Knowledge Construction in Computer Science and Engineering when Learning Through Making

Patricia Charlton and Katerina Avramides

Abstract—This paper focuses on a design based research study about STEM (Science, Technology, Engineering and Maths) learning by making through collaboration and production. This study examines learning by making by students to explore STEM using a constructionist approach with a particular focus on computer science and engineering. The use of IoT as a technology enhanced learning (TEL) tool created the learning conditions to be studied: (a) collaborative: no one person had the knowledge to complete the project alone, (b) problem-based: no off the shelf solution was used, and (c) multidisciplinary: the learning context pushed the boundaries across the subjects. The study investigated the learning conditions and indicators of collaboration and production taking place when learning about STEM. The results were used to inform the design of effective data analytics and visualization tools for the PELARS project to advance practice-based learning activities in STEM teaching. However, more specifically, the findings provide insight into the knowledge construction process when learning through making in complex environments. These insights illustrate the combined pedagogical value of collaboration and production supporting the multidisciplinary learning opportunities. The importance of community knowledge construction and its relationship to the pedagogical approach is examined. The significance of these findings in the context of IoT TEL tools in education is explored.

Index Terms—Collaborative and problem-based learning, knowledge construction, computer science, engineering, learner-centered design, technology enhanced learning, STEM, learning indicators, internet of things

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1 INTRODUCTION

This paper reports on a pilot study to investigate the use of tangible toolkits for physical computing [45], [22] to support pedagogies of collaboration and production. The focus of the study was learning through the Internet of Things (IoT) [50] about STEM (Science, Technology, Engineering and Maths [2]) in particular computer science and engineering. The result of the study is part of a larger EU project PELARS (http://www.pelars-project.eu). The pilot was designed to identify learning indicators of collaboration and production when studying STEM. The research informed the design of effective data analytics and visualisation tools for the PELARS project to advance practice-based learning activities in STEM teaching. However, more specifically, the findings provided a design structure and insight into knowledge co-construction. Furthermore, the findings illustrate how the IoT environment facilitated this investigation in knowledge construction and boundary crossing.

Design of the IoT environment provided a technology enhanced learning (TEL) context [35], [36]. Key to the design was to support the context of (a) collaborative learning as no one person had the knowledge to complete the project alone (b) problem-based learning as no off the shelf solution was used and (c) multidisciplinary learning by pushing the boundaries across the subjects.

The pilot study was conducted over a period of four months working with a group of 15 (year 10) students aged between 14 and 15 years. The students were new to computer science, but had some programming experience in python. None of the students had studied IoT, engineering or embedded systems. The start of the collaboration with the students in early January involved thinking about smart city projects. In groups they brainstormed ideas to investigate after attending a mini-workshop at the UCL Knowledge Lab. They attended the final two-day hackevent where their ideas were prototyped and finally presented at the London Festival of Education.

This design based research study investigated what useful learning indicators can be identified in STEM (Science, Technology, Engineering and Maths) collaboration and problem-based learning context [25]. The paper describes the methods used and the context of the study of learning about Computer Science and Engineering through IoT. The paper elaborates the design of the learning approach and discusses the findings. In particular, the emergence of community knowledge construction and its relationship to the pedagogical approach is examined in the context of IoT.

2 LITERATURE REVIEW

Dewey [20], Piaget [42] and Papert [39] and others have written about learning through the process of creating tangible objects and the development of critical thinking skills. Putting new knowledge into a larger context helps learning and IoT as a TEL tool provides such a context for learning about Computer Science and Engineering. Learning by making through TEL tools illustrates the potential of ‘constructionism’. ‘Constructionism’ [39] is the

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learning process of building a 'public entity', which provides a tangible context for a learner to reflect on.

Tangible technologies that are not constrained to desktop interfaces, but are embedded in everyday objects and the environment give people the chance to construct and share mental representations and models [38], [15], [16]. IoT tools provide an accessible range of devices that are affordable, enabling learning through prototyping in education settings. Hence, students experience a direct relationship between a design of a distributed application and implementation and how this new application forms part of the Internet. TEL, through ICTs, can increase the progression from concrete to abstract mental operations and vice versa, thus promote conceptual understanding and higher-order thinking skills among STEM students [4], [5]. Hence, the potential of investigating science and other domains through new visual and tangible representations enables access to science and understanding in new forms [33].

Different terms maybe used to identify the learning process but in general the tangible, hands-on, learning through making as an authentic learning setting provides deeper learning of concepts [4] learning achievements [21], spatial abilities [3] and motivation to learn science [46]. The importance of this authentic and context setting for the learner are further supported by the systematic review by Bennett et al. [7]. Essentially meaningful learning and collaborative learning often facilitates engagement [49].

The learning through making illustrates the power principal of constructionism: "the natural mode of acquiring most knowledge is through use leading to progressively deepening understanding" (p. 98) [40]. Learning about science using pedagogies of knowledge co-construction have demonstrated a positive impact on agency of learning and critical thinking [30].

More broadly the process of knowledge co-construction [17] and knowledge sharing through ICT tools via vocabularies of mediation [18] enable a 'meeting space' between the tool and the learner. This 'meeting space' vocabulary provides both a knowledge holder for the learner and a more direct means to collaborate and share knowledge in context with others [17]. Supporting knowledge construction in this way enhances the opportunity for 'learning with' rather than learning from [48], [49]. This can strengthen learning engagement and ownership especially when set in a community and social context [8]. Furthermore, valuing and validating a learner as part of the community of constructing knowledge through 'learning with' is key to motivation [47].

