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SUSTAINABLE ARCHITECTURE AND THE ROLE OF CYBER-PHYSICAL SYSTEMS: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

Cyber-Physical Systems are next-generation digital systems that focus on the intricate connections and integration between the physical and digital worlds. These systems have highly integrated physical, communication, control, and computing components. The study's purpose is to carry out a bibliometric analysis to explore the research trends, collaboration network, and thematic evaluation of papers on cyber-physical systems. The most prolific countries, authors, sources, highest citations received by authors, and co-occurrences in this research domain were identified. The bibliometric analysis method was employed to empirically analyze the research on CPS in architecture published between 2007 and 2022 in the Web of Science database. All retrieved records were initially filtered by excluding 364 non–non-peer-reviewed publications and another type of languages except English. After that, we excluded 8 records based on the criteria and scope, and again excluded records for duplicates 12 records. Finally, 1336 records met the eligibility criteria. The VOS viewer and biblioshiny software was used to construct the scientific maps. A total of 1336 publications were analyzed. The study results show that the highly cited papers have been published in 297 journals by 4520 authors from 1483 organizations in 83 countries. The most prolific journal was IEEE Access, with 104 publications, 3823 citations, and an h-index of 24. The number of documents progressively increased from 2010 to 2021. Further, 2009 has no publications, and the largest number of articles was published in 2021 (n=272). Furthermore, China led the way with the most publications, active organizations, prolific authors, and international collaborations. This is the first study to look at the global trends in research on CPS in architecture and provides valuable guidelines and motivations for further research. Future studies may also examine the main hazards connected with using cyber-physical systems to manage operations across various industries and sectors.

INTRODUCTION

Cyber-physical systems (CPS) are computer-aided systems that link physical reality activity to the computing and communication infrastructure (Alam & El Saddik, 2017). These systems follow the trend of having information and services available 24/7 in today's highly networked world. The ability to communicate with the physical world and expand its capacity through calculation, communication, and control is an important enabler of future technological advances (Jazdi, 2014). Academics, businesses, and governments worldwide are all interested in CPS. The technology employed in these systems is based on the more established technology of embedded systems. Albeit still very new, this technology studies computers and software in objects like vehicles, toys, hospital instruments, and scientific equipment whose primary function is not computation. Through abstractions and modeling, design, and analytic approaches, CPS combines the dynamics of physical processes with those of software and networking.

CPS can be used in various fields, such as architecture, intelligent transportation, agriculture, health, water, and aerospace. Therefore, service providers will likely focus on implementing CPS technologies in the future (Bagheri et al., 2015). Communication is required in CPS to transmit sensor monitoring data to regulators. Thus, communication is a crucial requirement for the functionality of architectural design systems.

Lee et al. (2015) proposed the CPS 5C architecture to construct CPS. They suggested that a cyber-physical system should consist of five levels: smart connection, data-to-information conversion, cyber, cognition, and configuration. The

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first step in creating a CPS application is gathering accurate and consistent data from devices and their parts. Sensors can gather data directly or via interfaces with business production systems. Afterwards, converting this data into relevant and predictive information, such as health and remaining usable life values, is critical in machine prognostics and health management (Lee, Ardakani et al., 2015). The cyber layer serves as the main information hub, combining information from equipment that are connected to create a vast network. As we move forward, the cognitive level of CPS implementation yields a deep comprehension of the system under observation, enabling knowledgeable decision-making via knowledgeable user interfaces. Lastly, feedback from cyberspace to physical space provides supervisory authority, allowing devices to self-configure and adjust for optimal efficiency (Yao et al., 2019).

