters, et al., 2013). Another advantage of game-based learning is its ability in bridging formal, non-formal and informal learning environments and developing durable and transferable learning gains (National Research Council, 2011). It may be due to this fact that game-based learning has been found to enhance interest in science (see Ketelhut et al., 2006), where formal educational settings often fail. The benefits of game-based learning do not seem to be confined to student attitudes towards science, however, but they extend to other learning objectives in science as well. Hickey et al. (2009) reported significantly more learning gains for students engaged in game-based learning as compared to a control student group, especially with regard to conceptual understanding and science process skills.

We used the inquiry cycle framework (Pedaste et al., 2015) and a specific operationalization of learning products (Weinberger et al., 2009) to enrich pedagogical design with a set of building blocks of learning scenarios, including phases and subphases, learning activities, reference material, support/feedback and learning products. In our integration, data collection driven by inquiry-based learning informs iterations in gaming with educational robotics, which evolve around core learning artefacts of ENGINO (www.engino.com) serving as organizing principles for pedagogical design and implementation (Hovardas et al., 2020). We exemplify all the above aspects by means of a project (bundle of three lesson plans) termed the "Mars Challenge". Students are immersed in the game through a narrative which runs throughout the project and secures its open-ended character, while peer assessment is employed to promote gamification and develop a community of practice around the challenge. Moreover, partially worked examples are recommended as support offered to students for managing cognitive load. We believe our approach can make an important contribution to teacher education and technology integration, which may refer to both pre-service teacher education as well as professional development for in-service teachers. Our work has been undertaken within the frame of the GINOBOT project, funded by the Cypriot Research and Innovation Foundation.

Methods

The inquiry cycle framework by Pedaste et al. (2015)

Pedaste et al. (2015) have proposed a strategy of inquiry-based learning, which includes the following phases (Table 1): (1) An *Orientation* phase, where students are introduced in the main challenge to be met (here students need to frame their mission and plan how to work in subsequent phases of their inquiry); (2) a *Conceptualization* phase, where students need to formulate potential relations between variables in the form of research questions of hypotheses; (3) an *Investigation* phase, where students gather data to address their questions and hypotheses (in the case of hypotheses, students will also need to design and execute an experiment); (4) a *Conclusion* phase, where students present the main outcomes of their inquiry and main trajectories taken. Throughout their inquiry, students may need to engage in reflection activities or to communicate their results to peers or the teacher, which have been outlined as a separate *Discussion* phase (5th phase) that runs through the learning path. In Table 1 we have added next to the phase column another column with subphases, which comprise alternative forms/versions of a phase (see Weinberger et al., 2009). Using these phases and subphases, teachers will be able to design multiple educational interventions to integrate educational robotics, game-based learning, and inquiry-based learning (see our examples in the next sections of this manuscript). For instance, the scheme proposed by Pedaste et al. (2015) involves two different learning trajectories, one that includes questions in the *Conceptualization* phase and exploration in the *Investigation* phase, and which is more suitable for novices in a domain, and a second trajectory, which includes hypotheses in the *Conceptualization* phase and experimentation in the *Investigation* phase, and is which more suitable for more experienced students in that domain (see Figure 5b).

Although the Pedaste at el. (2015) framework has been successfully implemented in inquiry-based learning for computer-supported learning environments (see Efstathiou et al., 2018; Hovardas et al., 2017; Xenofnotos et al., 2020), to our knowledge, there has been no study up to know which has implemented this framework to integrate inquiry-based learning with game-based learning. What is more, this framework will give the opportunity for designing subsequent inquiry cycles (see for example Hovardas et al., 2018) which will allow for game cycle iterations and the accommodation of project-based learning in pedagogical design.