The pedagogical context of problem-based approach to deliver an integrated STEM curriculum [31], [37], [13] is similar to the informal learning of maker communities [54]. Problem-based learning is popular with teachers [32], because it supports the development of 21st century skills, such as collaboration. However, Ertmer and Simons [26] identified three difficulties in implementing this approach: i) creating a culture of collaboration and teamwork in the classroom, ii) adjusting from a directive to a facilitative role, and iii) scaffolding student learning. Others have also noted the challenges teachers face in implementing STEM problem-based learning [1]. Honey et al. [31] found learners often lack knowledge and skills in individual STEM disciplines that hinder their ability to integrate learning across disciplines. These challenges need to be taken into account in the design of integrated STEM learning.

In Education there is a growing rise of interest in developing not just the learning about and understanding of STEM through different TEL environments but also the collaborative team engagement potentially fostered by learning environments [44], [28]. The importance of collaborative learning has long been recognized by Education. In particular the constructivist approach to learning is seen to add significant learning value both for students and teachers [41], [14]. However, it has also encountered resistance both by educators and students when set in a traditional assessment environment. Traditional assessment approaches focus on individual achievement and in collaborative tasks achievement of the individual becomes difficult to determine.

New education tools or environments or approaches maybe resisted if the claimed benefits for teaching and learning are not easy to examine or understand [11]. The benefit can be difficult to define given the process of learning is influenced by many factors and traditional assessment rarely tackles the diversity demands of boundary crossing or learning more generally [10]. The complexity and challenge of teaching and learning in an interdisciplinary context examined by Spelt et al. [52] supports similar concerns. However, learning about computer science and engineering through an IoT [34] context provides the conditions of 'boundary crossing' [23] that is a creative process of creating something new. This process of knowledge construction, by creating a shared 'public entity' of an IoT application, profits from collaborative learning community context [49].

In examining the pedagogies of collaboration and production in a multidisciplinary learning context there are broad and complex factors that influence the opportunities for learning to take place. Also, the literature review identified the importance of community knowledge building when investigating boundary crossing between domains. To examine the complexity of the diverse learning context requirements a design-based methodology [1], supporting an iterative approach, was used (see next section for the methodology details). Section 4 provides the context of study and Section 5 the analysis and findings. The results are discussed and examined in Section 6 and the contribution of the study summarized in the conclusion.

3 METHODOLOGY AND APPROACH

A design-based research (DBR) approach was used supporting the six characteristics of the methodology [1]. The details of six characteristics of the methodology are provided, as well as, the data collection and analysis approach.

3.1 Being Situated in a Real Educational Context

The study was designed to deliver on aspects of the Computer Science curriculum, such as computational thinking, algorithms and hardware. An authentic learning experience was designed that includes the students' (and teachers') ideas and knowledge as part of the learning process of 'meaning making' [24]. The study includes building shared

TABLE 1
Summary of the Study Context

Study Requirements	Affordances of IoT as TEL tool	Learning Indicators of collaboration, production and multidisciplinary learning
Fostering Collaborative learning (group 1)	Connected community of practice [34] Diverse physical and digital artifacts. Use of high and low tech to design and pilot ideas. Incremental construction and testing.	**(I1)** Social [8]: supportive, feedback, inspiring ideas and build on work of others
Problem-bases learning using tangible and digital artifacts (group 2)	Rich set of physical components [55], tangible hardware to build pilots of authentic problems. Supports incremental design and test of concepts with software.	**(I2)** Theme-based projects [47]: engaging with open-ended problems, setting one's goals, persistent, making connections, creating narratives and explanations
Enabling multidisciplinary learning (group 3)	Includes electronics, physical computing and software design and testing to see direct connection with hardware [34]. Supports access to internet layers for distributed communication protocols and data layer [abid].	**(I3)** Boundary crossing [23]: Connecting (a) design process with electronics and software[34]. (b) electronics with software and algorithms. [ibid]. Identifying bigger picture of connecting to the internet and the relationship with data [ibid]

community knowledge of 'learning with' context [49]. The knowledge construction process [30] is examined to identify the relationship between learning about computer science and engineering through IoT context [34].

3.2 Design and Testing of a Significant Intervention

This study investigates the collaborative and problem-based learning as part of learning about computer science and engineering.

The design of open-ended teaching and learning activities paid attention to the importance of context when learning about science [33] and the knowledge construction [30] and the role of IoT [34].

Table 1 provides the context for 3 coarse categories of learning indicators that draw from the research literature findings:

- Indicator group 1 (I1) is set in the context of collaboration and social context
- Indicator group 2 (I2) is set in the context of problem solving and production
- Indicator group 3 (I3) is set in the context of multidisciplinary learning and is related directly to learning about CS and Engineering.

3.3 Using Mixed Methods

A range of methods was used, such as video recordings of the design process, interviews, observations, surveys, collaborative designs and the products of the designs etc. The range of methods developed over the iterative approach to understand if and how learning indicators and conditions of collaborative and problem-based learning about STEM through IoT can be identified. The design of the study was as follows:

1. Initial request to attend the workshop and hack event with background about both the student's and the teacher's perspective and knowledge about computer science. This is key to ensure a shared knowledge between the researchers and the teachers and learners to enable designing an authentic setting for learning.
2. Videos and notes taken during the collaboration, designing, discussions and building activities to provide the context of the work and test out the process with the students on (a) Collaborative problem solving in pairs (b) working on STEM activities through using basic IoT settings and (c) presenting their ideas and what they would like to work on.
3. Audio recordings, email exchanges, phone interviews, and digital capture of discussions and problem-solving ideas collections from the school.
4. 2-day Hackevent, captured with artifacts, interviews and recorded presentations of
    a. Setting a group role-play for creative and interdisciplinary exchange;
    b. Designing a solution to the problem through collaboration;
    c. Building their solution (screen capture tools to see what the students do with the computers during the activities);
    d. Preparation and final presentation of results;
5. Follow-up interviews with the school and observations of presentation and demo of their work to other schools. Data was collected using both digital artifacts (surveys, photos) and observation notes.

