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IoT Educational Framework Case Study: Devices as Things for Hands-on Collaboration

Renato Perotto Machado, Ulrich Norbisrath, and Ruben Jubeh.

***Abstract*— As IoT continues to reshape industries and daily life, our research revolves around cultivating a generation of IoT-literate individuals capable of addressing today's challenges. In the Internet of Things (IoT) education, it is crucial to provide students with the ability to work with the technology and apply it to real-world problems. This creates a demand for teaching methodologies compatible with newly explored networked learning activities, for example, Challenge-Based Education (CBE). This study explores the IoTempower Framework, a versatile pedagogical tool dedicated to enhancing IoT CBE education. Its open-source nature and teaching support make it accessible and adaptable for IoT courses that support hands-on learning and teaching practices. This paper investigates IoTempower Framework's educational applications by analyzing three higher-education study cases where it was deployed. It explores the framework with its associated devices as tools for experiential collective and critical learning. Through a survey of students and participatory observations, the paper evaluates the framework's impact on fostering collaborative engagement in project-driven courses. It introduces the concept of devices as social-material entities or design things and how this approach to device development can aid collaborative teaching and learning experiences. The paper underscores IoTempower Framework as a social-material tool that is significant in shaping effective IoT education by highlighting the interplay between technical and social aspects of its devices as pedagogical tools.**

***Keywords*— Internet of Things; Education; IoT Framework; Devices; Design Things; Collaboration.**

***JEET Category*— Pedagogy of Teaching and Learning -Track - Collaborative, Experiential, and Outcome-Based Teaching-Learning Processes**

I. INTRODUCTION

IN the Internet of Things Education, innovative teaching methodologies are crucial for supporting a experiential challenge-based learning. Educational institutions need to prepare a long-term strategy capable of addressing the challenges of the new technological revolution (Ramlowat & Pattanayak, 2019).

Considering this scenario, we advocate that IoT education must empower students providing them with experiential teaching-learning engagement with the technology characterized by collaborative, hands-on, project-driven, and challenge-based practices. Pedagogical tools designed around the 'learn-by-doing' philosophy facilitate a deeper understanding of practical challenges. In this regard, knowing and doing are inseparable parts of the process and practical activities are considered to solve conceptual problems (Binder et al., 2011). Engaging in practical activities is a key strategy for solving conceptual problems. In IoT education, the complexities of designing learning devices that encompass hands-on experiential practices with IoT architecture, hardware, and networking are many. Merely incorporating devices into the classroom does not automatically translate to an experiential teaching-learning process and many more. Courses and devices must be cohesively designed considering a socio-material infrastructure that supports the educational environment and enables students to collaborate and develop their projects within the Institutions' limitations.

When designing such teaching tools, we must consider not only their technical aspect but also their social ones in order to accomplish the pedagogical goals. The development of such teaching tools needs to take into consideration Human-Computer Interaction (HCI), particularly the collaborative practices that are involved in project-driven outcomes. When creating such devices, we must also consider its accessibility, functionality, and adaptability in the context they are deployed as well as how they can enhance critical thinking about the technology. In essence, such devices must incite inquiry rather than merely a professional competency. In this paper, we set out to analyze the IoTempower Framework as such pedagogical tool and how it addresses some of these issues.

IoTempower is an open-source and affordable framework and environment developed for implementing full IoT projects in education as well as other DYI IoT projects. According to its documentation, the framework's main focus is to support classes to teach IoT. It is supported by an open-source community, and the main development has been on a public

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Corresponding authors: Renato Perotto Machado, Institute of Computer Science, University of Tartu, Tartu, Estonia.
Ulrich Norbisrath, Institute of Computer Science, University of Tartu, Tartu, Estonia.
Ruben Jubeh, Institute of Computer Science, OTH Regensburg, Germany.
Address: Narva mnt 18 / 51009 Tartu / ESTONIA
renato.perotto.machado@ut.ee
ulrich.norbisrath@ut.ee
ruben.jubeh@oth-regensburg.de

GitHub repository[1].

