Application of Arduino-Based Systems as Monitoring Tools in Indoor Comfort Studies: A Bibliometric Analysis

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Abstract: Studies that require environmental measurements often struggle with the cost of monitoring equipment. Costs will increase as more variables are required. Thus, scientists have been increasingly relying on Arduino systems to overcome such a challenge. This paper aims to review the literature on the use of Arduino as a viable measurement tool in indoor comfort research. For this purpose, the results from three databases were compared: Web of Science, Scopus and ScienceDirect. Results from the Scopus search were then analyzed using VOSViewer according to three questions: (1) what is the state of the art and trends using Arduino; (2) how is Arduino being used in indoor environments; and (3) which are the main authors using the system and what are the most cited Arduino-related sources. The maps showed that the system is very versatile and offers the opportunity to strengthen multidisciplinary approaches.

Keywords: Arduino, environmental measurements, VOSViewer.

1. INTRODUCTION

The study of climate and the environment and also the interrelationship between them and human beings require the collection of environmental data. However, to adequately assess each of these three domains, i.e. man, climate and architecture (to paraphrase B. Givoni [1]) implies measuring several variables that occur simultaneously (e.g. climatic variables such as air temperature, humidity, building physics and physiological data such as skin or body core temperature). Research focusing on the changes occurring in any of these realms individually or on how they impact each other requires firstly the understanding of the main influencing variables and then selecting which ones can be manipulated or controlled [2].

Difficulties posed to researchers arise when variables requiring specific monitoring equipment result in excessive costs [3-6]. Currently, the authors have to face this challenge as a part of a research enterprise on physiological effects arising from the outside view from the window in office workers. In order to test whether views from the window with either natural or built-up environments will play a role in their emotional state, apart from self-evaluated rating scales [7], questionnaires and descriptions, physiological data would involve the collection of data related to eye tracking, galvanic skin response, heart rate, body movement monitoring, electrocardiogram and functional magnetic resonance imaging scans [8]. To overcome the limitations of a low research budget and to avoid risking the completion of the project as a whole, Arduino modules could serve as an alternative, though there remains the issue of their overall reliability in scientific research.

The system enables users to design and utilize microcontroller-based development boards (Arduino modules), which are open-source prototyping platforms [9]. The first Arduino board was developed in 2007 to allow students and artists to create an interactive design. It should be "simple, easy to connect to various things (such as relays, motors, and sensors), and easy to program. It also needed to be inexpensive (...)" [10]. It consists of a microcontroller (Arduino board) (Figure **1**) that can read sensor values and display them on computer screens, as well as build other circuits. It is a versatile open-source system with support available from the online community of users [11] and can be programmed using Python and C languages.

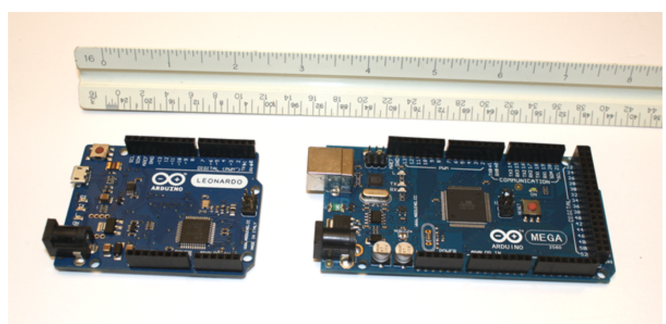

Figure 1: Arduino boards with different sizes.

Source: [10].

In the case of our research, the small size of the system (Figure **1**) and the possibility of integrating

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more than one sensor to a microcontroller would be convenient for the planned measurements.

Applications of Arduino can be found, among others, in indoor environment quality (IEQ) assessments such as in Karami *et al*. [12] which demonstrated reliability and robustness of the toolbox developed; long-term monitoring of indoor environmental data in school environments, as proved by Ali *et al*. [13], within the scope of the Open Source Building Science Sensors (OSBSS) project; or more recently in BIM research supported by Virtual Reality approach [14].

In this work, we conducted a review on the use of Arduino as a measurement tool for general environmental conditions indoors. In order to know the extent of the research areas already using it, we searched for the string ""Arduino" and "environment*" and "measure*"" in three electronic databases: Web of Science, Scopus and ScienceDirect. The results from Scopus were then used to answer key questions for research definition and orientation.

2. METHOD

The string ""Arduino" and "environment*" and "measure*"" was searched in the Web of Science, Scopus and ScienceDirect between 27th November and 24th March 2020. The database was determined according to (1) the highest number of results; and (2) the output information for analysis defined by the available sorting types. Table **1** shows the sorting types available for each database.