Phase	Subphase*	Description
Orientation	-	Students are introduced in a narrative and/or frame their mission; to do so, they are given access to selected reference material, e.g., videos or weblinks
Conceptualization	Questioning	Students state informed questions; they identify the main aspects for fulfilling their mission and/or identify the main variables to operationalize in their inquiry
Conceptualization	Hypothesis generation	Students state informed hypotheses; this subphase refers to students who are not novices in a domain and can execute theory-driven tasks

Investigation	Design	Students design an artefact/procedure based on blueprints with support for its different forms/functionalities; they outline product specifications
Investigation	Build**	Students create a real or digital artefact based on construction guidelines; they are supported with key aspects to pay attention to in the construction process
Investigation	Model***	Students create a real or digital model based on construction guidelines; they are supported with key aspects to pay attention to in the construction process
Investigation	Program	Students create a program based on conditional statements
Investigation	Explore	Students interrelate variables based on operation definition guidelines
Investigation	Experiment	Students design and execute a fair experiment and they gather data; they are supported in classifying variables and planning experimental trials
Investigation	Data interpretation	Students process data in the form of tables, graphs, and/or figures and identify main data trends
Conclusion	Evaluate	Students assess a learning product by comparing it with another learning product of their own or one of their peers or an expert one; they are supported with a rubric with assessment criteria
Conclusion	Report	Students present the main outcomes of their inquiry with the main choices made and main trajectories taken
Discussion	Reflect	Students reflect upon learning products/routes along a learning activity sequence in order to recollect their learning experience or suggest future learning paths
Discussion	Communicate	Students present and discuss their learning products/routes along a learning activity sequence

Note: The table has been prepared based on Hovardas et al. (2020), Pedaste et al., (2015) and Weinberger et al. (2009).
*Subphases of *Discussion* may be included in different parts along a learning activity sequence dependent upon pedagogical design needs; some subphases of other phases may not appear at all.
**Included in "Engineering design" learning scenario only, see Figure 5a.
***Included in "Model-based inquiry" learning scenario only, see Figure 5b.

Table 1. Phases and subphases of learning scenarios

Finally, this framework enables a comprehensive development of learning activity sequences so as to provide an adequate duration of gaming with robotic kits but also enable pedagogical design at a finer grain size for either structuring or problematizing student work, offloading or increasing germane cognitive load at specific points along student learning trajectories, as well as weigh play against learning. A concern for the selection of this framework is the demands it will entail in terms of teacher preparation and training, which needs to accompany pedagogical design and the development of teacher training material. In addition, the Learning Management System to be delivered within the frame of the GNINOBOT project as well as the community of practice it will host will be another component for student and teacher support. Furthermore, the framework of Pedaste et al. (2015) can accommodate both hands-on and online exploration and experimentation with real or virtual laboratories. It is also compatible with individual student work, group collaborative work or whole class activities. Recently, it has been tested for hosting programming as well as integrated STEM with quite promising results (see respectively Hovardas et al., 2020; Tasiopoulou et al., 2020).

Building blocks of learning scenarios

A common thread across all state-of-the-art constructivist approaches and main learning scenarios to how learning is accomplished is that students' active contribution is fundamental for achieving learning outcomes. The transition from a passive student role to an active student role may be described by various terms, but in each case, the point is that students can only learn by doing things. This means to denote that students cannot become self-regulated learners and take adequate ownership of the learning process unless they can judge between alternative options to select the one that fits most properly their learning objectives. Productive learning paths will need to be proven and preferred over other, alternative, "unproductive" paths. In this conceptualization, the role of the teacher is to have designed and organized student inquiry so as to secure that "unproductive" routes would not lock students in any bottlenecks and dead-ends, interrupting the flow of the game with robotics and the learning activity sequence. In other words, the teacher needs to know when and how to intervene to steer student work towards insightful trajectories, anytime this will be required. Taking all these considerations together, a major prerequisite is that time investment in pedagogical design should be substantially increased in comparison to current practice. Successful implementation of a lesson plan demands time allocation to an analogous effective pedagogical design and preparation of the lesson plan.

To address the need of having an active contribution by students, the most important building block of a learning scenario should start from an indispensable dyad of the learning activity resulting in a learning product (Figure 1). If we define a learning activity as a set of purposeful actions undertaken by students, then a learning product is any physical or digital artefact created by students during a learning activity. This creating, constructive approach to learning fulfills the basic requirement of constructivist perspectives as long as students learn by doing things. To create learning products during learning activities, students are supported by tools, as simple as a paper and pencil set employed to make a drawing, or as complex as a computer simulation, which can be employed to develop and test an experimental design. Apart from tools, students may need some reference material to be based while undertaking the learning activity (e.g., rules to play a game), while they may also need some support or feedback. This may be provided by either the teacher or through technological tools embedded in computer-supported or web-based learning environments (see Table 2 with definitions for all building blocks of learning scenarios).