In this paper, we focus on its educational application. We analyze how the framework, its devices, and accompanying teaching material have been used as a pedagogical tool. First, we look at the related work on how IoT has been used in other educational projects. Then, we introduce the concept of devices as social-material entities, namely, design things, and how this concept can help promote collaborative practices. Third, we present three case studies of how the framework has been deployed as a pedagogical tool in higher education institutions in Europe. We conclude the paper by evaluating how the framework and its devices augment collaboration and challenge-based teaching-learning through our participatory observations of the study cases and by analyzing a like-chart survey on its usability as a teaching framework.

II. RELATED WORK

In regard to IoT education, Ramlowat and Pattanayak (2019) emphasize the importance of creating a social and technical ecosystem comprising hardware, data, associated content, and relevant services. They also highlight the challenges arising from the application of IoT in education, such as security and privacy, data storage and management costs, and the training of teachers. Their paper presents study cases where IoT systems were used to foster educational practices. The "IoT-based Flipped Learning Platform (IoTFLiP)" is a framework intended for medical learning, and its development is a relevant case for our work since it uses IoT resources and infrastructure for supporting Case-Based Learning (CBL) in a flipped learning environment. Another study case presented is the IoT Manpower Training Using HOPPING and ESIC: It discusses a study that aimed to design a systematic educational program called "HOPPING", which is expected to provide effective and specialized physical training courses using IoT. (Ramlowat & Pattanayak, 2019).

Terzieva et al. (2022) point out the imminent potential of the Internet of Things (IoT) in establishing smart environments for schools and education. They explore how IoT devices can enhance educational efficiency within optimal learning spaces by providing valuable data about classroom learning environment.

He et al. (2017) explore a particular educational framework's ability to facilitate STEM undergraduate education. The study points out how the surge in IoT applications has created a demand for skilled professionals. Still, dedicated courses lack IoT training, leaving STEM students unprepared for the workforce. They propose an IoT-based learning framework prototype developed to be adapted to an undergraduate STEM higher education curriculum. The framework's solutions are discussed, including implementing a lab kit that enables wireless communication, which is particularly relevant to our paper.

The cases presented show the integration of IoT in many aspects of education, from the improvement of educational facilities to the improvement of the STEM curriculum. On the other hand, we noticed that none of the above resources explore how the social aspect of IoT devices can support teaching-learning practices and environments. This is why we set out to write this current study to explore how IoTempower framework is designed to empower IoT teaching and collaborative challenge-based learning.

We strongly believe that we need to start addressing social-material aspects of devices when developing Engineering educational tools and toolkits. Socialmateriality emphasizes the interactive relationship between social processes and objects, asserting that objects are not inert but actively contribute to shaping social meaning and behavior. This concept acknowledges objects' agency in influencing human interactions. Notably, technology plays a key role in contemporary socialmateriality, thus design research finds it essential to analyze the social and material aspects of devices created. We base our hypotheses on our finding from design research domain which has further addressed these issues. In the paper "Leaving the Field: Designing a Socio-Material Toolkit for Teachers to Continue to Design Technology with Children." (Scheepmaker et al., 2021) the study showed that tools technological tools created in academia to support education struggle with adoption and real-world use outside of research, and this remains a continuous struggle in Human-Computer Interaction (HCI). To ensure that HCI devices used in education can be used after researchers have left the fieldwork, they must collaborate with educators to create the social-material tools to accompany the toolkits. Unlike standalone design toolkits, the paper points out a distinctive aspect of a social-material toolkit is its ongoing infrastructure to guide and assist teachers to use and adopt them after researchers have left the field. The authors present the concept of design thing and how thinking of these pedagogical tools as such can improve usability. In the next section, we also adopt this expanded concept of thing to help us think critically of what is a device in a teaching-learning environment.