During the interviews, the pupils were asked exploratory questions regarding the nature of the experience of learning, the demands of the project work, the ways the collaboration worked, how they (the pupils) engaged with the project and what they felt they gained from these opportunities for learning. The questions investigated how the students responded to working collaboratively, and to the learning situations and environments encountered during the development of their projects. During the interviews, participants had the opportunity to review a selection of photographs, videos and demos taken at different stages and phases of the project. These stimulated reflective recalls [43].

3.4 Involving Multiple Iterations

A set of iterative design phases of the project supported an open-end approach for students and teachers to develop and engage with collaborative and production based learning. Each stage informed the next steps of design and engagement. The process required understanding the learning context of the students and the teachers at each stage. This required adapting the process, such as discussing and collaborating with the teachers and the students about their project ideas in detail and examining together feasibility of ideas.

3.5 Partnership between Researchers and Participants

Researchers and participants collaborated throughout the pilot, which developed the conditions for co-construction, sharing of knowledge and experimenting with ideas. This promoted a design-based approach to engage with the projects. This step is important to support value and validation of ideas and to enable ownership of the learning process both for the teachers and the students.

3.6 Evolution of Design Principles

The pilot was designed to derive learning indicators of collaboration and problem-based learning that can inform the pedagogical design context for STEM. These STEM learning activities design principles included determining whether or not or to what degree IoT as TEL can support engagement of collaboration and problem-based learning. In particular, the knowledge construction process in collaborative science learning context evolved.

3.7 Collection of Data and Analysis of the Data from the Study

The data analyzed included over 10 hours of video recordings of the mini-workshop and hackevent, 100 artifacts designed, created and shared during the study using the framework to identify the learning indicators. A flexible interview protocol was developed. There were also informal conversations with other staff from the school and researchers and industrial participants (data collection through video recordings, emails and interview notes). This was considered a useful way of validating research findings through triangulation [51]. This procedure yielded a comprehensive set of interview data along with documents such as photographs, designs, programs and pupils' presentations with narratives of explanations (video recordings) and prototypes.

The procedures of grounded theory qualitative content analysis were followed, using an open coding procedure where pupils' responses and articulations were placed into conceptual sub-categories using themes that emerged from the transcripts. The responses and articulations from the students are derived from (a) video recordings of sessions, (b) interviews with the students, (c) presentation recordings of their projects, (d) explanations of their designs, prototypes and other related observations and (d) follow-up presentations by the students.

The data was examined for evidence of learning indicators identified in Table 1 from literature. As the process was learning through making taking a constructionism approach there was no formal collaborative or problem-based setting. The students were not set with the explicit goal to learn these specific 'skills'. The projects were open-ended so would result in problem-based activities that were learner-led. The data was examined to see if any patterns emerged of significance in collaborative and problem-based learning. More specifically for knowledge sharing and boundary crossing through evidence of knowledge construction and building was investigated. This latter inspection of the data followed closely the analysis procedures in [30] to examine the possible relationship between the learning context and the development of knowledge construction responsibilities and agency of learning.

4 DETAILS OF THE PILOT STUDY

The details of the learning activities of the study are provided in this section that are analyzed in Section 5 in the context of collaborative and production-based learning. An overview provided here is to illustrate the variety and open-end learning activities:

(1) The mini-workshop
(2) The brainstorming activity
(3) The 2-day educational hackevent
(4) The follow-up presentation

4.1 The Mini-Workshop

The learning process from the beginning of the study embedded collaboration, which included learning through making approach. The initial discussion starts with exploring what exists, what can be changed and what students know. A 'VEX' activity (adapted from AppsforGood resource http://www.appsforgood.org) to start the problem solving process was used. The students work in pairs and think about 'Smart city' problems they would like to solve.

After sharing ideas about smart city applications and how they might be solved the students are introduced to experimenting with programming and electronics engineering. These form part of the tools that will be used to build their smart city application. An illustrative example snippet from the learning experience of two students experimenting with the program to see how the lights are controlled is provided. The students have just succeeded in getting the light to flash.

The facilitator proposed that they make the light flash faster. The facilitator walks away to let the students explore. First the students read through the program and then they experiment with the program. They understand at this stage that the light is controlled by the 'logic' in the program.

> Student 1: 'That makes it go slower'
> Student 2 is observing the experiment the student is hesitant and considering the expectation of the change to be different.
> Student 1 repeats 'That makes it go slower'
> Student 2 makes an "expression of realization" 'arr'.

There is visible recognition of engagement by student 2. The exchange has provided a change of understanding.

Student 1 now takes over the computer from student 2 – they know what to do – they understand how to 'control the experiment'. They do not necessarily understand the 'program' in a detailed way. This all happens in a few minutes. However, one can witness the students connecting the process of hardware and software.

> Student 2 tries some exploration with the program and they discuss what is happening.
> Student one explains what he/she thinks is going to happen – 'it's going to stop [the LED] and then go again'.
> Reading the program – student 2 says "it's going to stop [the LED] for one minute or something" leans back – Student 1 reads through the program counting . . .
> Student 1 "It's not going to blink"
> Student 2 (leans into looking at the physical experiment) says, "it is going to blink but you won't see it"
> Student 1 then elaborates the explanation "because it is too quick"

(The light stays on – they understand the control of the LED by the program – what to change and what will happen).