There is also the possibility of visualizing the results graphically. These visualizations give a pre-assessment on the search outcome in general. Web of

Table 1: Sorting Types Available in Web of Science, Scopus and ScienceDirect

Database	Web of Science	Scopus	Science Direct
Date	X	X	X
Relevance	X	X	X
Number of citation	X	X	
Usage count	X		
Authors	X	X	
Publisher	X	X	

Table 2: Graphic Visualization of Results in Web of Science, Scopus and ScienceDirect

Number of documents by	Web of Science	Scopus	Science Direct
Publication year	X	X	
Source titles	X		
Book series title	X		
Year by source		X	
Authors	X	X	
Affiliation / Organizations	X	X	
Research area	X	X	
Country / territory / regions	X	X	
Type	X	X	
Funding sponsor / Agencies	X	X	
Editors	X		
Group authors	X		
Languages	X		
Grant numbers	X		

Science presents more graphic options while Science Direct has no such result analysis whatsoever (Table **2**).

In addition, to ensure the selection of more recent output, we limited the results to the last 6 years (from 2015 to March 2020) and to conference papers and articles. The search was also refined by research fields which are more closely related to the relationship between humans and the environment.

Figure **2** shows the first part of the method used.

The final results were exported and used as input for the VOSViewer software. This software enables us to construct and visualize bibliometric networks [15] and it was used in this study for several analyses to answer 3 key questions:

- What is the state of the art behind research using Arduino as a measurement tool?
- How is Arduino being used for environment measurement related specifically to the built environment?
- Which are the main authors using Arduino for analyses on the built environment?

The list of topics and key words included many general words and expressions. Therefore, a Thesaurus file was written to eliminate them from the analysis. For example, “student” could be both in the context of someone being exposed to tests or someone learning to use Arduino. There were also many words, expressions and abbreviations that meant the same, such as “internet of things” and “iot”. The file also combined many terms that could be generalized for the purpose of this bibliometric review. That is the case of many indoor spaces such as rooms, museum, offices etc. that could simply be taken as “indoor environments”.

As for the analysis of journals, another Thesaurus file combined the search results that were counted more than once, also due to the abbreviations.

Figure **3** shows the general workflow with VOSViewer.

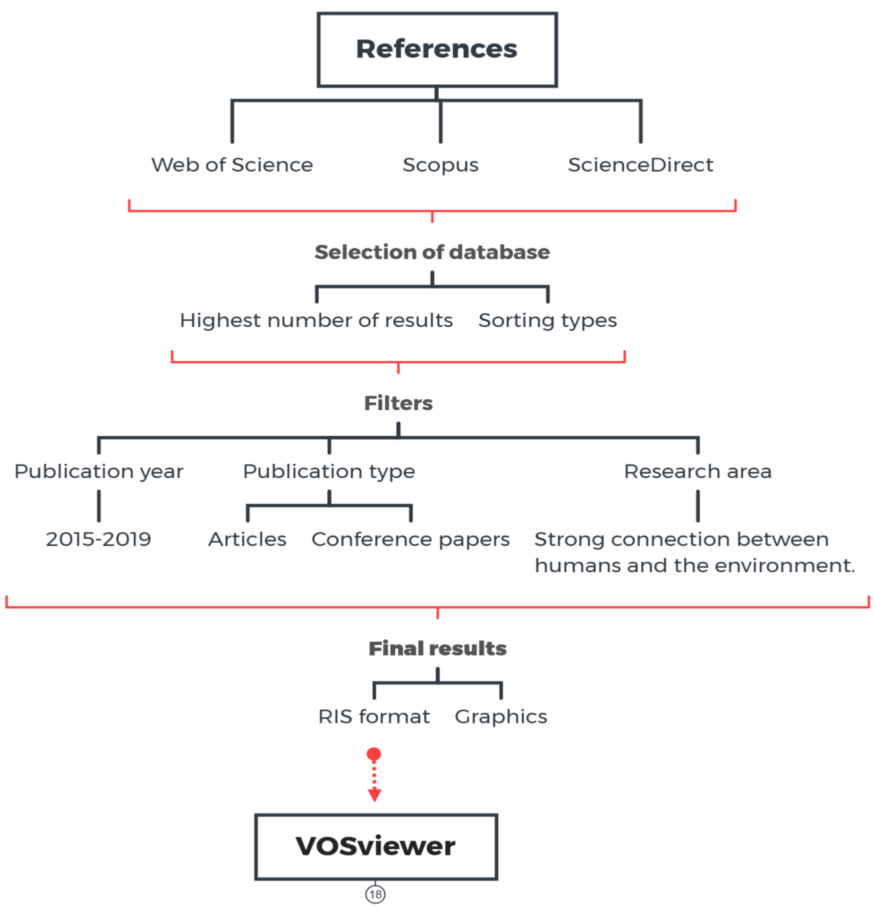

Figure 2: Schematic explanation for the database choice.