A. DEVICES AS COLLABORATIVE THINGS

When theorizing about the Internet of Things, an effort has been made to distinguish things from devices. The latter is usually associated with the electronic and computational artifacts responsible for technical communication. They are usually attached to or embedded in the objects that connect to a network. On the other hand, as we see in Haller, 2010, the thing has usually been associated with entities of interest in the physical world we want to monitor and interact with. According to Al-Taai et al. (2023, p. 21), "an IoT "thing" can be any object that has the required computing power, Internet connectivity, and the ability to collect and transmit data over a network without assistance or manual intervention." Still, as Stephan Haller suggests, a clear-cut distinction between thing and device is not always possible, and the role of devices and things can overlap depending on the perspective from which we analyze a thing or device and the stakeholders' interactions with it in a particular context (Haller, 2010). However, devices are

[1]https://github.com/iotempire/iotempower

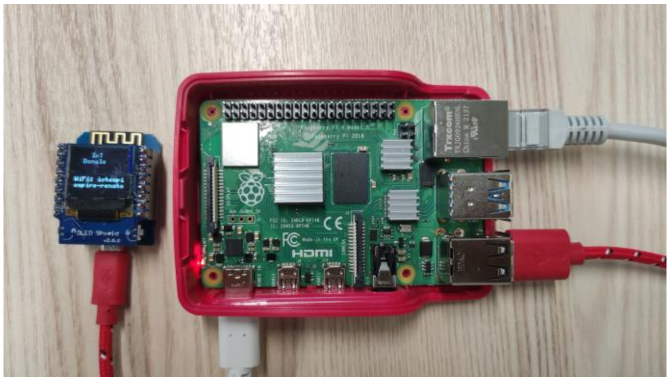

Fig. 1. Raspberry Pi Gateway with dongle attached. 2023. (Source: authors' archive).

not only associated with machine-to-machine communication. In many situations, Human-Computer Interaction needs to be taken into account, and it's something that often is ignored in the design of devices.

We argue that in the context of project-driven, hands-on Internet of Things education, devices, more often than not, play the role of things. In these contexts, human interaction must be considered when designing these devices. Moreover, the development of teaching tools is inherently a design process. The design approach to education is far developed regarding hands-on, project-driven education. Therefore, it can help us better develop these kinds of learning practices. (Cross & Holden, 2020).

The book "Design Things" by A.Telier explores the concept of "thing" in design from a social-material perspective (Binder et al., 2011). This approach is essential when we introduce IoT devices as intervention teaching tools in the classroom and as they play the role of a thing that is interacting with the students and shaping their social behaviors.

The authors highlight that design should embrace the concept of a thing as proposed by Martin Heidegger to be able to understand its socialmaterial implications. Departing from the conventional notion, Heidegger aimed to redefine "thing" by emphasizing its relational nature and rejecting the idea of passive objects. He saw a "thing" as something that can promote a gathering and by focusing on how things transform our interactions, we can enhance self-awareness and comprehension of the world. For example, in teaching IoT, a common task might be to design a system to optimize energy consumption in a smart home. But its development cannot only take into account the technical aspect of such devices. It also must consider how people will interact with the system and how it can shape their social behaviors and interactions not only with the house but between its inhabitants. How will they interact with the system in the real-world? Will it make them more aware of their energy consumption? Will it change their daily routines or habits?

These are questions that a designer must consider, highlighting the importance of the socialmateriality concept, and this way of thinking can help us better design our IoT pedagogical tools. We argue that in IoT education, the socialmateriality of devices used in classrooms is usually ignored during their design processes, but in the courses, students must interact with devices as things for their learning processes to be effective. That is why we propose that devices in IoT education must be designed and thought of as things. We propose to analyze the IoTempower, kit, and gateway as design things in search of insights into how we could better develop such devices for education and promote collaboration.