In Table 3 we present a detailed account of all phases, subphases, learning activities, reference material, support/feedback, and learning products in our approach, which can be employed by teachers to develop their learning scenarios. Learning activities in the *Orientation* phase usually open an inquiry cycle. However, this phase may be omitted and students can start the inquiry cycle with activities in the *Conceptualization* phase, especially if their initial ideas need to be recorded without students being influenced by any reference material or support. This may be the case in variations of learning scenarios in model-based inquiry (see a relevant example in Figure 5b). The *Investigation* phase and its subphases are the central part of the inquiry cycle, where most design and support effort by teachers is expected. The *Investigation* phase may involve designing and building artefacts in learning scenarios inspired by engineering design, as well as modeling in model-based-inquiry. Programming is an insightful addition in the inquiry cycle framework for covering a main necessity in educational robotics. Exploration and experimentation present the main alternatives already present in the inquiry cycle framework, while *Data interpretation* denotes the final subphase in the *Investigation* phase after data collection and processing. The *Conclusion* phase is the last in student inquiry. In the *Evaluation* subphase we integrated peer assessment as a major aspect of game-based learning, which may be related to assigning badges and developing a wide community of practice around the core learning artefacts of learning scenarios. Subphases of *Discussion* can be included in in different parts along a learning activity sequence according to pedagogical design needs. Overall, we need to highlight that some subphases or even phases may not appear at all in some pedagogical designs, however, teachers will be able to develop a wide array of learning scenarios based on the building blocks presented in Table 3.

Results

Bundle of prototype lesson plans, general description and rationale

The bundle of prototype lesson plans consists of three lessons and it is termed the "Mars Challenge". These lesson plans have been prepared for students in upper secondary education, while the project can be implemented in lower secondary education if programming requirements are simplified. The main idea is to program the GINOBOT so that it can scan effectively an unexplored, unknown surface in Mars, in order to identify the location of areas of interest or concern, namely, rocks to be avoided (represented as red cells on a grid) and dusty hills to be explored (represented as green cells on a grid). Students have to find a way to make their robot move over the entire surface and, at the same time, use the sensors of the GINOBOT to screen the surface and identify rocky areas (red cells) and dusty hills (green cells). After screening the Mars surface (grid), students must draw a line for robots to move on the Mars surface (grid) in order to avoid rocky areas (red cells) but pass over dusty hills (green cells), where the GINOBOT will stay for some seconds for further exploration. At the end of the Mars challenge, students will create a short documentary highlighting the rationale behind their work and conclude the mission by specifying the next steps for continuing the exploration of Mars.

Before this bundle of lessons, students need to follow an introductory lesson (Lesson 0) to familiarize themselves with the GINOBOT and the KEIRO software. In this lesson, students will learn how to record a program on GINOBOT (manual programming), how to save it and open it later in KEIRO. Moreover, they will use the step blocks to make the GINOBOT move forward and backward, they will use the rotation blocks to make it turn left and right, and finally, the will use the navigation blocks to make it move and turn, as an alternative way, instead of using the step and rotation blocks.

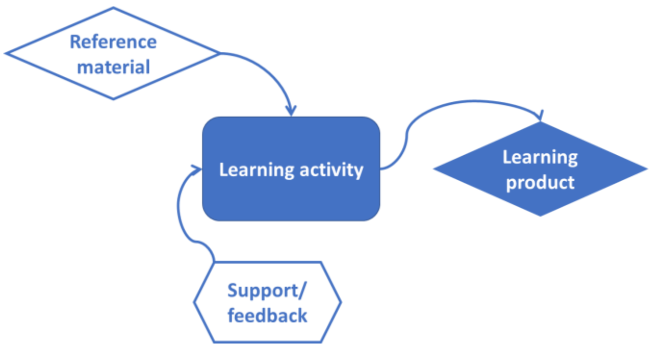

Figure 1. Pedagogical design at a micro-scale: Learning activities are designed for students to construct learning products, where students are provided with reference material and supported by teacher or system feedback (tools to be used by students to undertake the learning activity and produce the learning product are not graphically depicted). All these parameters are described in detail for all phases of our approach in Table 3.