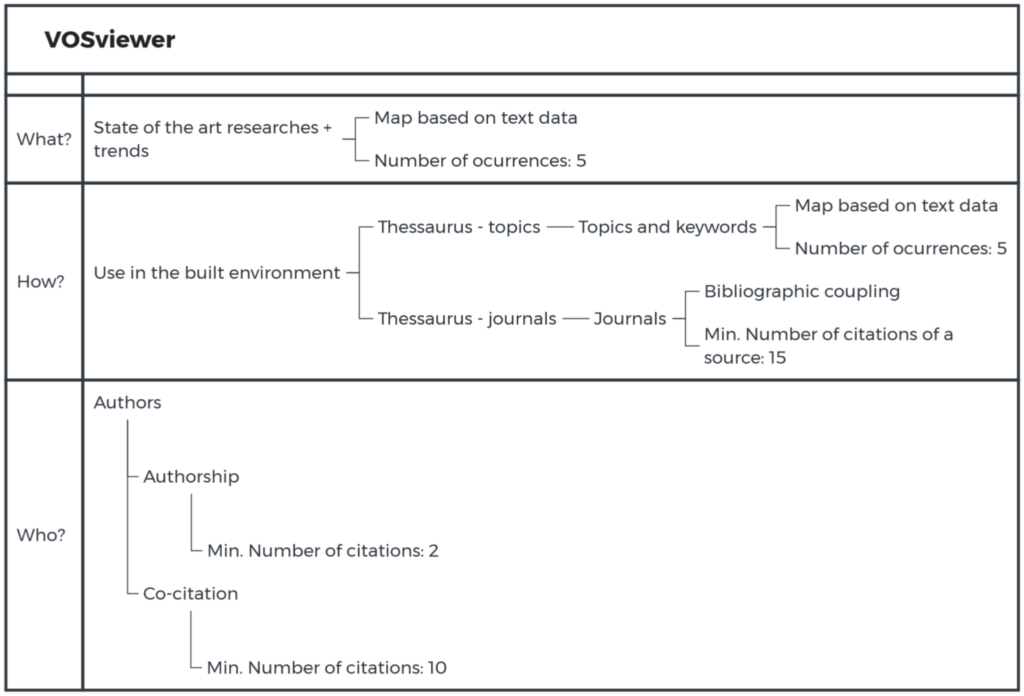

Figure 3: Schematic explanation for the VOSViewer workflow.

3. RESULTS OF LITERATURE RESEARCH

The results of the literature search in Web of Science, Scopus and ScienceDirect are presented in Table **3**. Web of Science did not show a significant number of articles and therefore was not used in further steps of this review paper.

Although ScienceDirect showed a number of articles, significantly higher than the other databases, results included articles published before Arduino was invented. This called our attention and a thorough analysis of the results showed that, contrary to the other two databases, ScienceDirect included authors named Arduino, such as D. Arduino [16] and M. Arduino [17]. In addition to that, ScienceDirect only allows date and relevance sorting (Table **2**). Also, the website does not provide any graphs for data visualization as the other two websites do.

Therefore, considering that Scopus showed a higher amount of results (filters applied), did not consider authors named Arduino on the results and also allowed more sorting types, we chose this database as a reference in our study.

Table 3: Results for General Literature Search on "“Arduino” and “Environment*” and “Measure*”" in Web of Science, Scopus and ScienceDirect

Database	Web of Science	Scopus	Science Direct
Total number of results	260	440	2.248
Results from 2015-2019	230	398	1.997
Limited document type	230	388	1.774
Limited Research fields*	73	351	383**
Exclusion of E. Arduino	73	351	6

*The following research fields were excluded: Biochemistry, Genetics and Molecular Biology; Agricultural and Biological Sciences; Agriculture Multidisciplinary; Agricultural Engineering; Geosciences Multidisciplinary; Biochemical Research Methods; Chemical Engineering; Chemistry; Chemistry Analytical; Chemistry Multidisciplinary; Chemistry Physical; Electrochemistry; Economics; Immunology and Microbiology; Engineering Ocean; Oceanography; Engineering Marine; Entomology; Horticulture; Management; Microscopy; Physics Atomic Molecular Chemical; Telecommunications; Engineering Electrical Electronic; Energy Fuels; Education Educational Research; Metallurgy Metallurgical Engineering; Education Scientific Disciplines; Nuclear Science Technology; Nanoscience Nanotechnology; Mechanics; Engineering Aerospace; Physics Fluids Plasmas; Radiology Nuclear Medicine Medical Imaging; and Transportation Science Technology.

**ScienceDirect has no filter for research areas, so the refinement was done by publication title. Articles published in “Computers and Electronics in Agriculture” and “Sensors and Actuators B: Chemical” were excluded.

3.1. Arduino as a Measurement Tool

The interest on the use of Arduino in research started in 2009, two years after its initial development (Figure **4**) and the number of publications has continuously increased until 2019. The decrease in 2020 cannot be taken into consideration though, because the search period was limited to 2020´s first trimester.