III. FRAMEWORK, GATEWAY AND KIT

In this paper, we set out to analyze the solution provided by the framework IoTempower, which its main purpose is to foster IoT education. It was first used to support the teaching of a home automation course but expanded to address full IoT courses. The framework has been in constant development since 2016, and its main iterations are in the educational setting. In this sense, it is a pedagogical tool for supporting IoT learning and teaching practices. It has been used in higher education institutions in Austria, Estonia, and Germany, and workshops in Austria, Brazil, Singapore, Indonesia, and the US. Its audiences range from computer scientists, software engineers, academics, and artists. It's important to note that the framework is not only an educational tool, but it also functions as a stand-alone infrastructure for independent projects. Since its release, it has been adopted by tinkerers, makers, programmers, hobbyists, students, teachers, artists, and professionals to explore and develop their own IoT projects. It has also been deployed in agriculture, interactive arts, home automation, and logistic projects. All of the software of the framework uses permissible licenses and libraries, and it is fully open-source. For this reason, it is also focused on empowering local community projects and alternative teaching where resources are limited.

When used as an educational tool, IoTempower is usually accompanied by a gateway (Raspberry Pi single-board computer or a laptop with certain network capabilities specifications), a kit with microcontrollers with wireless technology.

The framework, kit, gateway, and can be intricately woven together, forming a self-contained IoT infrastructure capable of convenient transport and deployment in various locations as required.

A. GATEWAY

In our study cases, the framework operates by services that run on a Raspberry Pi 3 or 4 gateway that comes accompanied by an image of its operating system for seamless functioning (See Fig.1). The IoTempower stack runs on top of a DietPi distribution, and its image can be easily downloaded and flashed onto a SD-Card. In this setup, it comes equipped with all the necessary software components for configuring an IoT system. This setup runs as headless server that can be accessed via SSH. The gateway offers functionalities for operating and overseeing a WiFi router and an MQTT broker. This makes it a comprehensive platform encompassing configuration management software and dataflow management services.

Fig. 2. IoT kit with sensors and actuators. 2023. (Source: authors' archive).

In the classroom, these gateways serve as both an access point and a service provider, ensuring connectivity among the nodes and endpoints for lab activities, prototyping, and final projects. The gateway is where most of the student's interaction with the framework happens. It is also a hub for groups of students to gather around and collaborate on projects.

Nonetheless, it's also possible to implement IoTempower on a dedicated Linux or Mac system allowing the incorporation of distinct gateway services. This implies the potential setup of a WiFi router to manage your IoT edge network. (IoTcommunity, n.d.).

B. KIT

In the IoT courses, the framework is accompanied by a toolkit of IoT devices that can be configured in different ways to function as nodes. These are also referred to as "things" within an Internet of Things architecture (Github Documentation, n.d.). Nodes are wireless elements that engage with tangible items, often featuring multiple connected devices. The devices associated with nodes can encompass sensors or actuators. All class projects and tasks can be accomplished with the parts found in the kit. In the IoT courses, each group of students (2 - 4 students) is given a kit that was carefully crafted for hands-on activities, and which can be easily replicable and accessible in other settings.

The framework supports open hardware, and the nodes are deployed using microcontrollers. Currently, it supports the esp8266 boards: Wemos D1 Mini, NodeMCU, ESP-M1, Espresso Lite V2, Sonoff and Sonoff Touch. It also supports the esp32 boards: wroom-02, esp32minikit (mh-et live).

The software provided by IoTempower allow for easily deployment of nodes on the esp8266 or esp32 running on independent firmware coded in C++, which is all managed via PlatformIO. The framework this way simplifies many repetitive device management tasks for users, for example, connecting a device to a node with the framework typically involves only composing a single line of code. This code can be customized using numerous available examples and documentation that can be found on GitHub and on the gateway itself.

Example of code:

```
input(button1, D3, "released","pressed").with_debounce(5);
```

(IoTcommunity, n.d)

The sensor and actuator from the kit can be arranged in many different configurations depending on the course specifications and the complexity of the projects. As of 2023, IoTempower supports the following categories of components: Sensors: This includes color, gesture, distance, capacitive touch, temperature, movement, water quality, gas detection, IR, humidity, flame, knock/shock, acoustic distance, magnetic, and PH sensors. Actuators: This encompasses OLED screens, relay switches, motors, solenoid drawer locks, and buzzers. Communication Modules: Such as RFID card readers, NFC tags, and esp32 modules with camera capabilities. Power and Connectivity: USB power meters, charging ports, and various cables. Miscellaneous Components: Including breadboards, LED strips, load cells, resistors, LEDs, capacitors, and power adapters[2].