Term	Definition
Inquiry cycle	A sequence of learning activities which offer a complete learning experience in inquiry-based learning
Phase	Set of learning activities, which conclude a part of the inquiry cycle
Subphase	Alternative forms/versions of a phase
Learning activities	Set of purposeful actions, which are meant to address a concrete aim
Reference material	Material offered to students, which will assist them in undertaking learning activities; the reference material does not change or differentiate during an educational implementation
Support/feedback	Help offered to students during the enactment of learning activities, which is contingent upon student prior knowledge and skills and current performance, and which may take the form of partially worked examples, highlights or prompts; support/feedback may be introduced or fade out and it may be differentiated/change during an educational implementation, for instance, prompts and highlights may fade out, while partially worked examples and rubrics will be completed by students
Learning products	Artefacts created by students during the enactment of learning activities

Note: The table has been prepared based on Hovardas et al. (2020), Pedaste et al., (2015) and Weinberger et al. (2009).

Table 2. Definitions of building blocks of learning scenarios

Detailed description of lesson plans

Lesson 1 (see Figure 2): After watching a short video about the mission of the NASA's Curiosity rover to Mars, students are asked to think how they could create a program for the GINOBOT to scan a given surface and detect the elements that must be avoided (red cells) and the elements that need to be further explored (green cells). To be able to program the GINOBOT properly, students learn about how to incorporate the necessary sensors and blocks into the KEIRO software. Specifically, they get familiar with the color sensor, the buzzer, the conditional statements if, if/else, repeat times and repeat forever, the logical comparison block and the function block.

Lesson 2 (see Figure 3, learning activities 11-17): In the second lesson, students transform their decision trees into coding in the KEIRO software. The coding should incorporate all the necessary commands that they have learned in the previous lesson. Then, students create a grid paper with colored cells (red and green) that will be assigned for exploration to another group of students. The main challenge is to run their programs and identify the location of the elements (red and green cells) based on the GINOBOT's movement over the Mars surface (grid). Based on the location of the elements, students draw a line on the grid, in order to create an optimal route for the GINOBOT to avoid the red cells and drive over the green ones. In addition, they create a line-follow program in the KEIRO software for the GINOBOT.

Lesson 3 (see Figure 3, learning activities 18-21): In the third lesson, students are assigned the role of peer assessors and peer assessees. Each group evaluates if the identification of the location of the red and green cells by another peer student group was correct. Moreover, they evaluate if the line-follow program of the assessee group worked correctly. The peer assessment process gives the opportunity to the students to improve their work.

Based on their scores, students can receive recognition badges for completing the Mars challenge. Another recognition badge to be awarded is the peer assessors' badge, which will be contingent upon validity and reliability ratings of peer feedback. The lesson concludes with the creation of a short documentary video about their mission and a reflection on the possible next steps for continuing the Mars' challenge.

Modularity of learning scenarios

Using the description of phases, subphases and other building blocks of learning scenarios in Table 3, teachers will be able to develop learning activity sequences to respond to varying pedagogical design needs. Figure 4 presents, for example, a prototype learning scenario for engineering design. The scenario does not include programming, but provides the option for iterations after the *Conclusion*, *Evaluate* phase, where students may need to reconsider main aspects of their mission and return back to the *Conceptualization* phase, or reconsider their design and return back to the *Investigation, Design* phase. These options are given in a synopsis in Figure 5a. Figure 5b presents possible iterations in a hypothetical learning scenario in model-based inquiry, involving an exploration learning trajectory (left half of Figure 5b) or an experimentation trajectory (right half of Figure 5b). In both cases, students may return to the *Model* (*Investigation*) or *Conceptualization* phase, after *Evaluate* (*Conclusion*).

Discussion

The perspective proposed in this manuscript allows for a comprehensive approach in integrating educational robotics, game-based learning and inquiry-based learning, starting with a micro-design, focusing on each learning activity separately, through a meso-design, with reference to a coherent set of learning activities resulting in a learning activity sequence, and ending up in a macro-design, concentrating on sets of learning activity sequences. Micro-design enables a detailed planning of each learning activity in computer-based learning environments, with reference material and support or feedback provided to students in order to create their learning products. Meso-design can be promoted by learning management systems and web-based platforms such as golabz.eu, where teachers can use several resources (e.g., virtual and remote laboratories; applications for inquiry-based learning; learning analytics applications to monitor student performance) and authoring tools to develop sequences of learning activities for concluding an inquiry cycle. Macro-design is compatible with recent developments in pedagogical design, for instance, learning progressions (see Hovardas, 2016). Our work will inform future developments in the frame of the GINOBOT project, for instance, the development of a Learning Management System, which will offer an authoring tool for pedagogical design at the intersection of educational robotics, game-based learning and inquiry-based learning. In addition, an eportfolio will be developed for students, which will host learning products and enable peer assessment.