The students were new to programming and had never done any electronics. They progressed from discovering the perspectives of their peer, sharing knowledge and to exchanging understanding. At the end of the mini-workshop students presented their ideas and experiences to the class.

4.2 Brainstorming Session in the School

The students were tasked to come up with ideas that they would like to design and build as part of a smart city. After a few weeks the researchers visited the school to hear the ideas from the students. The ideas were more elaborate and challenging compared to the mini-workshop. They included each other's ideas and recognized ideas that were of value.

The students were asked to refine their ideas and identify three ideas they would like to work on. The plan was to have three groups of five students. Before the Educational hackevent the students sent their initial ideas, which were: (a) Smart glove for controlling the home, (b) dog tracker and (c) robot to collect coins at school.

4.3 Education Hackevent

To support the learning experience involved bringing in designers, technologists, computer scientists and engineers to design and work with the students over two days. The collaborative problem-solving design process was an important part of the learning experience. The general design of the two-days was:

(1) Explore and design a solution: Expanding on the students' initial ideas;
(2) Present back to the whole group at intervals;
(3) Experiment and develop solutions
(4) Demo solutions;
(5) Final presentation preparation for a live audience at the London Festival of education;

4.3.1 Design Phase

Fig. 1 shows the initial design and ideas for the smart glove. The students with researchers and designers discussed and thought about the type of solution they would like. Many creative ideas emerged. They presented an innovative vision of all the features this 'intelligent glove' would do. The narrative around the features, explaining the why and the how was an interesting result of learning through IoT, which will be examined in Section 5.

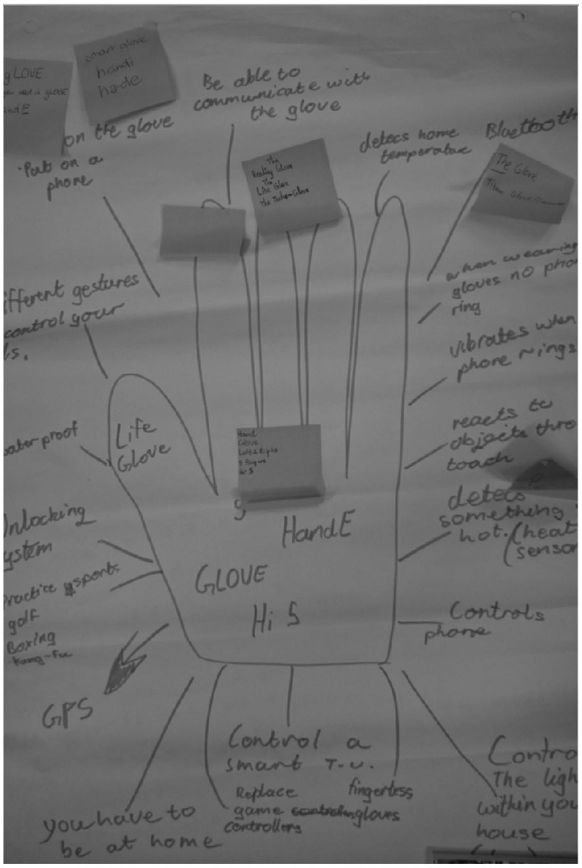

Fig. 1. Design of smart glove.

4.3.2 Making, Experimenting, Testing, and Fixing

Going from an idea to an actual prototype required the students to collaborate, set out tasks and get help from experts when things didn't work. They had expectations, and ideas similar to the mini-workshop but they did not always work. Compromises were made and new designs tried. Each project required bringing components together to work and so a shared exchange took place. Some of the experiences and what evolved were tracked online (the storify link provides a good overview[1]). The focus and engagement throughout for all participants was intense. At each stage there was feedback and checking by the researchers, students were clear on their goals, although they did not always know how they were going to reach their goals. Within groups students would work on different tasks, sometimes in pairs and sometimes on their own. Their designs and developments needed to be tested and brought together. The integration showed the usual challenges of technology not working seamlessly or as expected. Fig. 2 shows the building of smart glove, which required many components both hardware and software.

The purpose and goals were defined and the students, in fact the 'community' stayed on task to design and develop the solutions collaboratively. Everyone was helping each

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[1] 1. Storify link: sfy.co/p0AVQ

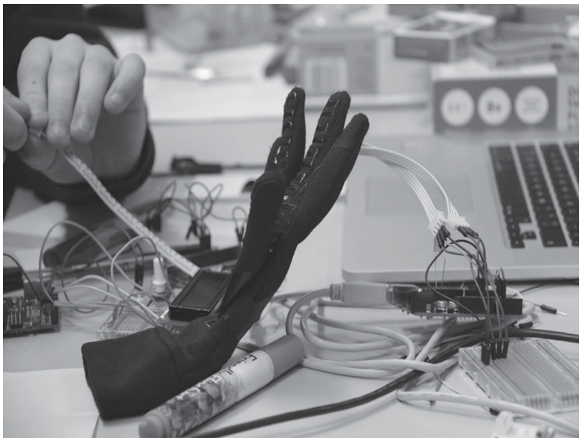

Fig. 2. Building an ‘Intelligent Glove’.

other where they could. Although there was some ‘mild competition’, banter and good humor between the groups it is worth noting that collaboration went across projects between students.