IV. STUDY CASES

In this section we will present three stories where IoTempower Framework has been deployed as the main pedagogical tool in higher education courses.

A. International Master Student and the HarvestMate Smart Planter

Let's follow the story of Karli[3], an international master's student from the Institute of Technology at the University of Tartu, Estonia. All the lab activities in Karli's course happened in groups of 2-5 students. Every lab session, Karli had to figure out how to work with new hardware and its related software in a hands-on tasks. Every lecture was complemented with videos, which helped Karli prepare for the practical lab sessions. The videos were usually step-by-step guidelines on how to install and work with the hardware and the framework in practical ways.

After a few weeks, Karli could already apply some skills she acquired in class to solve an IoT Challenge at her home. She used the framework and kit to develop a home automation system to control the lights wirelessly in her apartment. From the survey from Karli's semester, we learned that six out of twenty-one students used the IoT kit and IoTempower in their own personal projects outside the course during that semester. Also, fifteen students claimed they see themselves using the framework in future projects. One of the students commented: "I will definitely use it since I have now learned how to use it. To be honest, I don't even know how to prototype projects without it."

We have also learned from the survey that all students found it "very useful" or "somewhat useful" that the IoTempower infrastructure (kit and framework) is portable and can be used anywhere outside the classroom with no restrictions. This is

[2]There are also suggestions of kits available at https://ulno.net/iot/hardware/.
[3]All the student's and educators' names in this section are fictional to protect their privacy and identities.

Fig. 3. HarvestMate planter box project. 2023. (Source: authors' archive).

particularly relevant in the University of Tartu IoT course, as the classes are taught in a generic classroom setting and not in a laboratory space. Students had to find different spaces to work on their projects outside the classroom, and projects had to be assembled and disassembled every lab session. In week 10, it was time to come up with a challenge for the final project on the topic of "Sustainable Living". Based on the Story Driven Modeling method (Norbisrath et al., 2017), students imagined scenarios that would best describe a real-world challenge. These stories serve as tools for the groups to pitch their project ideas to the rest of the class and to come up with a detailed plan for their project's needs. Karli and her teammates chose a story about a student who had moved to Estonia and wanted to grow their own lettuce and herbs from her students' flat window.

The initial problem was how to measure natural light and compensate it with artificial lighting specially during Estonia's notoriously dark winters. The solution was to design a smart planter that would help her with watering and measuring vital information for the plants, like light intensity and soil and air humidity. For the final project, Karli's group set out to build this smart planter equipped with sensors and services using IoTempower which they named HarvestMate.

The project relied on IoTempower for managing and deploying the sensors, the gateway (Raspberry Pi 4) to run the services, notifications, local database logging, and dashboards using Node-RED integrator for data visualization using an old laptop.

The project was demoed at the University Tartu IT Academy summit and at the semester-end student's competition. Also, other faculty members were interested in having a HavestMate in their homes and offices. The prototype developed for this project also functions as a social-material thing that broadens the opportunity for interaction between students and the rest of the learning community. The students even got to interact with the university's gardener through this project.

B. Story of an Austrian Bachelor Student and the Smart Nursing Home

A computer science student, Toby, is one of the participants in the IoT course at the University of Applied Sciences Upper Austria, in Linz, Austria. From the first class, which was an intensive 8-hour session, he was able, with his study buddy Arti, to set up a gateway with Raspberry Pi 3 to run the framework and a full wireless access point, even though there was a lot of trial and error. The other classmates were also very helpful and even shared information directly on the internal classroom chat so everyone could move on quickly. They built their first network system, remotely controlling a simple LED light with a button on another microcontroller. The first lab challenge was to use the framework and kit to build a system to measure different liquids in very different and creative ways. The challenge was based on a real-world scenario for automating and monitoring all the liquids in a small sailboat. The projects were designed and derived from the storytelling (Norbisrath et al., 2017) approach in a very detailed level.