The fact that learning products stored in student portfolios are a main focus of our approach enables teachers to concentrate on these products, which reflect student knowledge and skills, for diagnosing student performance and providing timely feedback to students. In this regard, learning products allow for an innovative strategy for formative assessment, which may be operationalized without the need of other instruments external to the learning activity sequence where the students are engaged (Hovardas, 2016). Another major addition of our approach is peer assessment, again facilitated by learning products and their storage in student portfolios, which enriches learning scenarios and integrates game-based learning with educational robotics and inquiry-based learning. What is more, carefully selected learning products or whole portfolios may foster a dialogue between stakeholders, e.g., teachers, ministries of education, and industry partners, about learning standards needed in STEM education, assessment methods, and certification.

We are currently working on creating versions of learning scenarios, which can be implemented in either physical or digital classrooms but follow the same sequence of phases and subphases. Such a design would make it easier for teachers to switch from physical to digital classrooms when needed, for instance, in the case of pandemics, and exploit both types of classrooms to enrich student experiences and gain from their learning opportunities and benefits. Future design initiatives will involve participatory design activities with teachers and students to validate several aspects in our approach. We expect that our perspective will assist in increasing the coherence in both pedagogical design and educational interventions in integrating educational robotics, game-based learning and inquiry-based learning.

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

Note: The table has been prepared based on Hovardas et al. (2020), Pedaste et al., (2015) and Weinberger et al. (2009).

Table 3. Phases, subphases, learning activities, reference material, support/feedback, and learning products in learning scenarios