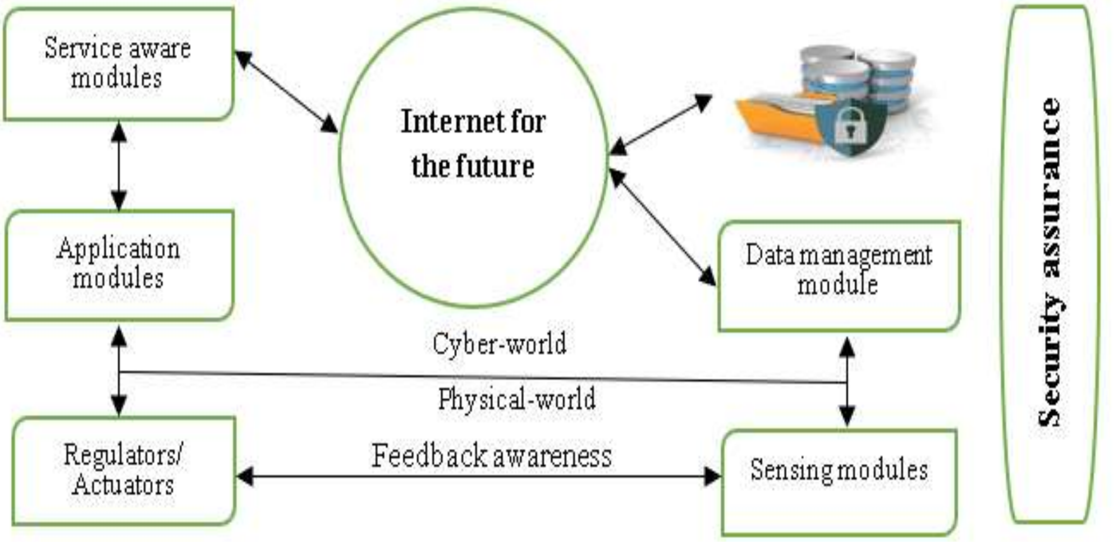

Figure 1. CPS architecture

A bibliometric analysis is used to identify research gaps in the field of sustainable architecture and CPS. The results provide a number of promising directions for future research. The socioeconomic effects of integrating CPS in sustainable building designs, such as how these technologies might be made accessible and inexpensive for various groups, are the subject of little research. Moreover, there is a dearth of multidisciplinary collaboration among computer scientists, engineers, and architects, indicating the need for more integrated design and implementation methods. Finally, long-term case studies evaluating CPS's environmental effects and effectiveness in sustainable architecture are limited, showing a need for more empirical evidence to validate theoretical models.

This study seeks to examine the present state of CPS in architecture research. The following research questions have been addressed in this study:

- Which countries have the highest number of publications?
- Which sources/journals have the highest number of publications?
- Who are the authors who have the highest citations received in the field?

The study has the following sections: Section 2 discusses Literature reviews, Section 3 outlines the research methodology, Section 4 provides findings and analysis, Section 5 addresses the importance of CPS in architecture, Section 6 discusses the study, and Section 7 discloses the conclusion.

LITERATURE REVIEW

CPS models for architecture have given rise to various initiatives to establish CPS projects in a factory setting. The current industrial CPS efforts have been thoroughly reviewed to identify their shortcomings, potential fixes, and recommendations. The 5C Architecture was the first CPS architecture widely used in industrial applications and was developed in 2013 (Ahmadi et al., 2017).In architecture, CPS integrate physical elements with computational algorithms to create smart environments that improve building sustainability, safety, and efficiency (Bonci et al., 2019; Darwish & Hassanien, 2018; Kalluri et al., 2021). Research has demonstrated that CPS can improve occupant satisfaction by modifying environmental conditions according to users' preferences (Stamatescu et al., 2016; Schmidt et al., 2017) and optimize resource allocation based on real-time data (Agostinelli et al., 2021; Ane et al., 2023; Barroso et al., 2023), both of which can result in a large reduction in usage of energy.

Implementing CPS in architecture also presents issues that must be addressed, including security and privacy concerns due to the large volume of data collected (Giraldo et al., 2017; Fink et al., 2017; Ane et al., 2020; Chong et al., 2019). Moreover, many obstacles remain to overcome before various systems and standards can function together seamlessly, frequently calling for specialized solutions (Givehchi et al., 2017; Kunold et al., 2019). Notwithstanding these difficulties, CPS in architecture has indisputable advantages, improving building performance and opening the door to new business models like energy-as-a-service and predictive maintenance (Correa, 2018; Banerjee & Nayaka, 2022). The necessity of cross-disciplinary collaboration is emphasized by research that is still focused on creating standardized protocols and frameworks to facilitate the wider use of CPS in architecture (Vogel-Heuser et al., 2020; Mizutani et al., 2021); Horváth, 2023).