For the final project, Toby and Arti had come across a story-worthy case related to his own grandma who was in an elderly care home. How can IoT help to make life easier and safer for old people and their nurses in an elderly care facility? His grandma had recently fallen (escaping a major injury but still creating a scary memory). Toby and Arti set out to create a system that could alert staff and family when some elder has fallen, thus developing the case of their "Smart Nursing Home". The two students teamed up with another pair for this challenge, Christa and Oliver. Their final project idea was born and ready to be prototyped. The four teammates delivered a perfect script showing the whole nursing home system prototype in practice, including a cardboard walker with fall-over detection, a two-way notification system, and a Lego pill dispenser. All the services and the network infrastructure were done using the IoTempower framework and gateway.

Toby's team project helped not only him, but the entire class become more aware of the social problems revolving around the elderly community and how technology and its devices can improve their quality of life. They also understood the usability of these IoT things. Thus, by being able to prototype and design solutions in the classroom, the learning community can better understand IoT's strengths and weaknesses and its potential to help us deal with today's challenges.

C. Teaching IoT IoTempower Framework

Professor Ruben Jubeh, who recently returned to university and started a professorship with an IoT focus decided to use IoTempower in his newly designed course. As he described, using a Raspberry Pi as gateway helped the students gathered into small teams around mobile infrastructure and strongly facilitated hands-on lab work supporting IoT learning and teaching processes.

There was even some small collaboration on the IoT discord server between the Professor Ruben Jubeh and the University Tartu class, held nearly in parallel. Also, his class showed a very high retention of students. Connecting lectures and labs with lots of discussions felt natural and was supported by having planned 4 hours of integrated lecture/lab each time he and his students met.

Due to the openness of IoTempower, he was able to add some support for Apple hardware right during the class and added some ideas to IoTempower's central issue repository that could easily lead to thesis topics for students. He also looks forward

Fig. 4. Students collaborating around the gateway and kit. 2023. (Source: IoTempower Community' archive).

to adding more teachers to the mix and growing the community of teachers and learners around IoTempower.

V. Findings

These three study cases illustrate the impact of the framework on fostering innovation, collaboration, and societal awareness through challenge-based projects and education. Also, as the framework and its devices harvest projects that created gatherings in many social levels, we affirm that the devices, projects and the social infrastructure that composes IoTempower can all be considered as design things. HarvestMate and the elderly home project are more than projects, as they function as design things capable of reshaping individuals' perceptions of their surroundings. Through collaborative endeavors with peers and social circle outside the classrooms, the groups were able to address tangible challenges and attune to issues affecting the local communities. By presenting their final projects to the entire class and to the academic community, other students and educators could reflect on the potential of IoT technology to address local challenges.

Like Scheepmaker et al. (2021), we observed that a social infrastructure is needed to support any attempt to introduce devices in a classroom. As the authors put it: "we learned from our collaboration with the teachers that their situated context requires not only stand-alone materials but also a social infrastructure in which the digital or physical materials are embedded." (Scheepmaker et al., 2021) By making the teaching material available and the framework open-source, online discussion groups, access to teaching materials and videos, and by supporting affordable hardware, other educators can adopt it for their courses and contribute to further development of it. This interaction is crucial for running the project, fomenting the social infrastructure, and improving the framework's usability. By creating a social infrastructure, students and other educators are incentivized to contribute to the further development of IoTempower by testing, reporting bugs, suggesting features, and working hands-on in development as their thesis topic.

Notably, in the educator's story, we found that the inclusive and accessible teaching materials, the framework's open-source nature, and its support for affordable hardware can empower educators to embrace IoTempower in their curricula while contributing to its ongoing evolution. All these aspects which are considered as a social infrastructure around the framework aid its implementation in different teaching-learning settings. The whole social infrastructure needs to be taken into account in the further development of the framework.

