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Open-Source Hardware in Education: A Systematic Mapping Study

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ABSTRACT The open-source hardware movement is becoming increasingly popular due to the emergence of successful low-cost technologies, such as Arduino and Raspberry Pi, and thanks to the community of *makers* that actively share their creations to be freely studied, modified, and re-distributed. Numerous authors have proposed distinct ways to seize this approach for accomplishing a variety of learning goals: enabling scholars to explore scientific concepts, promoting students' creativity, helping them to be more fluent and expressive with new technologies, and so on. This paper reports a systematic mapping study that overviews the literature on open-source hardware in education by analyzing and classifying 676 publications. The results of our work provide: 1) guidance on the published material (identifying the most relevant papers, publication sources, institutions, and countries); 2) information about the pedagogical uses of open-source hardware (showing its main educational goals, stages, and topics where it is principally applied); and 3) directions for future research.

INDEX TERMS Educational technology, literature review, open-source hardware, systematic mapping study.

I. INTRODUCTION

Open-Source Software (OSS), i.e., software licensed to enable users to modify and further distribute its source code, has acquired enormous importance. As a result, there are many successful projects following this philosophy, e.g., the Linux operating system, the Apache web server, etc. OSS has been the inspiration for another movement that brings the open-philosophy to the electronic hardware design: *Open-Source Hardware (OSHW)*.

According to the Open-Source Hardware Association [1], OSHW is defined as: "hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, OSHW uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. OSHW gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs."

With the emergence of open and low-cost technologies including micro-controllers, 3D-printers, sensors, and actuators, OSWH has become increasingly widespread. OSWH suits particularly well for a variety of educational purposes [2]–[4]: it helps students to become more fluent and expressive with new technologies; it enables students to explore concepts in science, maths, or engineering; it provides students with better learning experiences where they are actively engaged designing and creating things, etc.

Accordingly, the use of OSHW is spreading across a variety of domains and educational degrees, and its corresponding research community and scientific paper production are expanding considerably. This paper reports a *secondary study* that overviews the educational uses of OSHW. For that, it follows the *systematic mapping study* approach [5]–[10] to analyze and classify 676 *primary studies*, including scientific publications, as journal articles, conference proceeding papers, and books. Thereby, this paper provides both researchers and practitioners with the following information:

1) *Guidance on the vast literature available about OSHW in education*. This paper identifies (i) the most relevant publications in the field, (ii) the main publication sources (i.e., journals, conferences, etc.), and (iii) the institutions/countries that have contributed the most to the research area.
2) *Knowledge about the pedagogical potential of OSHW*. This article identifies (i) the principal motivations for applying OSHW in education, (ii) the stages when OSHW is mostly used (e.g., K12, university, etc.), and (iii) the knowledge domains where OSHW is being employed.
3) *Directions for future research*. This paper classifies the publications according to a variety of criteria. Categories with few publications or a lack of empirical evaluations reveal chances for further research.

The remainder of this paper is structured as follows: Section II summarizes related work. Section III describes the methodology used to undertake our study. Section IV reports the results obtained, and Section V discusses them. Finally, Section VI summarizes the main conclusions of this paper.

II. RELATED WORK

Every year, around 2.5 million new scientific papers are published [11]. Accordingly, there is an increasing need for secondary studies that deal with such immense quantity of publications, synthesizing the knowledge of an area by systematically processing and structuring its research. Secondary studies benefit both researchers and practitioners: they help the formers to direct future work towards research gaps and enable the latter to understand the effectiveness of, for instance, a specific method or technology [12].

To the extent of our knowledge, this paper is the only secondary study that overviews the educational uses of OSHW. Other secondary studies slightly related to ours are the following ones:

1) Saari *et al.* [13] survey 15 primary studies about network sensor solutions developed with the open technology Raspberry Pi for the Internet of Things. Just 2 of the considered studies are related to education.
2) Sullivan and Heffernan [14] report a systematic literature review on the use of robotics construction kits in STEM disciplines. This work differs from ours in focus and methodology.

   It is not oriented to OSHW; indeed, the query used to retrieve the studies from bibliographic databases obviates any terms regarding open technologies and explicitly includes the word "Mindstorms", referring to the LEGO proprietary tool.

   Moreover, systematic literature reviews and mapping studies differ in the analysis procedures and scope. Systematic mapping studies, also known as *scoping studies*, are used to structure a research area, while systematic reviews are focused on gathering and synthesizing evidence [7], [15], [16]. Mapping studies work essentially through classification and counting contributions about the categories of that classification. Moreover, the scope is often broader in mapping studies [5], [6], [12], [17]. Whereas Sullivan and Heffernan review 41 primary studies, our work examines 676.

III. RESEARCH METHOD

This section describes the systematic procedure followed to carry out our study.