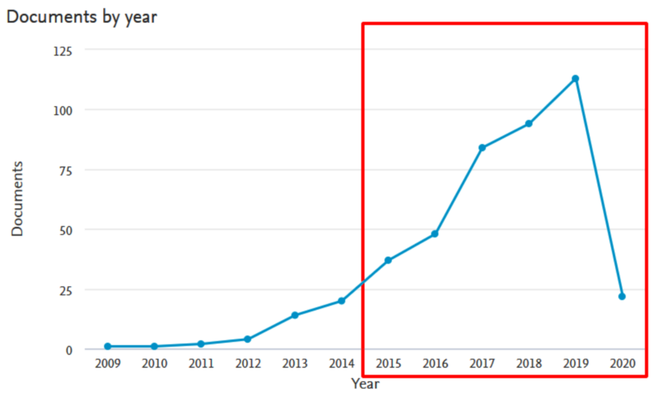

Figure 4: Number of articles and conference papers using Arduino as measurement tool by year. The chosen limiting period is highlighted in the red rectangle.

Source: Adapted from Scopus, 2020.

The key questions listed in the methodology define the following subsections. Subsection 3.2 will give a broad analysis of how Arduino has been used as a research tool, what areas are using it and what are the most recent research topics related to it. Subsection 3.3 refines the analysis to topics and shows how Arduino relates to the indoor environment. The authors using Arduino and their citation impact are presented in subsection 3.4.

3.2. State of the art Behind Research using Arduino

Figure **5** presents the many research fields using Arduino. It is expected 'Engineering and Computer Sciences' to be more relevant because electronic devices relate more closely to them. However, it is possible to note the versatility of the system – it is also used in social sciences and environmental sciences as well as in disciplines classified as "others": medicine; business, management and accounting; multidisciplinary sciences; arts and humanities; health professions and neuroscience.

The use of Arduino is related to four main groups (Figure **6**): industry and power generation in red, robotics in blue, medicine in green, and architecture in yellow.

The cluster 'Industry and Power Generation' included photovoltaics, remote monitoring, humidity, fire, precipitation and sound. One example is the study of López-Vargas *et al*. [18], where they used Arduino to measure electric and climatic data (including humidity and rainfall) to remotely monitor a standalone photovoltaic system to enhance both the system´s performance and maintenance. Alam *et al*. [19] monitored dust and noise in cement industries to compare with international standards for healthier environments.

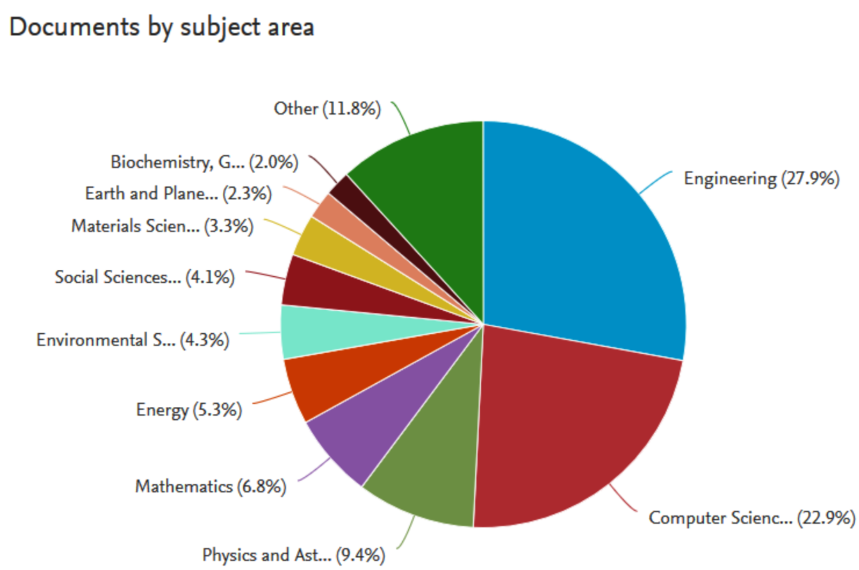

Figure 5: Research fields using Arduino.

Source: Scopus, 2020.