Now, we will present some of the findings from the survey applied to students and educators from Karli's semester and the educator's course at the University of Applied Sciences Regensburg. In total, there were twenty-one students and two educators who participated in the survey.

Firstly, we discovered that an innovative aspect of this specific combination of framework and kit is the gateway, which also functions as a hub for collaboration. It is a device that functions as a thing that intervenes in the learning environment, expanding it to become a social gathering based on participation. The gateway serves as a platform where students from the same group share services and resources and must find ways to cooperate to solve challenges. The survey showed that the gateway allowed the students, professors, and teacher assistants to collaborate on practical hands-on projects. Twelve students "strongly agreed," and six others "somewhat agreed" with the statement: "Collaborating with others was important for my IoT learning experience." This is made possible by having practical tools that can be used in real-life projects and specifically designed for learning, such as the IoTempower Framework (or gateway?) and kit. All students "strongly agreed" or "somewhat agreed" that gateways are central to IoT infrastructure.

When students were asked about the pros and cons of sharing a gateway for group projects, the answers were:

Pros:

"It is easy to collaborate and quickly implement ideas." "We can complete the assignments at home." "I saw no issue sharing the gateway with my teammates. They would sometimes need it for their BA thesis, but I would only use it in class so no problem with that." "Everyone can work on the same project on different devices and features but on the same gateway." "It forces people around one device." "Sharing the gateway made me do more human-readable stuff. since other people also use it." "Considering the level of abstraction, it was easier to work together as it was easier to focus of the tasks more and not really bother with the technical side." "Good teamwork and time management training." "Get remote access working and it would be truly an IoT experience where one person could be at home sending data from one sensor to another person who has the gateway and node red automation." "Understanding how the gateway system works can be compared to a pair programming exercise. If one of us couldn't understand, then the other of us could." "Sharing with other people gave us opportunity to learn from each other by fixing errors or even by observing different methods for solving the same issue." "Got some different viewpoint." "All the created nodes are in one place, easy to share." "Instead of working individually, it helped me a lot in learning process because solving problems together is better, faster, funnier." "Needed to interact, got to know my mates better." "Learned that Node-Red exists and how easy to use it is - Learned about the remote Deploy feature of PlatformIO -

Simple Things were easy to implement and deploy." "Could complement skill with other group members for better overall result." "I learned faster."

Cons:

"It is not accessible remotely." "Sometimes the gateway doesn't support all the users so we can be disconnected at any time." "It's hard to get people at the same time around the device." "Only one person can have the gateway at a time, so others would have to use simulation to get things working. "One person may end up working with the hardware and one with the software." "I think with two people, using the same gateway is fine but with more people comes more logistical problems, i.e. when can someone meet up where etc." "The Node-RED conflicts were the only noticeable annoying part of sharing a gateway." "It was time consuming." "For simultaneous use, I think we did not use it like that." "Sometimes working on the same node-red flow was a pain to merge." "Multiple People working at the same time in Node-Red is a nightmare - The amount of abstraction really limited what you could learn." "Had to meet in person if needed to use Gateway." "It required coordination."

Despite the positive remarks, the majority of students reported that they would like to be able to access the gateway and its services remotely. One of the students declared: "Getting remote access working would be truly an IoT experience where one person could be at home sending data from one sensor to another person who has the gateway and node-red automation." In this regard, the students reported that it was hard to coordinate the group to meet physically to keep working on their projects outside of classroom time. They also found it difficult to work with the Integrator service, Node-RED, at the same time as it is not optimized for that, though there are ways to work around this issue. One student reported: "The Node-RED conflicts were the only annoying part of sharing a gateway. To alleviate that, we used Node-RED locally in our computers and passed the flow's .json files around."

We would also like to point out that ideally, an IoT learning environment should be designed to simulate real-world scenarios that professionals encounter and a place with inspirational objects where creativity and experimentation can take place for extended periods. Unfortunately this is hardly the case. Many institutions do not have a proper lab or a designated space for projects to take place. This is currently the case at the University Tartu and University Regensburg. Regarding these limitations, the IoT kit and gateway were designed to function as a mobile lab solution, allowing students to take and deploy their networks as needed inside and outside of the classroom and university.