A. RESEARCH QUESTIONS

This study aims to answer the following *Research Questions* (RQs):

1) RQ1. IN WHICH EDUCATIONAL STAGES AND KNOWLEDGE AREAS IS OSHW APPLIED, AND FOR WHAT PURPOSES?

Rationale: A primary goal of this study is to understand the pedagogical potential of OSHW. To do so, it will identify (i) the central motivations for applying OSHW in education, (ii) the stages when OSHW is mostly used (e.g., K12, university, etc.), and (iii) the knowledge domains where OSHW is being utilized.

2) RQ2. WHAT ARE THE MOST RELEVANT PUBLICATIONS, RESEARCH INSTITUTIONS, AND PUBLICATION VENUES?

Rationale: Another goal of this study is to provide guidance on the increasingly vast literature available about OSHW in education. The study will identify (i) the most relevant publications in the field, (ii) the main publication sources (i.e., journals, conferences, etc.), and (iii) the institutions/countries that have contributed the most to the research area.

3) RQ3. ARE THERE ANY GAPS THAT DEMAND FUTURE RESEARCH?

Rationale: A common objective for secondary studies is finding niches for future research [18]. Mapping studies are especially well suited to this purpose because they provide a publication categorization, e.g., papers describing novel approaches, new application fields, evaluation reports, etc. Those categories with few publications or a lack of empirical evaluations often need further research [7], [19]. This way, our study will point out challenges for future investigations.

B. STUDY IDENTIFICATION

As noticed by other authors [5], [7], [12], finding all the articles relevant to a mapping study is an unrealistic goal. Hence, we focused on getting a publication sample that represents the population adequately. The systematic procedure described in the following subsections was adopted to fulfill such objective.

Figure 1 depicts the number of publications considered during the study identification process, which will

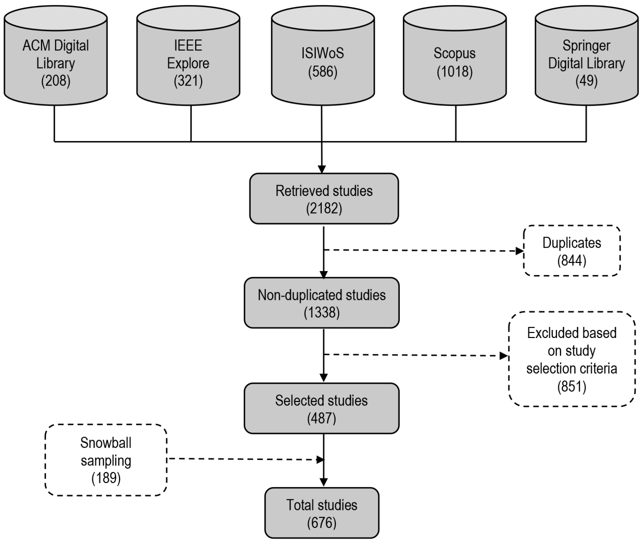

FIGURE 1. Number of publications considered during the study identification process.

be described in the following subsections. It started with 2182 publications retrieved from different bibliographic databases and ended up with 676 publications for analysis and classification.

1) SEARCH SCOPE

A standard approach for getting a sound publication sample is querying high-quality bibliographic databases [5]–[7]. It is worth noting that some popular databases, such as Google Scholar (GS), have been reported to be low reliable for performing secondary studies [20]. GS tends to include everything that resembles scholarly work, based on automatic format inspection rather than content inspection, which tends to produce the inflation of its record [21]. Because of its mechanical inclusion process, GS is susceptible to make errors in metadata [22] and to index non-scientific works [21]. In contrast, other databases, such as ISI Web of Science (ISIWoS), use a selective inclusion procedure where in-house editors assess candidate publication outlets using criteria such as peer-review process, international diversity of editors and authors, citation impact, and self-citation rate. Accordingly, we selected the following databases, which have been successfully applied in other secondary studies [17], [23], [24]: ISI Web of Science (ISIWoS), Scopus, ACM Digital Library, IEEE Explore, and Springer Digital Library.

It is intended that our study describes the research evolution of OSHW in education from its beginnings to nowadays. Thus, the publication search was not constrained to any initial date.

2) STRING QUERY

Trial searchers were performed on the aforementioned databases. Initial queries were iteratively polished until reaching the following final one:

```
1 TOPIC =
2   ("education"  OR  "learning"  OR  "teaching")
3   AND ("open source hardware" OR "open-source hardware"
4        OR "open hardware" OR "construction kit"
5        OR "raspberry pi" OR "beaglebone" OR "arduino"
6        OR "orange pi" OR "intel galileo")
7   AND NOT "machine learning"
```

Line 2 constraints the results to the educational realm. Lines 3-4 refer to OSHW. Line 5-6 collect technologies widespread applied to develop OSHW projects (we explored adding other technologies to the query, but no significative additional publications were found). Finally, Line 7 removes false positives related to artificial intelligence instead of education.