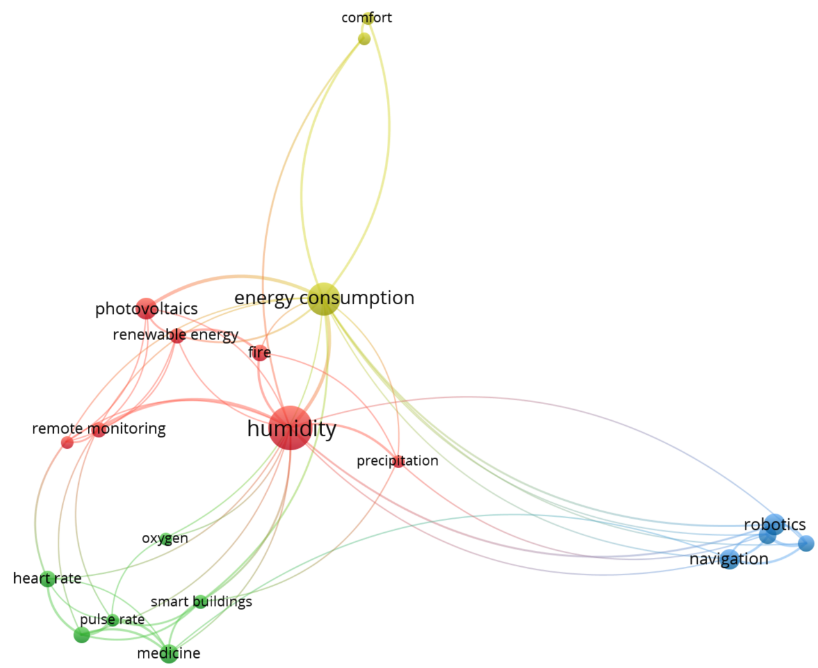

Figure 6: Overview of the main interests related to the use of Arduino. Colors represent the different research clusters.

The Robotics cluster covers navigation, distance measurement and ultrasound. Although these topics may suggest works concerning the technology of drones [20], for example, Karim *et al*. [21] and Sendra *et al*. [22] used Arduino to design systems that could help people with disabilities move safely. The technology proposed by both studies use ultrasonic sensors to measure the distance between the person or the wheelchair and the obstacles and help avoid collisions.

The cluster related to Architecture included comfort in general, thermal comfort and energy consumption. The relationship between thermal comfort monitoring via Arduino and the building energy performance are approached, for example, by Scarpa *et al*. [23] and

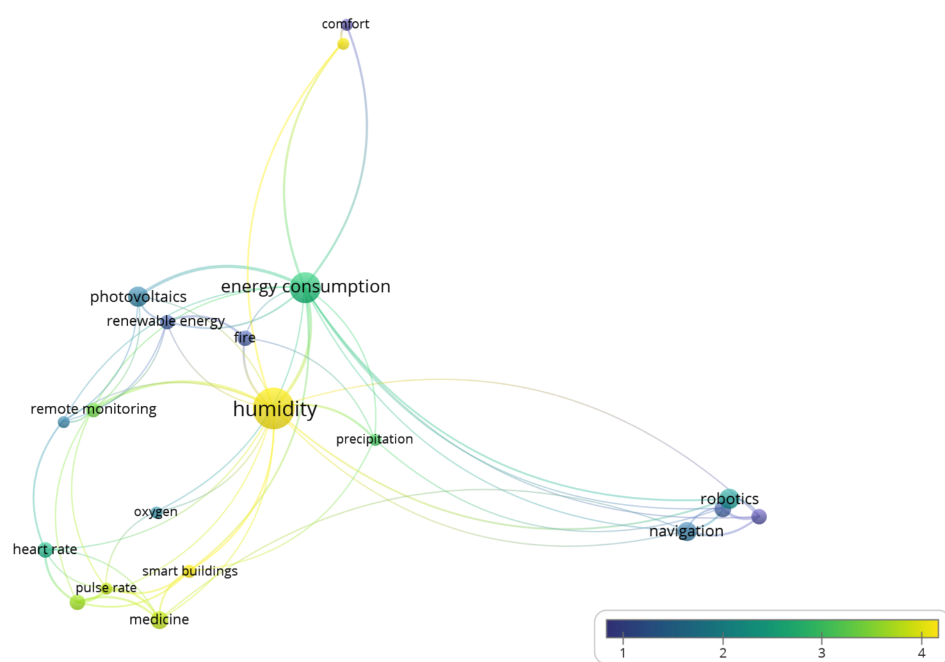

Figure 7: Citation impact of the terms related to the use of Arduino. Terms with cold colors represent the research activities with lower number of citations compared to the terms with yellowish colors.

Sung *et al*. [24]. Another aspect of indoor comfort is the visual one. Cesario *et al*. [25] used Arduino to design a façade-automated system in order to ensure indoor visual comfort whilst preserving the aesthetic characteristics of historical buildings.

Finally, body temperature, heart and pulse rate, oxygen and smart buildings are included in the medicine cluster. It is especially interesting to see how smart buildings fall under this cluster and how such usage is strongly connected not only to energy consumption [26], but also to body temperature and pulse rate. In fact, smart healthcare is a part of the eight key concepts of smart cities, along with smart buildings. The work of Tarapiah *et al*. [27] shows how remote monitoring of the heart rate and skin temperature can help to connect patients to their doctors. Yet, the analysis of the resulting articles did not find any work connecting both biomedical and environmental data simultaneously. The only exception would be [28], which designed an infant smart care system for incubators, with sensors for temperature, humidity, CO_2 and water level.