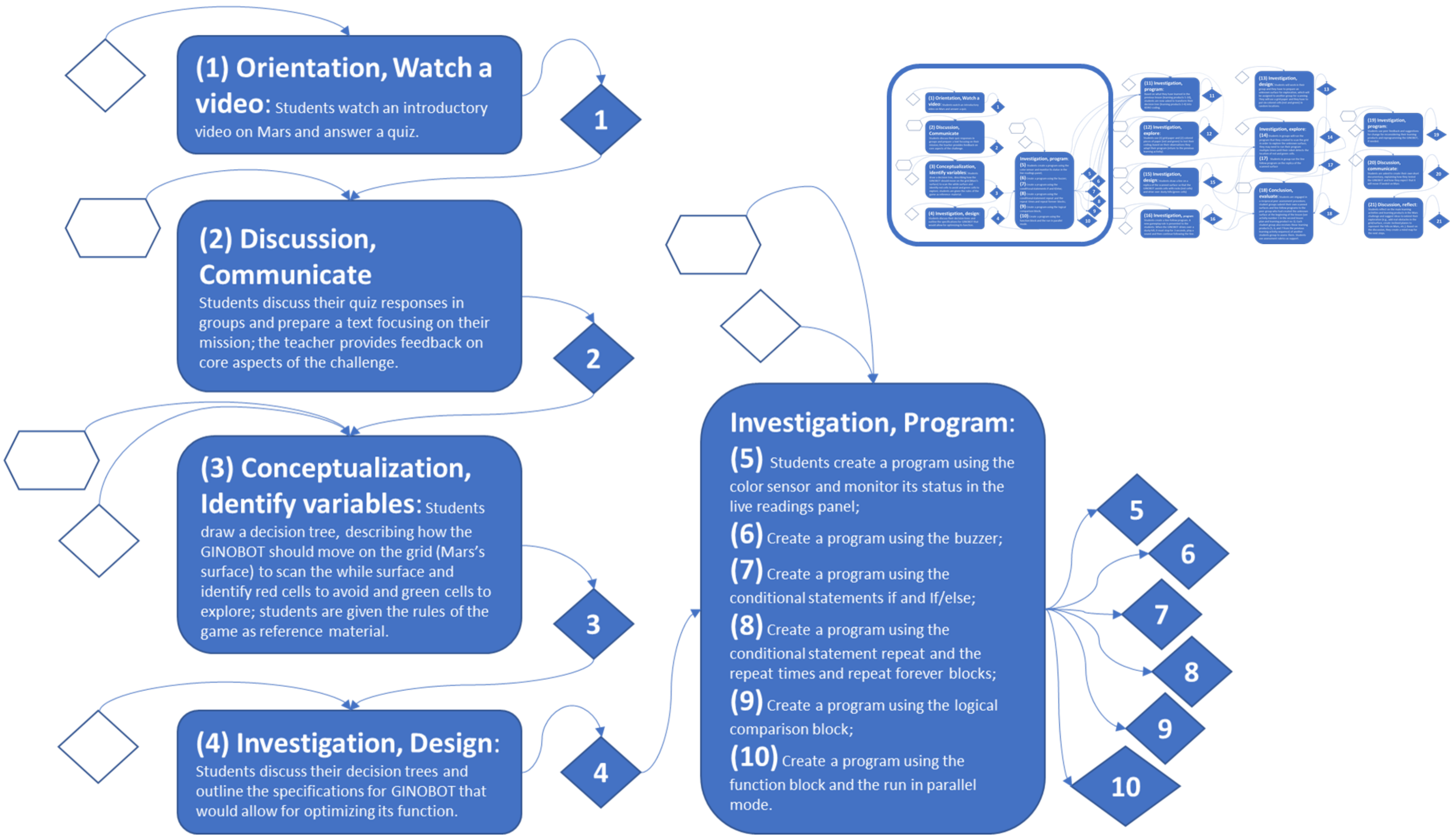

Figure 2: Detailed presentation of the first lesson plan. The nested picture on the top-right corner shows the relative position of this lesson plan in the bundle of the three lesson plans we present in this manuscript. Dark rhombuses present learning products, white rhombuses present reference material, while hexagons present support/feedback to be offered to students while enacting the learning activities