3) STUDY SELECTION

The query above was run on 11th September 2018, and the publications extracted from the databases were filtered according to clearly-defined inclusion and exclusion criteria. In particular, inclusion was supported by the following criteria:

- I1 Publications focused on applying OSHW in education.
- I2 Publications that contribute to ask at least one of this study RQs (see Section III-A).

The next criteria were used for excluding studies:

- E1 Non-peer reviewed publications.
- E2 Publications not written in English.
- E3 Publications not accessible in full-text.
- E4 Publications not focused on free and open-source hardware.
- E5 Papers presenting summaries of conferences/ editorials, or published in the form of abstract, poster, tutorial or talk.

For filtering the publications, each paper was randomly assigned to two of this paper's authors, who judged it according to the inclusion/exclusion criteria above. Whenever there was disagreement between the reviewers, another one of us worked as referee to achieve a consensual decision.

4) SNOWBALLING

The *snowballing* guidelines, given by Wohlin [19], were applied to guarantee that our study was not missing any relevant publications. Once the initial sample set of publications was filtered, the snowballing approach enlarged that collection by checking their references as well. It is worth noting that snowballing is an iterative process: in each cycle, new publications were identified, and the references were analyzed in a subsequent iteration. The process stopped when the size of the sample set could not be incremented more than a 5%.

C. DATA CLASSIFICATION

To answer this paper's research questions, the publication sample was categorized according to a variety of criteria. Each publication was classified by two of this paper's authors.

In the case of disagreement, a third person played the referee role.

1) TOPIC-INDEPENDENT CLASSIFICATION

Standardized topic-independent classification schemes support:

- Comparing research on different areas of knowledge. For instance, the maturity level of distinct fields can be evaluated by counterposing their number of papers published in journals and conferences.
- Examining the coherence of mapping studies on the same field. For example, Wohlin *et al.* [12] detected inconsistencies in two studies carried out in a particular area as they raised different and contradictory results under the same classification scheme.

Our study applies two of the most frequently used facets for topic-independent classification [7]: type of publication venue and type of research.

We considered the following possible values for *publication venue*: journal articles, conference proceeding papers, and books (including chapters in research books).

Regarding the *type of research*, we followed the classification proposed by Wieringa *et al.* [25], which is common for mapping studies [7], [12], [15], [16], [26]. Accordingly, a publication can be categorized as:

- *Solution proposal*. It presents a new approach or improves an existing one to solve a problem.
- *Opinion paper*. It expresses the authors' subjective opinion about the strengths and weaknesses of a particular technique, or how things should be done (i.e., it is neither supported by related work nor research methodologies).
- *Philosophical paper*. It provides an innovative way of looking at existing things by organizing the field as a taxonomy or a conceptual framework.
- *Experience paper*. It summarizes the authors' personal experience about what and how something was done in practice.
- *Validation research*. It reports an approach evaluation in a laboratory setting.
- *Evaluation research*. In contrast to validation research, it describes an evaluation that takes place in the real world.

2) TOPIC-SPECIFIC CLASSIFICATION

Besides the topic-independent criteria above, each publication was classified under the following topic-specific perspectives as well:

- *Primary pedagogical goal* the publication pursues (e.g., reducing laboratory costs, engaging female students into technological areas, etc.).
- *Education stage* where OSHW was applied (K-12, university or adult education).
- *Knowledge domain* of the topics whose learning was supported by OSHW. Our publication categorization follows the *field descriptors* proposed by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [27].

D. IDENTIFICATION OF THE MOST RELEVANT PUBLICATIONS

Garfield [28] defined the concept of *citation classics* to identify the papers most frequently cited in a research field. Analyzing the citation classics of an area (i) helps to recognize the significant advances in the discipline, (ii) provides a historical perspective of its scientific progress, and (iii) identifies the main intellectual actors of the research field.

To detect the citation classics, we adopted Martínez *et al.*'s approach [29], which adapts the H-index [30] definition as follows:

"a research field has index h, if h of the n papers published in the area have at least h citations each, and the other $(n-h)$ papers have $\leq h$ citations each".

The top h papers of a research area constitute its *H-core*, which identifies the highest-performance publications of the area.

IV. RESULTS

This section summarizes our study's results. The complete outcomes are available at the following public repository:

https://rheradio.github.io/OSHWInEducation/

A. PUBLICATION EVOLUTION, MOST CITED PAPERS, AND MAIN PUBLICATION VENUES

Figure 2 shows the evolution of the number of publications over time, being the releases of the most relevant OSHW technologies highlighted in red. In 2005, the first Arduino board was launched to support controlling student-built interactive design projects in an affordable way. Two years later, research on the pedagogical use of that technology started being published, coinciding with the release of LilyPad Arduino, which enables the creation of electronic textiles. In 2010, the most widely used Arduino board was released: Arduino Uno; another highly remarkable event happened in 2012: the launch of the first Raspberry Pi. Those prominent boards (Arduino Uno and the successive generations of Raspberry Pi's) together with other less common ones (e.g., Beagle Bone, Intel Galileo, and Orange Pi) have supported, from a technological point of view, most of the educational research published since 2007.