Still, "smart buildings" is one of the terms with the highest citation impacts of all the papers that include the corresponding term, as shown in Figure **7**. In this map, the terms with cold colors represent the research activities with lower number of citations compared to the terms with yellowish colors [15]. The majority of the other items highlighted in yellow are also related to the medicine field.

Figure **8** shows the state of the art in research on the use of Arduino according to the applied filters. Each circle corresponds to the average publication year of all the papers that include each term. "The terms with cold colors (e.g. blue) represent the research activities with older average publication year and the terms with hot colors (e.g. red) show the terms with more recent average publication year" [15]. "Body temperature", "smart buildings" and "pulse rate" appear in the most recent studies, along with renewable energy monitoring and fire detection (research area industry and power generation). The highest occurrence of those terms is between 2017 and 2018, as shown by the legend of Figure **8**. With regard to biomedical related topics, their novelty is in accordance with the recognition of the potential of digital technologies in public health by the World Health Assembly, in 2018 [29].

3.3. Arduino and Indoor Environmental Research

Based on Figures **6-8**, it is also possible to infer that Arduino systems are strongly related to indoor environments due to the predominance of the topics´

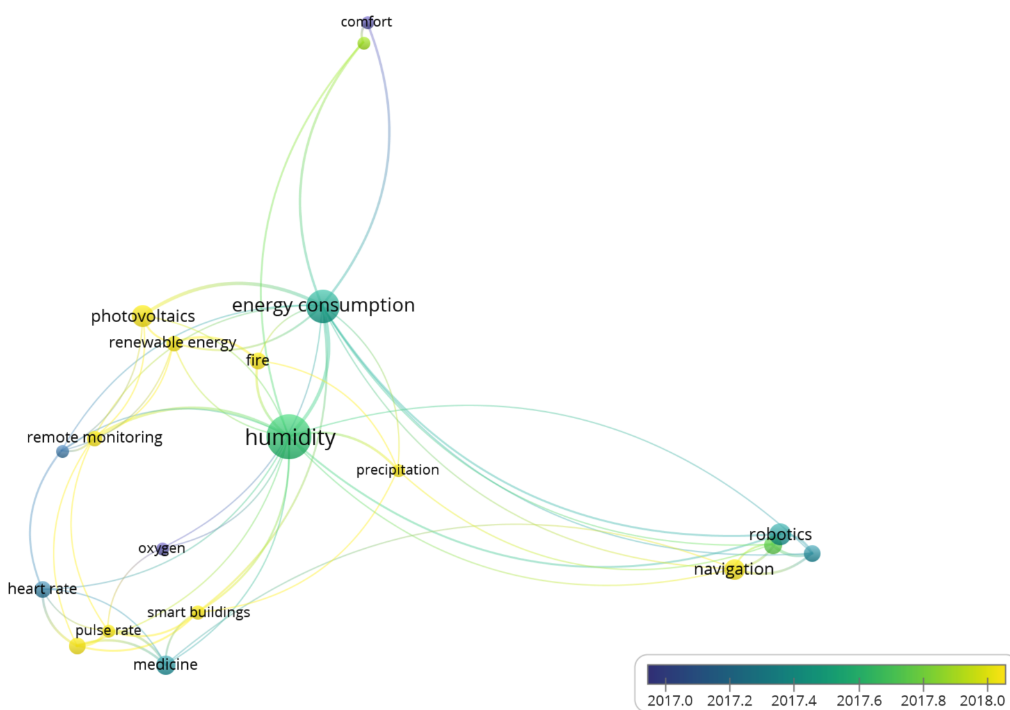

Figure 8: Top cited sources for arduino related articles between 2015 and 2020. Terms with cold colors represent the research activities with older average publication year and the terms with hot colors show the terms with more recent average publication year.