The researchers helped the students to break down the problem and investigate sensors and how they worked. Often the researcher(s) didn’t know how the sensor worked but could help the students think through the problem solving process through an iterative process. They needed to research the sensor function specification online. The concrete engagement with physical and digital worlds to problem solve highlighted the multiple representations and interdisciplinary context of the learning process taking place.

4.3.3 Presentation Phase

The focus on the presentation was equally challenging. The students needed to explain in a short space of time about ‘Smart Cities’ to a large audience. This was an important activity as it gave a sense of completion to the project work and would be useful for later when they reflect about their experience. In preparation the students presented in their groups and then in front of the ‘community ‘(all the students and researchers at the event) before going to the London Festival of Education to deliver their talk to a large audience.

Final ideas and working pilots that emerged (1) Glove that controlled the home devices, (2) Mobile robot to help the blind with navigation and (3) Coin reward system that gave credit to students who collected coins.

5 FINDINGS AND ANALYSIS

The data was analyzed using the study context from the literature findings in Table 1. Analysis of the video data and artifacts produced by students was to identify indicators of collaborative and problem-based learning. To demonstrate the analysis process each activity is examined. A summary of the relationship and mapping to the indicators is provided in Table 2 of the mini-workshop. This analysis provides a mapping between the learning activities (analyzed below) and the learning indicators illustrating examples of collaborative and problem-based learning. The analysis of the data from the hackevent is further examined for evidence of collaborative knowledge building and boundary crossing learning.

TABLE 2
Findings When Learning Through IoT from the Mini-Workshop

Learning activity context	Learning through IoT Technology Learning indicators
(1) Setting the context of Smart Cities & IoT & the aims.	Bringing in student knowledge: Ideation process of smart things that exist in the city and innovative thinking. Facilitator creating the context for exploration and collaboration **(I1 social dim.)**
(2) Problem identification/ ideas forming.	Identify problems that could benefit from a smart city. Learner centred experiences and thinking about ‘what if’ ideas. **(I1 inspiring)**
(3) Sharing & discussing what kind of problems & why they might be interesting to solve.	Experience of and ideas about IoT technology understanding are presented through their ideas Facilitator led encourages collaboration. Inviting students to share ideas. Students are hesitant. **(l1 inspiring)**
(4) Working in pairs to get hands-on experience.	Exploring with sensors. Students explore ideas through a simple setting. Although initially facilitator led, students start to take authorship/ ownership of learning through tangible experiments **(l2 making connections)**
(5) Reflecting on their hands-on experience.	Linking their hands-on experience to solving bigger problems. Scaffolding based on a collaborative community approach. Students draw on existing skills & participate in the dev. of problem solving. Personal learning embedded at its core. **(l3 bigger picture)**
(6) Presenting their finds at the end of workshop.	Initial connections being made between Smart Cities and sensors. Challenging for students even in pairs/groups to provide feedback. Some were reluctant to present but did in the end. **(l2 narrative)**

5.1 Analysis of Activity 1

A VEX factor resource was used to facilitate the students in examining ideas/problems they would like to solve.

For example, student 4 relates to a real life problem “when you are crossing the road sometimes the lights change too quickly, it’s dangerous”. The sharing of ideas starts to emerge.

Student 3 asks how we might do this. Student 4 relates this to a smart city about changing the lights timing through sensors that check when people have crossed the road to safety. They begin to explore and examine the problem and the solution. These resulted in learning indicators mainly from group 1 of supportive, feedback and inspiring ideas (I1).

5.2 Analysis of Activity 2

The students share their ideas. The discussion takes place e.g., about the alarm bed that slowly wakes you up or a notification system that tells you when the bus will really arrive and if seats/space are/is available. A shared understanding emerges as they negotiate the meaning of a problem. In one group an iterative process of refining and reshaping the problem into solution steps at conceptual level occurs. The elaboration process moves between critically analyzing the problem and sharing potential solution pathways. The students discuss problems and ideate using the 'VEX' factor which stimulates the creative process. This resulted in learning indicators mainly from group 1 of feedback and inspiring ideas (I1).

5.3 Analysis of Activity 3

The researcher scaffolds the ideas the students' have into the context of the smart city. The students are invited to contribute how they think about their problems. They are hesitant. The researcher bridges some of the concepts to facilitate building shared representations through knowledge construction and critical thinking. They watch a video to learn about building some initial experiments with LEDs and sensors and the broader picture of networks, communication and the Internet. This activity resulted in learning indicators mainly from group 1 of inspiring ideas. Also, the building on the work of others starts to emerge (I1).

5.4 Analysis of Activity 4

The tangible hands-on experimental learning experience is illustrated in Section 4 through the short dialogue exchange that shows student 1 and student 2 moving between analyzing the problem and knowledge constructing an explanation narrative as they explore how to control the LED (see earlier example). They mediate between explaining what is happening and then testing their theory/idea and re-thinking when it doesn't quite work. It is during this phase of building to discover and tangible exchanges of meaning (problem solving) in pairs that the engagement of staying on task to complete their experiments is clearly identified. This activity resulted in learning indicators mainly from group 2 of making connections, creating narratives and explanations (I2).

5.5 Analysis of Activity 5

After the students had completed 3 or 4 experiments they were asked where these experiments might be useful and whether or not they could use any of them to help solve some of their original ideas. They had difficulties in making the connections. The researchers scaffold the process to examine the links. This activity resulted in learning indicators mainly from group 3 of seeing the bigger picture (I3).