Figure 2 details the publication evolution distinguishing between the types of publication venues.

Table 1 lists the H-core of our study, i.e., the **citation classics** on educational OSHW usages. Typically, relevant publications may appear in several databases with different citation counts. In these cases, the maximum count has been selected, as proposed in other secondary studies [24], [31]. For instance, Buechley *et al.*'s article [3] has 93 citations in ISIWoS, 230 in Scopus, and 148 in ACM Digital Library. Consequently, the paper appears with 230 citations in Table 1. It is worth noting that the H-index of the area is 22.

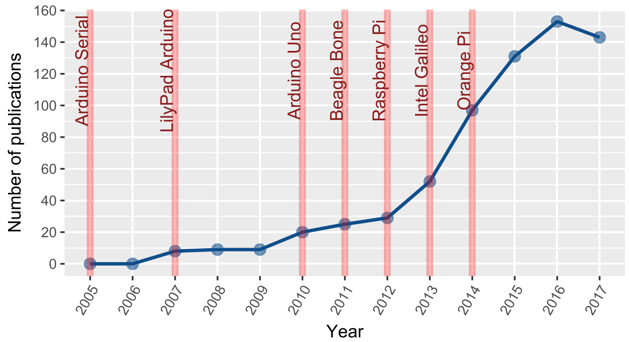

FIGURE 2. Temporal evolution of the number of publications.

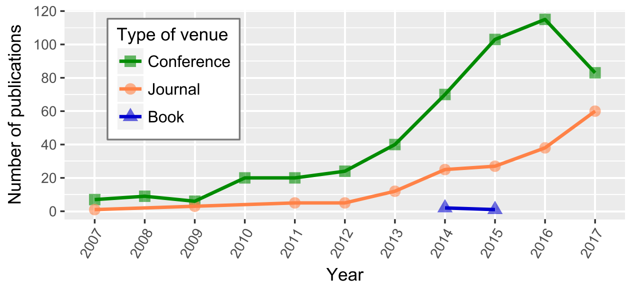

FIGURE 3. Evolution of the number of publications per type of venue.

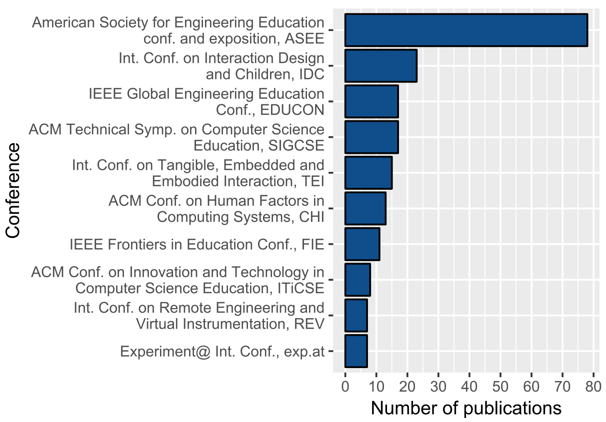

FIGURE 4. Most prolific conferences.

Figure 4 shows the **conferences** that have published most papers, and Figure 5 reports the most prolific **journals**.

Figure 6 provides a general overview of the **countries' contribution** to the field, being each country colored according to the number of documents its researchers have published. The information is detailed in Figure 7, which shows the **institutions** whose researchers have published more papers.

B. PAPER CLASSIFICATION

This section describes the results of classifying the publications according to a variety of criteria. Figure 8 depicts the temporal evolution of the number of publications, classifying them according to their **type of research** (as mentioned in Section III-C.1, the *type of research* has been categorized following Wieringa et al.'s convention [25]). It is surprising the low number of publications focused on evaluating/validating the pedagogical value of OSHW (just 10.20% of the papers).

TABLE 1. Citation classics.