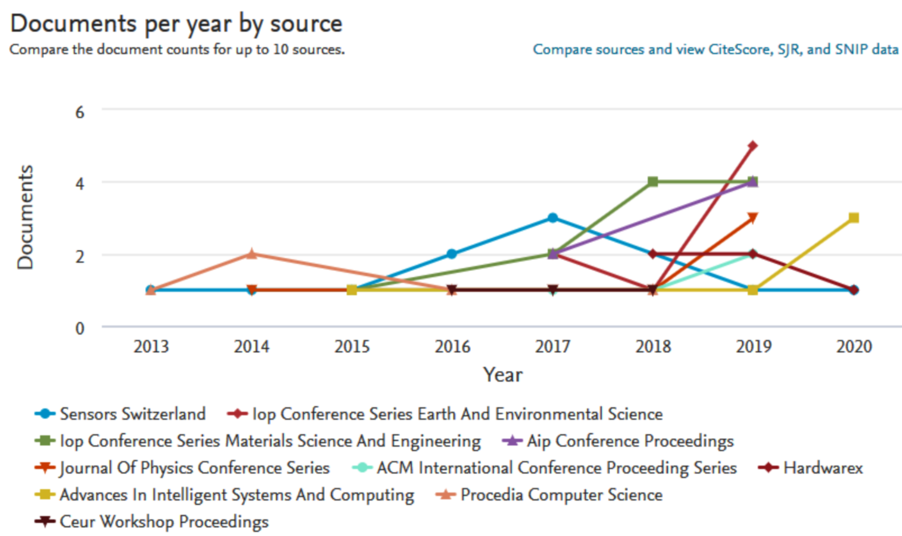

Figure 9: Top 10 cited journals the highest number of publications using Arduino as a measurement tool between 2015 and 2020.

comfort, thermal comfort and smart buildings. However, from the top 10 cited journals, only one of them is related to the built environment specifically through civil engineering (HardwareX). The others are in the following fields: computer sciences (ACM International Conference Proceeding Series, Procedia Computer Science, Advances in Intelligent Systems and Cumputing, and Ceur Workshop Proceedings); Physics and Astronomy (Journal of Physics: Conference Series); environmental sciences (AIP Conference Proceedings and IOP Conference Series: Earth and Environmental Science); material sciences (IOP Conference Series: Materials Science and Engineering); and only one is specifically about measurements (Sensors Switzerland) (Figure **9**).

3.4. Author Landscape

Table **4** shows the authors with the highest number of articles related to the use of Arduino as a measurement tool. While most of them used the system for temperature, relative humidity measurements [30-41] and air pollutants monitoring [30-41], other uses include electrochemical impedance spectroscopy for corrosion behavior of metallic works of art [4], light intensity [35-36], fire and rain detection [35], and wind speed [37-38]. The map in Figure **10** shows the top 10 authors already mentioned in Table **4**; the connection between them represents the co-authorship in papers [15]. Once again, cold colors represent the authors with lower number of citations compared to the authors with yellowish colors.

Table **5** and Figure **11** show the top 10 authors most frequently cited by the papers selected in this review. Their researches are mainly in the field of energy efficiency [42-47] and material sciences [48-51], represented by the colors red and green, respectively. It is important to stress that those are the authors that somehow provided the foundation for the papers

Table 4: Top 10 Authors with the Highest Number of Publications using Arduino as a Measurement Tool between 2016 and 2020 (Adapted from Scopus)

Author	Number of publications	Field of study
Li, X.	4	Air quality
Parvis, M.	4	Material Science, System Engineering
Angelini, E.	3	Material Science, System Engineering
Corbellini, S.	3	Material Science, System Engineering
Grassini, S.	3	Material Science, System Engineering
Sunehra, D.	3	Indoor environment monitoring
Sung, W.T.	3	Indoor environment monitoring
Abraham, S.	2	Material Science, System Engineering
Ali, A. S.	2	Indoor environmental comfort
Arifin, A. S.	2	Indoor environmental comfort