5.6 Analysis of Activity 6

Each student was asked to give a short presentation at the end of the workshop about what they had learned, what they liked, what they didn't like and what they might like to do as a project for the hackevent. During this activity they were practicing presenting a hypothesis. All of the students came to the front. They were still in pairs. Most explained about learning about the Arduino (https://www.arduino.cc) and programming and explaining what they had understood. Their main feedback was positive and they all felt at this stage they had no idea about what to design for the hackevent. Some general follow-up questions about what they had achieved and learned e.g., making music and changing the sound or controlling the sensors etc. showed some initial linking of their knowledge to other activities they had covered in computer science. This was challenging for the students but they did start to articulate these relationships. This activity resulted in learning indicators mainly from group 2 of narratives and explanations (I2).

5.7 Analysis of the Mini Workshop

From the analysis of the data between the initial presentations of their ideas the students appeared more confident at the end. The students provided longer narratives about their experiences and more students presented their work and shared ideas back to the class. Although all students came to the front of the class (in their pairs) sometimes only one student would give feedback. However, they were still hesitant and only one student from the class was prepared to provide some feedback on what he/she thought could have been done better.

5.8 Brainstorming

During this process the researchers were able to see the students moving between sharing meaning (ideas) and unpicking the ideas (tasks to enable this). The discussions illustrated evidence of tentatively critiquing ideas and 'high-level' solutions being discussed (e.g., for feasibility and/or usefulness). These discussions were led by the students and facilitated by the teacher. This resulted in learning indicators mainly from group 1 of feedback, inspiring ideas and building on each other's ideas (I1). However, it was clear from the discussions that some students' set their own goals and were making connections. This illustrated a movement between collaborative learning of knowledge sharing to thinking through how to produce a solution (theoretically) at knowledge construction level.

5.9 During the Two-Day Hackevent

When presenting their designs, a clear engagement with solution formation and hypothesis forming was evident. The ideas had matured clearly compared to the end of the mini-workshop. Their self-efficacy had developed. In the presentation, for example about the 'intelligent glove' student 3 gave recognition to his peer for the original idea. During the design phase the learning indicators of problem-solving in open-ended context emerged, students setting their own goals (I2) and identifying with the bigger picture (I3) and building on the work of others (I1).

During the creation of pilots and presentation preparation the students provide feedback and adapt the team organization and roles. During this activity there was less explicit monitoring activity and the students were sharing their knowledge and understanding with each other. They demonstrated an acknowledgement of each other's mastery and valued each other's success. This is an important step in the learning process within the context of collaborative and problem-based learning in terms of validation both from peers and the community. The recognition brings value to the learning that has taken place. In this phase the

TABLE 3
Intelligent Glove Design Phase Analysis

Knowledge building ($DF = 9$, $p < 0.05$)	M	SD	Learning indictors context	IoT as TEL observations
Self-initiated questioning and theorizing (249 coded observations)	24.4	6.8	Identifying facts Representing knowledge (l1)	Discussion about how this might work
Self-directed knowledge-advancing activities (135 coded observations)	13.5	6.7	Generating Hypothesis (l1 and l2)	Role play, acting out of ideas, humour
Self-assessment (26 coded observations)	2.6	4.7	Planning and reflecting (l1 and l2)	More conceptual validation and value

TABLE 4
Building an Intelligent Glove

Knowledge building ($DF = 9$, $p < 0.05$)	M	SD	Learning indictors context	IoT as TEL observations
Self-initiated questioning and theorizing (44 coded observations)	4.5	4.5	Generating Hypothesis (tends towards l2)	Testing ideas between sensor and software
Self-directed knowledge-advancing activities (115 coded observations)	11.5	2.5	Enact plans (l2 and l3)	Integrating components, testing Hypothesis
Self-assessment (250 coded observations)	25	4	Monitoring, Reflecting and applying (l2 and l3)	Debug, reflect, discuss, fix

persistence and making connections (I2) and the more technical learning indicators emerged (I3). They were moving between the concrete representations and knowledge building considerations.

5.10 Collaborative Knowledge Construction

The data from the hackevent over two activities was analyzed further for knowledge construction responsibility and agency of learning [30]. Table 3 provides an analysis of the details during the hack-event design phase and Table 4 part of the building phase of the glove. The two activities of design and building the Intelligent Glove were reviewed to see the different types of knowledge indicators emerging. In the design phase there is a richer articulation and exchange of 'self-initiated questioning and theorizing' and 'self-directed knowledge' with less focus on self-assessment. In the building phase there is a shift to more self-directed knowledge advancing activities and self-assessment. In the design phase the development of building a shared representation and generating hypothesis focuses on self-initiated questioning and theorizing and formed part of the 'self-directed knowledge advancing activities'. The self-assessment observations to create, share, test and fix the building of the intelligent glove provides the context for identifying knowledge and monitoring. This gives an insight into the indicators emerging relating to the learning activities.

The detailed analysis of the video during the design phase, which was over 3 hours of activities, provided over 449 observations related to collaborative knowledge building. The mean and standard deviation is given for each observation.

These findings suggest the relationship between the activities phase and knowledge construction. The self-assessment is significantly different for the build phase (see Table 4 where over 409 observations of 3 hours of activities related to collaborative knowledge building were identified). This could be due to a number of factors: conceptual level is difficult to self-assess without experience, building a public entity of an idea develops reflection and self-assessment and potentially recognition that the design phase of the project is more open-ended. In the build and create phase theorizing was less observable but the self-assessment became more obvious and concrete.

5.11 Boundary Crossing: Computer Science and Engineering

During the analysis IoT facilitated the knowledge construction and sharing. The direct relationship between experimenting with 'raw' tools enabled the students to see the development of concepts/designs into working pilots connecting the algorithms to the application. Each project has a number of components that need to be integrated as part of Internet services and networked to share data and services. The iterative and distributed nature of IoT tools and environment facilitated component-based building approach used by the students.