Publication	Type of source	Year of publication	#Citations
Buechley et al. [3]: The LilyPad Arduino: Using Computational Textiles to Investigate Engagement, Aesthetics, and Diversity in Computer Science Education	conf.	2008	230
Rowe et al. [4]: Cheapstat: An open-source, "do-it-yourself" potentiostat for analytical and educational applications	journal	2011	90
Buechley et al. [32]: LilyPad in the Wild: How Hardware's Long Tail is Supporting New Engineering and Design Communities	conf.	2010	90
Zhang et al. [33]: Open-Source 3D-Printable Optics Equipment	journal	2013	86
Baden et al. [34]: Open Labware: 3-D Printing Your Own Lab Equipment	journal	2015	82
Sarik & Kymissis [35]: Lab kits using the Arduino prototyping platform	conf.	2010	54
Kafai et al. [36]: A Crafts-Oriented Approach to Computing in High School: Introducing Computational Concepts, Practices, and Perspectives with Electronic Textiles	journal	2014	54
Cox et al. [37]: Iridis-pi: A low-cost, compact demonstration cluster	journal	2010	43
Katterfeldt et al. [38]: EduWear: Smart Textiles As Ways of Relating Computing Technology to Everyday Life	conf.	2009	38
Straub et al. [39]: OpenOrbiter: A Low-Cost, Educational Prototype CubeSat Mission Architecture	journal	2013	37
Booth & Simone [40]: End-user experiences of visual and textual programming environments for Arduino	conf.	2013	33
Mellis & Buechley [41]: Case Studies in the Personal Fabrication of Electronic Products	conf.	2012	32
Peppler & Glosson [42]: Stitching Circuits: Learning about Circuitry through E-textile Materials	journal	2013	32
Peppler [43]: STEAM-Powered Computing Education: Using E-Textiles to Integrate the Arts and STEM	journal	2013	31
Millner & Baafi [44]: Modkit: Blending and Extending Approachable Platforms for Creating Computer Programs and Interactive Objects	conf.	2011	29
Saenz et al. [45]: Open and Low-Cost Virtual and Remote Labs on Control Engineering	journal	2015	27
Araujo et al. [46]: Integrating Arduino-based educational mobile robots in ROS	conf.	2013	27
Weller et al. [47]: Posey: Instrumenting a Poseable Hub and Strut Construction Toy	conf.	2008	26
Zachariadou et al. [48]: A low-cost computer-controlled Arduino-based educational laboratory system for teaching the fundamentals of photovoltaic cells	journal	2012	26
Buechley et al. [49]: Towards a Curriculum for Electronic Textiles in the High School Classroom	journal	2007	25
McClain [50]: Construction of a Photometer as an Instructional Tool for Electronics and Instrumentation	journal	2014	23
Schelly et al. [51]: Open-source 3-D printing technologies for education: Bringing additive manufacturing to the classroom	journal	2015	23