When the students were asked, "Do you find it useful that the IoTempower infrastructure (kit and gateway) is portable and can be used anywhere outside the classroom?" Nineteen participants declared that they "strongly agree" and the rest "somewhat agree." None of them disagreed. The mobility of the kit and gateway and the ability to function in a stand-alone manner without the need for external services (no internet uplink necessarily required, documentation included) gives IoTempower the adaptability needed to permit hands-on IoT teaching and learning practices despite the space where these activities are taking place. For this reason, we found that the ability to provide students with a portable infrastructure allows projects and courses to be configured in multiple ways. This characteristic also allows the tool to be used in workshops and short courses in places with precarious or no infrastructure. This is an innovation solution to the learning-teaching challenges of IoT education.

Finally, results also showed that all participants either "strongly agreed" or "somewhat agreed" that IoTempower was a useful tool for understanding the practical aspects of IoT hands-on. On the other hand, not everybody felt comfortable using the framework independently. Three of the participants "strongly agreed," and six others "somewhat agreed" that the support of a technical person is needed for them to be able to use the IoTempower.

VI. Conclusion

Our conclusion from our participant observation and survey analysis is that IoTempower can support IoT education by encouraging critical reflection and practical hands-on learning experiences that foster collaborative project-driven education. This is because its devices function as things in its broader sense of promoting the gathering of students and community. The framework shows potential to be applied as a pedagogical tool for challenged-based education. Some of the Learning-teaching outcomes observed from our study cases were: Students were able to collaborate in the design, implementation, and tests of various IoT systems; Students greatly improved their ability to work with hardware devices and connect them via wireless networks; Students were able to deploy systems to collect, visualize, analyze, and act on data from the physical world; Students could identify real-world challenges and prototype IoT solutions, understanding the technological advantages and limitations.

We have shown how the devices, framework and kit operate as design things by fostering collaborative processes. But we also realized that the projects as well as the story driven modeling method used in the case studies can be also considered as a design thing.

HarvestMate is a good example of how the IoT project can be a catalyst for gathering. It provided a collaborative learning experience around not only the material, but also immaterial social aspects. It is an example of how IoTempower fosters the development of challenged based, small local projects that can be deployed in real-world, and how devices function as things gathering students in ways to promote creative solutions.

The elderly home project was also a good example of how projects are also design things. Toby's team was able to not only collaborate creatively with his group mates but also with his classmates, family members and care home staff. Thus, we believe that all together: devices, framework, teaching materials, projects, material and immaterial infrastructures all play a role if we want to develop devices as social-material collaborative pedagogical tools.

Results have also shown that despite the framework's usefulness for education and practical use, the study acknowledges that there is room for improvement, especially in expanding the accessibility to this infrastructure by allowing remote access to the gateway and services, thus providing more flexibility for collaborative work. As Prof. Ruben Jubeh pointed out, another improvement is to make the teaching framework more available. For his course, he declared that public access to all teaching material, videos, course infrastructure, framework, and the framework's community facilitated the adoption of the tools and devices in his spring 2023 course at the University of Applied Sciences Regensburg, Germany. In this sense, other strategies need to be applied to increase participation and contribution by students and educators in the community, as it is pointed out by Scheepmaker et al. (2021): "Especially when technological artifacts are created, it is challenging to ensure lasting engagement with the technology which is left behind." These strategies are central to the continued development of the framework as a pedagogical tool.

From our observations, we can also conclude that IoTempower serves not only as a technical tool for learning IoT but also as a social-material one that is fit for the challenges of today's education, making it possible to be taught in different institutional settings and timeframes. The portable and mobile characteristics of the learning tool are a truly innovative approach to IoT education, and we intend to continue to research this topic. We will extend the research to further courses and workshops planned for 2023 and 2024 that will use IoTempower as its main pedagogical tool and use its results to further develop the framework.

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