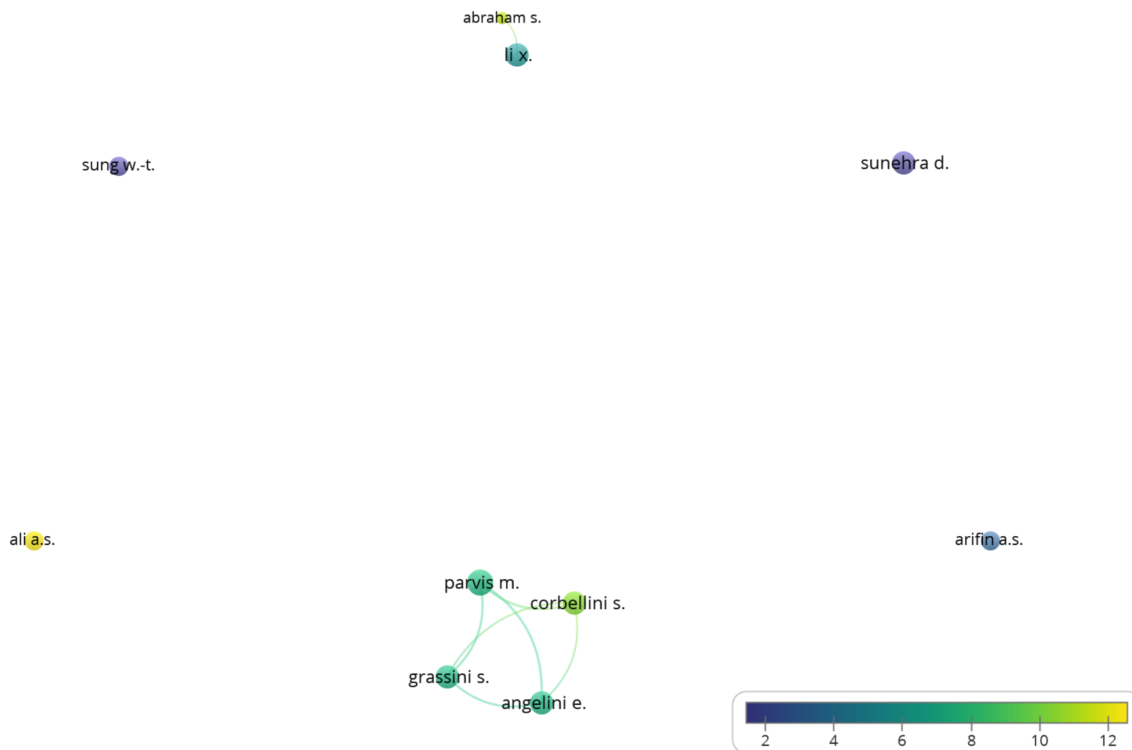

Figure 10: Top 10 authors with the highest number of publications using Arduino as a measurement tool between 2015 and 2020. Cold colors represent the authors with lower number of citations compared to the authors with yellowish colors.

Table 5: Top 10 Most Cited Authors using Arduino as a Measurement Tool

Author	Number of citations	Field of study
Zhang, Y.	26	Material Science, Engineering
Li, X.	22	Air quality
Salamone, F.	15	Indoor environmental quality and energy efficiency
Danza, L.	14	Energy efficiency
Lee, S.	14	Material Science, Engineering
Belussi, L.	13	Indoor environmental quality and energy efficiency
Meroni, I.	13	Energy efficiency
Wang, Z L.	13	Material Science, Engineering
Ray, P. P.	12	Energy efficiency
Ghellere, M.	10	Energy efficiency

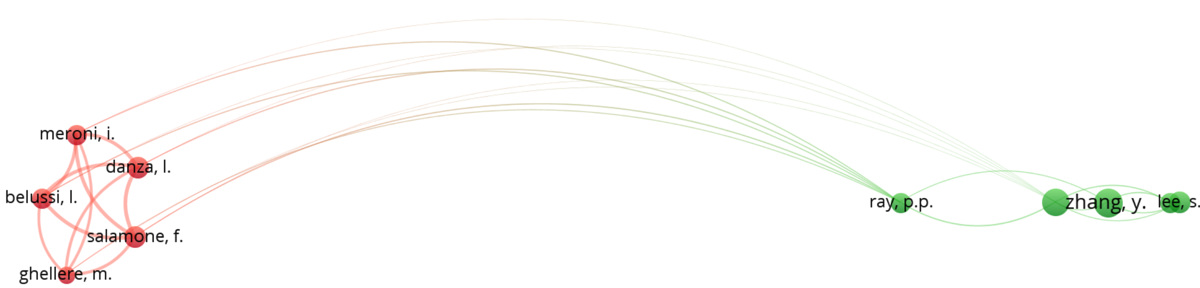

Figure 11: Top 10 most frequently cited authors. Colors represent authors from the same research fields – red for Energy Efficiency and green for Materials Science.

analyzed in this review. Therefore, they are not necessarily limited to the time and research fields imposed in this study.

Furthermore, because Arduino is usually mentioned as a tool and not as the main subject of the research studies, both authorship and co-citation analysis show the lack of communication between the fields. Thus, it does not mean that there should be communication – it only makes clear the versatility of the system once again.

4. CONCLUSION

Equipment costs are a part of research budgets [52] and it was also a challenge for our research conducted on the physiological effects caused by the different types of views through the window on office workers. In this context, we came across Arduino systems, which have low cost as one of their main features [53-58].

The other argument for its adoption is the relative simplicity [56-58]. Depending on the research approach, the equipment could even be operated by someone with no technical background and / or be placed somewhere outside the laboratory [58].

This paper had the goal of reviewing the use of Arduino as a measurement tool for researches in indoor spaces. For that purpose, three main questions were established: (1) what is the state of the art and trends using Arduino; (2) how is Arduino being used in indoor environments; and (3) who are the main authors using the system and what are the most cited Arduino related sources.

The many research fields identified on the analysis of the topics, the authors´ field of studies and journals make clear that the system is versatile in measurement types for indoor use. However, its adoption in architectural studies is still rather new and limited mostly to energy performance and thermal comfort. There is also a lack of studies connecting biomedical and environmental measurements, which is the intention of the authors´ future research.

Therefore, this paper shows that there is a big opportunity for expanding measurements in indoor environments. In addition, the versatility of the system would also benefit multidisciplinary works, such as those connecting architecture and health areas.

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