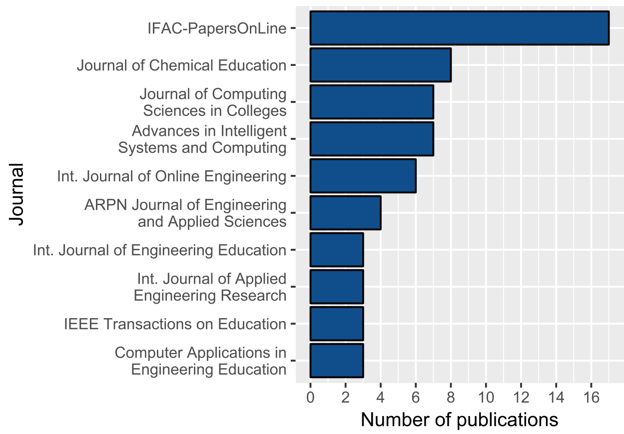

FIGURE 5. **Most prolific journals.**

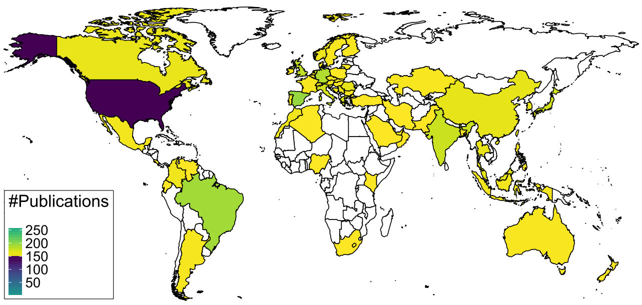

FIGURE 6. **Number of publications per country.**

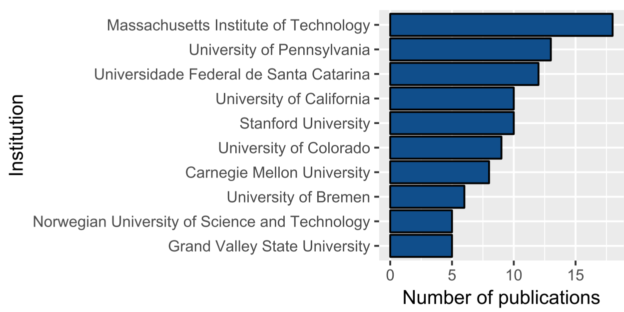

FIGURE 7. **Most prolific institutions.**

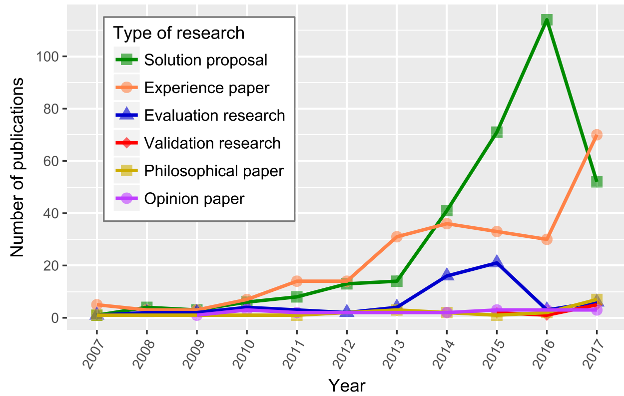

FIGURE 8. **Evolution of the number of publications per type of research.**

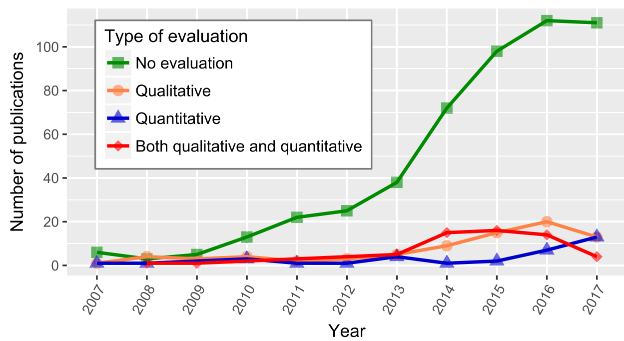

FIGURE 9. **Evolution of the type of evaluation reported in the publications.**

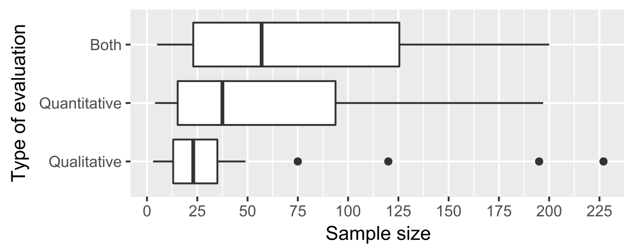

FIGURE 10. **Sample size per type of evaluation reported in the publications.**

As Figure 9 shows, a few other papers not strictly focused on evaluation also report some empirical assessments. Nevertheless, out of the 676 publications analyzed in our study, only 169 of them include some type of evaluation, and just 132 report the sample size. Figure 10 depicts the sample size per type of evaluation.

Regarding the **educational motivations** for using OSHW, the following ones appear recurrently in the analyzed publications:

- *Improving the teaching method*. OSWH is often used to provide students with experimentation resources that help them to understand abstract concepts of science and engineering.
- *Reducing costs*. Open technologies tend to be cheaper than their corresponding proprietary alternatives. Moreover, the designs of OSWH devices are freely shared so they can be reused at no expense. As experimentation is essential to learn engineering and scientific disciplines, and OSWH can diminish laboratory costs, multiple publications discuss the positive impact that OSWH can have, for instance, in the context of undeveloped countries where labs have been practically unaffordable to date, or to create innovative laboratories.
- *Promoting students' engagement*. Technology is often appealing to young students. Thus, diverse publications explore the use of OSWH devices to increase learners' interest and engagement.

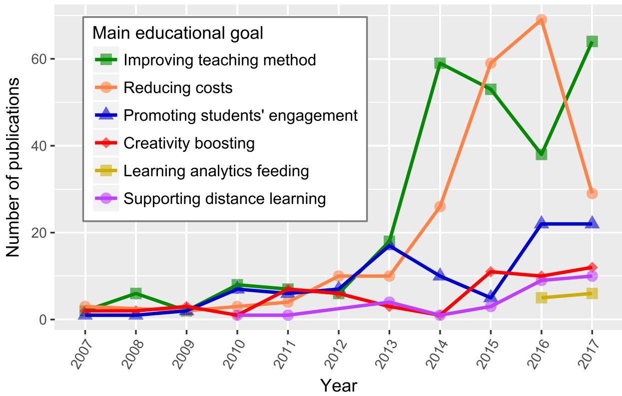

FIGURE 11. Evolution of the number of publications per educational goal.

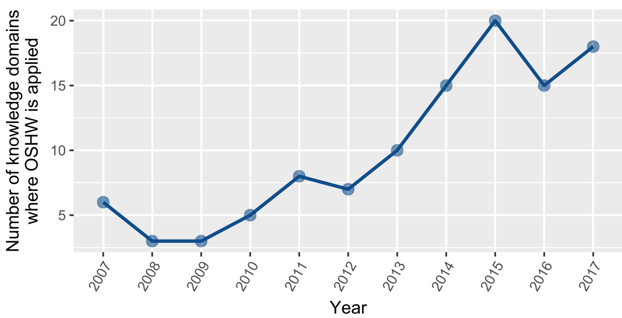

FIGURE 12. Evolution of the number of knowledge domains where OSWH has been applied.