The following provides an example of learning about CS and engineering (an analysis is provided in Table 5). The example highlights the benefit of incremental examination and testing of ideas and making connections between computer science and engineering. The students decide to use an accelerometer to create an interactive glove (setting their own goal). They create a small circuit to test the sensor with a simple program. The initial testing of the sensor with software was to develop the tracking of the glove movement. The accelerometer 'sounds' like the right sensor for this. Three students are working together.

1. They test their program and 'the program isn't working' and students investigate the circuit and change the connections to the board and device. Nothing is working.
2. They check the documentation and go online. They re-fix the circuit as they realize that the original connections were correct.

TABLE 5
Boundary Crossing Analysis Example

Boundary crossing	IoT context	Learning Indicators context	Knowledge building
Connecting design process with electronics and software	Using an accelerometer to create an interactive glove	Hypothesis sharing related to the idea (l3 but supported by l1 and l2)	Incomplete knowledge 'misconception' Self-initiated questioning
Connecting electronics with software and algorithms	Testing out ideas and finding how to make the sensor work	Iteration of enacting plans, identify knowledge deficiencies, monitoring and fixing (l3 but supported by l1 and l2)	Iterative test of 'misconception' realization 'error' 'Self-directed knowledge ' & 'Self-assessment'
Bigger picture of connecting to the internet and the relationship with data	Experimenting with data from the sensor to control remote operations	As above	Expected and actual results: 'Self-directed knowledge ' and 'Self-assessment'

3. They try again with software and 'hack' with let's see if changing the output will work. They seem to add some 'random' additions to the program.
4. They decide the sensor is broken. They choose another accelerometer.
5. Researcher works with them walking through the program asking the students questions about the program. They make changes as they reflect on the 'algorithm'.
6. Certain now that the hardware and software are correct they test by moving the accelerometer quickly. Again nothing. They are now convinced that this sensor isn't working. The data from the sensor is intermittent and incorrect from their expectations.
7. After some discussion with researcher and each other they investigate how an accelerometer works and find that it is not measuring velocity. They realize their misconception and fix their program.
8. They fix their own misconceptions in the process of debugging.

Here is where the cycle of problem solving is evident but many steps occurred to achieve this. Also, the collaborative element means that this newly constructed knowledge of understanding is shared. The boundary crossing of seeing the bigger picture is within the context of computer science and engineering. However, there is a broader context of boundary crossing that of project design and seeing larger view of where the 'interactive glove' fits within a smart home project.

By examining boundary crossing of learning about computer science and engineering through the experimental affordances of IoT in the context of knowledge building the experience of the new knowledge constructed and shared through 'self-assessment' becomes evident. Reflection about one's own knowledge through building a 'public entity' occurs in debugging, testing and analyzing. There is no explicit detailed plan, the process is iterative experimentation with sensor, software, algorithms and data services and 'debugging'. The debugging experience was both the experiment and the students' knowledge (such as miss-understandings are corrected when re-thinking and working with the logic). They went hand-in-hand. The details of collaborative and problem-based learning are uncovered through the knowledge building analysis.

6 DISCUSSION

The aim of the study was to identify learning indicators within three dimensions (a) Social: the context for collaborative learning (b) Theme-based: for problem-based learning and (c) Boundary crossing: for multidisciplinary learning. The broad pedagogical context of constructionism underpinned the learning activities to support open-ended student-led learning. The benefits of learning through IoT are examined and the broader understanding through this investigation and analysis of the data are summarized.

6.1 Social Dimension and IoT

The analysis of the findings highlights the value of the collaborative learning experience. Identifying and sharing ideas at the beginning set the tone of the learning experience, validating and valuing all contributions [30].

Throughout the study the students exhibited behavior of acknowledgement e.g., of others' ideas, of appreciating knowledge and sharing 'know how' and feedback. The building community knowledge and the development of this process from hypothesis to self-assessment are supported through the tangible components and experimentation aspect of IoT [55]. The collaborative process enabled an explicit exchange and sharing of knowledge demonstrating the potential of collaborative boundary crossing, thus a whole group benefits from a change in understanding that is grounded [33].

6.2 Theme-Based Dimension of IoT

The problem solving process observed through the tangible approach, enabled by an IoT environment, supported relevant and purposeful engagement with STEM. The findings are similar to those expressed by Blikstein [9] "*students have the opportunity to come across several concepts in engineering and science in a highly meaningful, engaging, and contextualized fashion. Abstract concepts such as friction and momentum become meaningful and concrete when they are needed to accomplish a task within a project*" (p. 18).

6.3 Boundary Crossing Dimension and IoT

One important realization in a science experiment is the potential significance of an experiment. They could experiment with these sensors and make connections to the problems they were trying to solve. Similar to Vossoughi et al. [53] this study found students shifted their relationships with problems and drafts over time, and came to embrace the process of iteration. This incremental and experimentation nature of IoT technologies supports the context of making and experimentation. The "mistakes" and moments of struggle are often reframed as essential to the iteration and experimentation process that is highly valued in design, problem solving and STEM.

As the students' knowledge changed through sharing ideas and experimenting then their authorship' over material ([27]) became more evident e.g., see the comparison between the design phase (Table 3) compared with building phase (Table 4) showing a shift in self-assessment of knowledge.

The IoT environment enabled flexibility of 'making' and encouraged experimentation as the materials available did not exactly do the job to help solve the problem directly. The students needed to find solutions and were motivated to do so – purposeful learning is always 'active' [30].