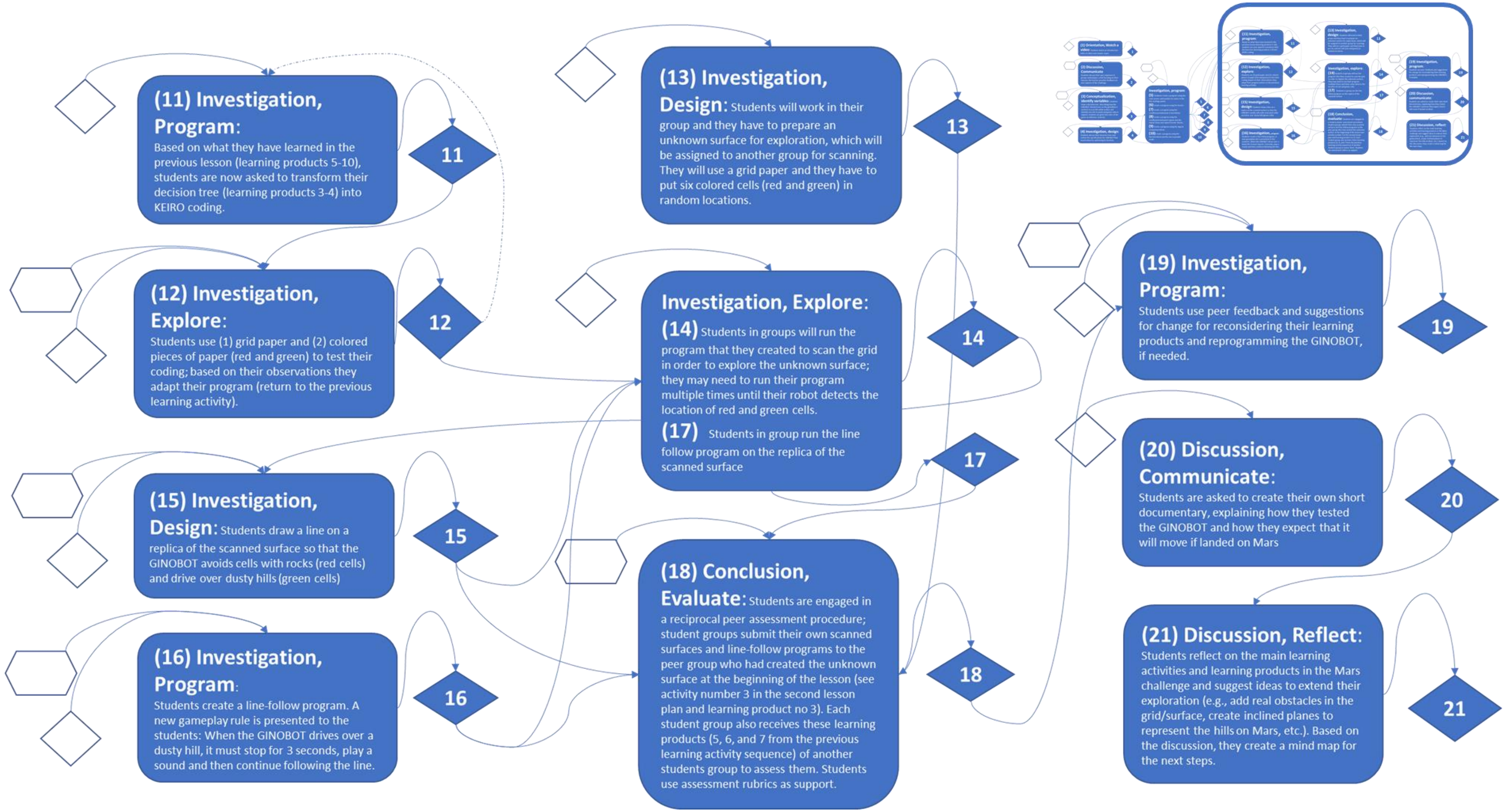

Figure 3: Detailed presentation of the second (learning activities 11-17) and third (learning activities 18-21) lesson plan. The nested picture on the top-right corner shows the relative position of these lesson plans in the bundle of the three lesson plans we present in this manuscript. Dark rhombuses present learning products, white rhombuses present reference material, while hexagons present support/feedback to be offered to students while enacting the learning activities. Dashed lines describe possible retrospective action by returning back to previous stages of student inquiry (iterations)