- *Fostering students' creativity*. Thanks to OSHW, students can move from simple technology users to the more active role of *makers*. Hence, distinct publications discuss how to exploit the creative potential of OSHW.
- *Supporting distance learning*. OSWH are sometimes used to build remote laboratories, which enable students to carry out experiments at distance.
- *Learning analytics feeding*. OSHW devices can be used to track students activities (e.g., geolocating the place where students are, accounting for the time students work together, etc.). This information may complement other data to carry out learning analytics.

Figure 11 shows the temporal evolution of the number of publications according to their central educational goals.

The pedagogical value of OSHW has been explored in many knowledge areas. Figure 12 represents the amount of areas where OSHW has been applied per year.

Figure 13 shows the most common **application domains**, which have been classified according to the *field descriptors* proposed by the *UNESCO International Standard Classification of Education* [27].

The educative use of OSHW ranges from children to adults. Figure 14 shows the evolution of the number of publications per **educational stage** (adult education, only K12, only University, and both K12 and University).

Figures 15 and 16 represent the co-variation of the educational stage with other two classifiers: type of research and main educational goal (e.g., according to Figure 15, almost 50% of the publications exploring the use of OSHW into university courses are solution proposals).

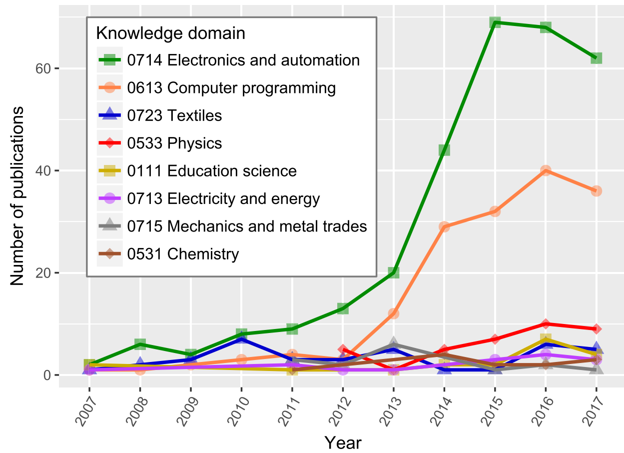

FIGURE 13. Evolution of the number of publications per knowledge domain.

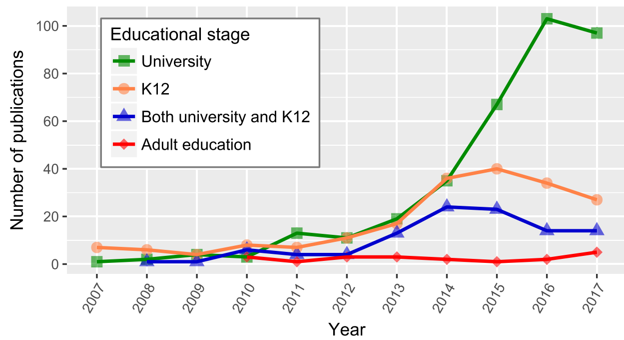

FIGURE 14. Evolution of the number of publications per educational stage.

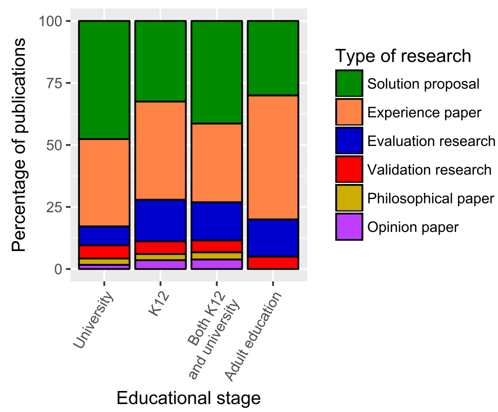

FIGURE 15. Type of research performed in each educational stage.

V. DISCUSSION

Figures 2 and 3 show a continued increment on the number of publications, especially since 2012, that reflects the enormous interest that OSHW has aroused in the educational research community.

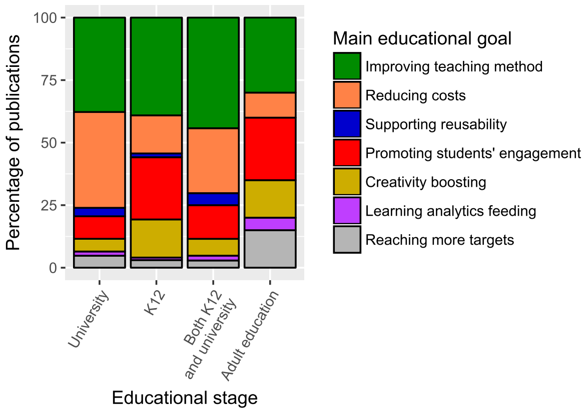

FIGURE 16. Main education goal pursued in each educational stage.