6.4 Summary

The design-based research study contextualized the learning processes in more detail making explicit the pedagogy of collaboration and production. A deeper analysis illustrates where interdisciplinary learning across computer science and engineering is possible. The study and the knowledge construction context means that the learning has boundaries to identify the kind of learning taking place. Hence, this research is re-usable in a variety of contexts. The challenge is that the learning design/lesson plan of the activities needs to be understood in some detail to determine the aspects of STEM domain specifics that relate to the curriculum. For example, an activity when students learn about circuits and sensor controls they are meeting curriculum targets both in CS and physics (and possibly other areas as well). The study does not provide this kind of information (nor should it). The research methodology and contextualized indicators (see Tables 1 and 2) aids to explicitly identify the learning activity context. The activity details can be adapted to different aspects of STEM learning.

The study context to identify learning indicators leaves a lot open to interpretation. While details and examples have been provided the design context as a learning process for collaborative and problem-based (production) learning can be applied to any study that is investigating these learning contexts. However, it is not sufficient as collaborative and problem-based learning are not agnostic of the context of the domain(s) that are core to learning. Interdisciplinary learning when analyzed as a knowledge building process provided the insight into the students experiencing first-hand the value of collaborative learning [30]. Hence, the shared 'public entity' jointly constructed provides a reflective space for self-assessment of moving between abstract concepts and concrete solutions. Clearly, the students experience the process of jointly constructing as well. Whether or not this experience creates a transferable skill of a deeper understanding of collaborative learning is not evident. However, the community knowledge building process when examined in detail shows collaboration and problem-based learning as by products. This would be expected when learning through making context. The data shows that collaboration and problem-based learning is taking place but there is not sufficient data at this stage to determine 'patterns of learning' to automate or specify specifics.

IoT TEL tools of the future, from a pedagogical perspective, could support students to annotate and to capture the process and findings of an experiment. Then such experiments can be examined for example as a planning or experimentation process. The reflection on the process through such an artifact would provide specific context on possible improvements or modifications. Although, a well-planned project from the beginning may provide a more efficient solution it may miss two core elements (a) student ownership of the project and (b) the power principal of constructionism that is "the natural mode of acquiring most knowledge is through use leading to progressively deepening understanding" (p. 98) [40]. While it is possible to track and provide instruction driven sequencing to ensure task completion this approach does not necessarily enable 'learning with' and the empowerment of knowledge building collaboratively.

7 CONCLUSION

The design-based research approach was used to investigate what kind of collaborative and problem-based learning can be observed. The study led to important findings in the collaborative knowledge building process. The results, by learning through IoT context, illustrated specific links between the pedagogical design and collaborative learning, which resulted in identifying the shared learning in boundary crossing context. This follows closely to the more informal learning in maker communities [8] and the formal learning in knowledge building [30]. In general, the study illustrates how to design and investigate collaborative and problem-based learning in STEM providing details of the design-based research methodology, learning activities and the analysis of findings.

A contribution of this study is three-fold. First, the design-based investigation details the approach characterising the activities that can be applied to other domains. The specific study illustrates how the analysis was performed to identify the collaborative and problem-based learning, which can be applied in other STEM settings. The findings of learning through making in the context of constructionism illustrates specifically that collaboration and problem-based learning take place as part of the process. Secondly, the study contributes to the importance of tangible hands-on activities to support constructing and sharing of a public entity through IoT as TEL tool. The importance of IoT in this context is it is a flexible tool that can be iteratively used to design, explore, build and share and puts the learners in direct contact between algorithms (programs) and sensors (hardware) so that abstract ideas become concrete and realisable [6].

Third, the collaboration and problem-based dialogues and interactions between the students, researchers and teachers illustrated a knowledge co-construction process [12]. This follows closely the findings in knowledge building process and 'learning with' [49] through development of agency of learning through self-initiated questioning and theorizing during the activities [30]. Self-directed knowledge-advancing activities emerged and the capacity to reflect was identified as a form of self-assessment. However, this was only possible to ascertain through a deeper investigation of knowledge construction. The study illustrates the process of knowledge construction and design challenges fostering collaborative and community engagement. In this context expressions of reflection and inquiry-driven questioning were identified, which form part of the critical thinking and problem-solving skills required when studying STEM.

Using IoT TEL tools helped focus away from the specifics of programming or engineering. The tangible aspects provided an exploratory approach to learning. As the students developed more knowledge and insights they were able to make deeper investigations. Related to learning about STEM, IoT as a TEL environment highlights for the learner how data can be captured (by sensors) and interpreted (by programs they created). The learner designs and implements a computation system to execute decisions autonomously based on 'the data'. The students were able to experiment iteratively with different components and component integration. The engagement was not about CS or engineering but about creating 'their project'. This focus meant the learning had purpose.

The IoT environment enabled the exploration of an incremental approach and to evaluate that experience both in the context of teaching and learning. The value of incremental learning means that not all the hard learning needs to be done in one go, thus making an impossible learning task possible.

The results, of this study, have been used to inform the design of effective data analytics and visualisation tools for the PELARS project to advance practice-based learning activities in STEM teaching. In particular the details of knowledge construction process has informed the analytic design for supporting practice-based learning [19].

The study has led to further questions related to the interdisciplinary learning about STEM. For example, are there effective patterns of learning that can be identified in the process of collaboration, such as the knowledge co-construction process started to identify? What are the multiple roles of IoT in knowledge building and learning and do these roles enable more authentic learning of STEM that develops agency of learning? More importantly, if collaboration and problem-based learning are by products of building community knowledge, then how can IoT TEL tools advance this process and go beyond the findings of Gomez et al. [29].

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