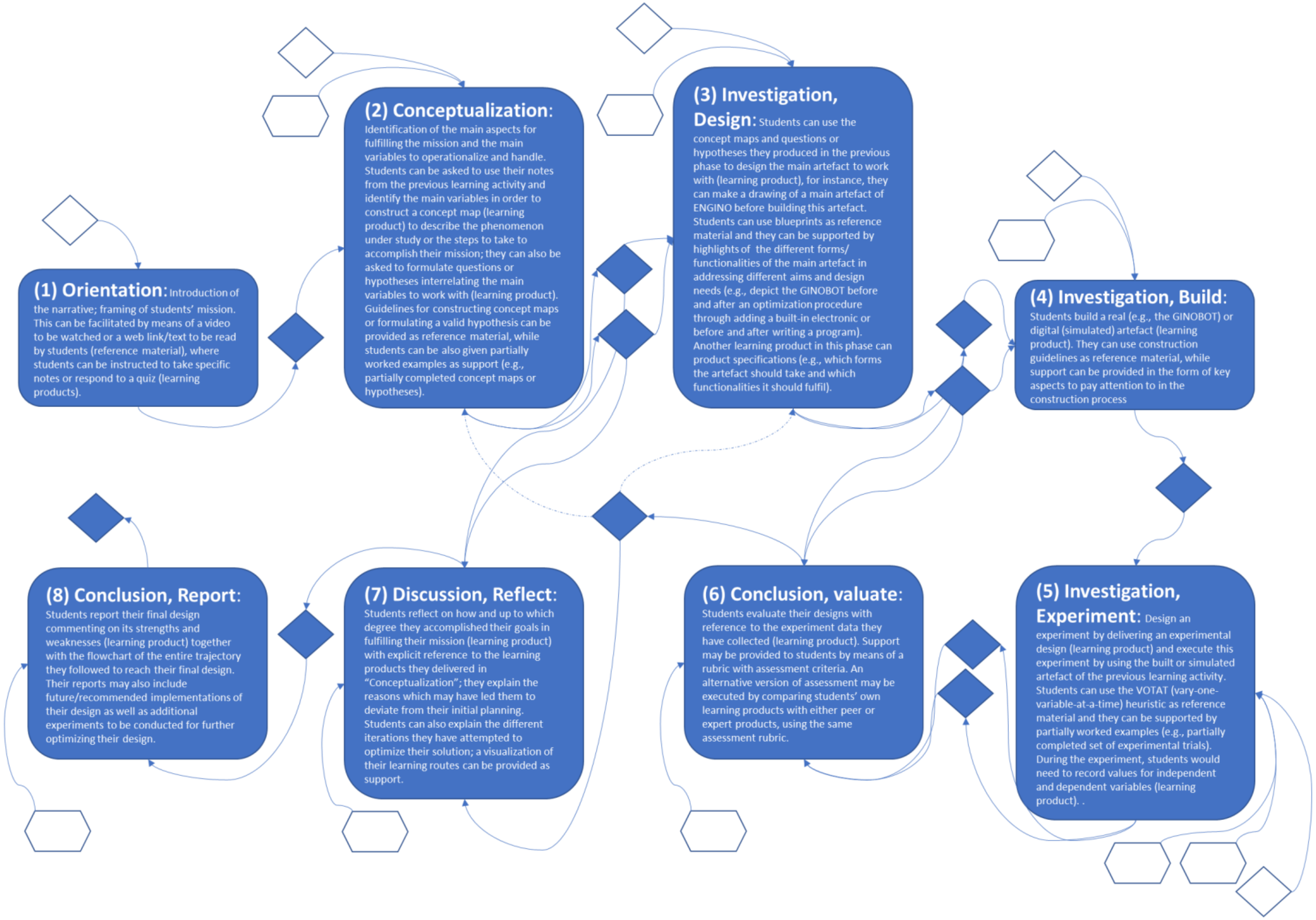

Figure 4: Prototype learning scenario for engineering design. Dark rhombuses present learning products, white rhombuses present reference material, while hexagons present support/feedback to be offered to students while enacting the learning activities. Dashed lines describe possible retrospective action by returning back to previous stages of student inquiry (iterations)

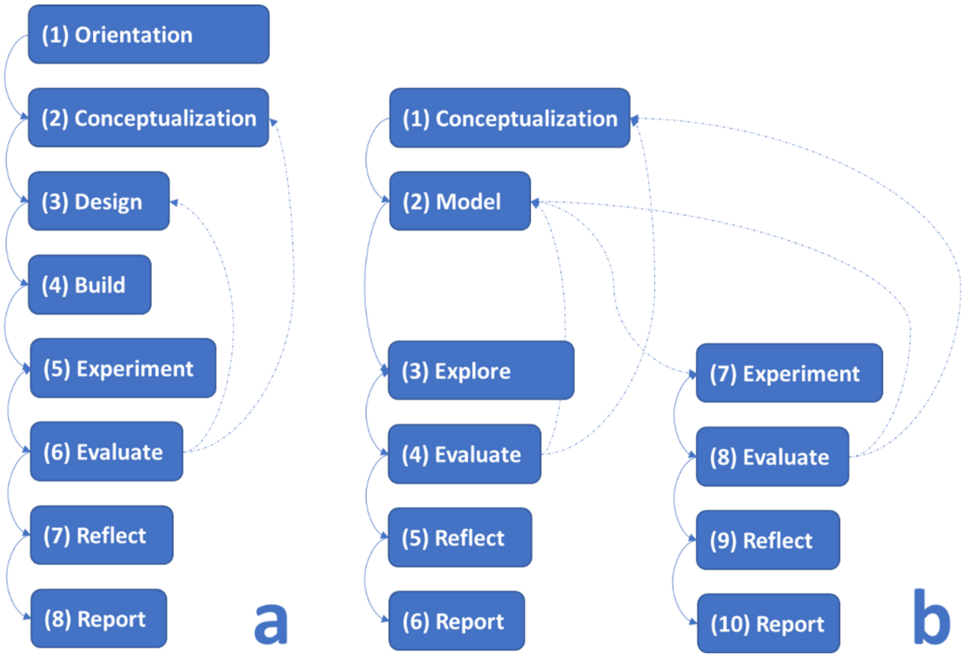

Figure 5. Sequence pf phases/subphases in the prototype learning scenario for engineering design (a) and two versions in a prototype learning scenario for model-based inquiry (b). Dashed lines describe possible retrospective action by returning back to previous stages of student inquiry (iterations)

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