1) RQ1. IN WHICH EDUCATIONAL STAGES AND KNOWLEDGE AREAS IS OSHW APPLIED, AND FOR WHAT PURPOSES?

Nowadays, OSHW is mostly used to teach electronics, automation and computer programming (see Figure 13). However, the variety of disciples where OSHW is applied grows rapidly (Figure 12). In our study, 29 application domains have been identified, including art education [52], medicine [53], textiles [54], chemistry [55], aquaculture [56], impaired children education [57], and so forth.

OSHW is used in all educational stages: K12, university, and adult education. From 2007 to 2010, most research happened at K12 level; however, this trend has changed in favor of university studies, especially since 2014 (see Figure 14).

Figure 16 highlights that OSHW is principally used to enrich education by enabling learning-by-doing experiences, but it also shows that there are other motivations more specific for particular educational stages: whereas OSWH is used in K12 and adult education especially to boost student's engagement and creativity, a major motivation at university level is reducing the costs of the laboratories.

What is said above is reflected in the H-core of the field, as two groups of citation classics can be distinguished in Table 1: a few seminal papers published from 2007 to 2009, and the rest. The goal of three of the four seminal classics [3], [38], [49] was to promote K12 students' creativity and interest in new technologies, especially trying to attract young women to typically male-dominated disciplines (e.g., computer science or robotics). After this initial period, the motivations to apply OSHW changed: 66.66% of the classics published since 2010 pursue the improvement of university education and the cost-reduction of experimental setups.

2) RQ2. WHAT ARE THE MOST RELEVANT PUBLICATIONS, RESEARCH INSTITUTIONS, AND PUBLICATION VENUES?

We have identified the most relevant publications in the field (Table 1), the main publication sources (Figures 4 and 5), and the institutions/countries that have contributed the most to the research area (Figures 6 and 7).

So far, US institutions have played the leading role on the OSWH educational research, having published 38.01% of all papers (see Figures 6 and 7). Other countries are also contributing to the research, but with a considerably lower intensity: Spain (6.06% of the papers), Brazil (5.32%), Germany (4.58%), and UK (3.69%). Moreover, the most prolific publication venue is also American: the ASEE Annual Conference and Exposition (see Figure 4).

This situation is somehow surprising for distinct reasons. The most used boards for OSHW, which are Arduino and Raspberry Pi, were created out of the US (in Italy and UK, respectively). Besides, one of the primary motivations for applying OSWH in education is reducing laboratory costs. Hence it might be expected more research by emerging countries that would benefit the most from the cheap experimental resources that OSHW provides.

3) RQ3. ARE THERE ANY GAPS THAT DEMAND FUTURE RESEARCH?

Most published research are solution proposals and experience papers, being 48.37% and 36.39% of the total, respectively (see Figure 8). Curiously, the preeminence of these kinds of research happens in all educational stages (see Figure 15).

Complementary types of research need to be carried out. Opinion and philosophical papers would enrich the field by providing fresh ways of thinking about OSWH in education. For instance, as enabling student's creativity is a secondary goal for using OSHW in university studies (see Figure 16), innovative approaches should look for giving this essential competency a more prominent role.

Particularly worrying is the limited empirical evaluation reported in the publications. 75% of them do not report any evaluation at all (see Figure 9), and the ones that do so are performed on small samples, being the median of the sample size 23 students for qualitative evaluations, 37.5 for quantitative evaluations, and 57 for those studies that combine both approaches qualitative and quantitative (see Figure 10). Researchers should not lose sight that the ultimate reason for their work is enabling students' learning. In the future, most publications should provide empirical evidence of the educational value of their OSHW approaches. Complementarity, a meta-analysis study could be useful to aggregate the already available evaluations and thus give a general perspective of the pedagogical value of OSHW.

VI. CONCLUSIONS

The amount of research published about the pedagogical uses of OSWH is growing incessantly, and also its application domains. In order to provide a general and historical overview of this research, a systematic methodology has been adopted, retrieving, analyzing, and classifying a sample of 676 publications. As a result, this paper identifies the primary educational motivations for using OSHW, the knowledge areas where OSHW is mostly applied, the institutions that lead research on educational OSHW, the most relevant publication venues, and the most cited publications. Furthermore, the paper also points out some gaps that demand future research.

As an additional contribution of our work, four catalogs are provided at https://rheradio.github.io/OSHWInEducation/, which can be helpful to browse the available literature on OWSH in education. Each catalog organizes the publications this paper analyzes according to their application domain, educational stage, central pedagogical purpose, and type of research.

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