Using AI and machine learning to create adaptive educational environments that change based on past data and user behaviour is one of the emerging themes in CPS architecture (Radanliev et al., 2021). Building more effective and individualized management systems that can change the environment without human involvement may result from this strategy. Furthermore, by integrating renewable energy sources and encouraging resource efficiency, CPS can support sustainable urban development (Shih et al., 2016; Kleissl & Agarwal, 2010). The architectural sector is well-positioned to gain from technological breakthroughs as they happen, leading to the creation of built environments that are more intelligent, robust, and sustainable (Bakakeu et al., 2017; Akanmu & Anumba, 2015; Bonci et al., 2019).

MATERIALS AND METHODS

Database Selection

This study conducted a scientometric/bibliometric analysis of the literature on CPS in architecture. Bibliometric/scientometric analysis has been frequently used to refine prominent research and identify trends using quantitative analysis. In this research, various performance indicators were extracted, and the most active countries, prolific sources, highest citations received by authors, and co-occurrences were identified in the relevant literature (Hossain & Batcha, 2021).

The Web of Science (WoS) database was used to retrieve raw data related to CPS in architecture. 'Cyber-physical systems' and 'architecture' were the two main keywords selected and used to search in the title, abstract, and keywords for the WoS database documents fields. According to the initial results, 1720 papers published between 2007 and 2022 were identified. These results include information regarding the title, author names and affiliations, citations, abstracts, keywords, and references related to the publications. They were all saved in plain text format. Microsoft Excel was used to create statistics about the evolution of the topics over time, the journals or conference proceedings, citations, keywords, authors, and geographical distribution of the studies in terms of software packages.

Documents Eligibility

The PRISMA method identifies and evaluates research studies relevant to a particular research question or topic. In the context of CPS in architecture, a bibliometric analysis using the PRISMA method would involve a systematic search of relevant databases, such as WoS, to identify relevant articles once they have been identified, screened, and evaluated for relevance based on specific inclusion and exclusion criteria (Hossain et al., 2022).

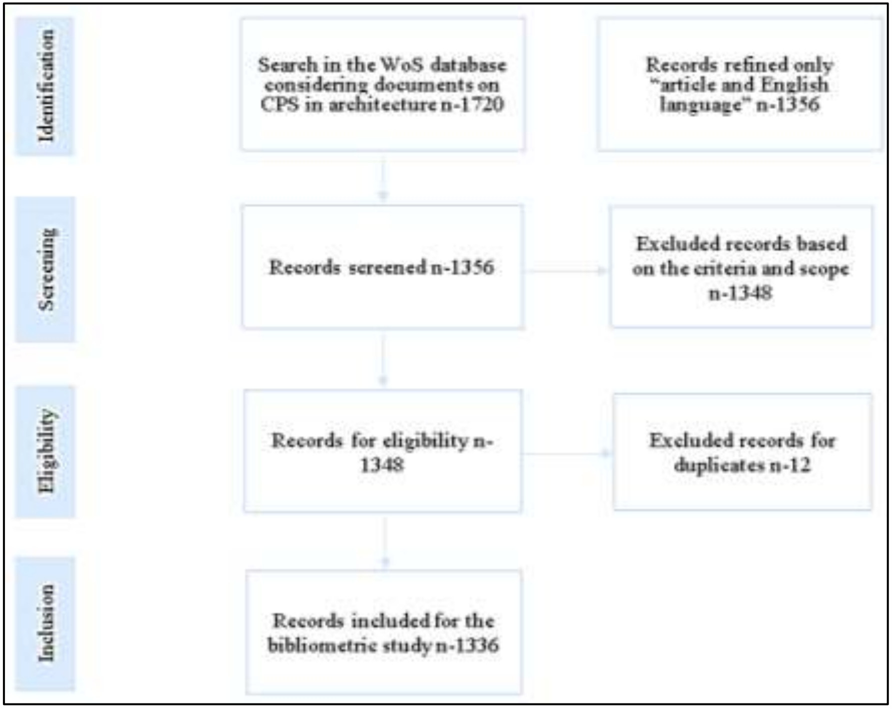

Figure 2. Detail flowchart illustrating the PRISMA on CPS in architecture research

As shown in Figure 2, the researchers followed the PRISMA meta-analysis steps on EMRs research, which includes four steps: (a) identification as recording identified through database searching, (b) screening the record documents, (c) eligibility records, and (d) selecting studies, as follows:

- Empirical articles published between 2007 and 2022 were included.
- We excluded other documents (e.g., conference papers and review papers).
- We excluded duplicate records.

Software

In total, 1720 documents were obtained from the WoS database on April 20, 2022. These retrieved records were initially filtered by excluding 364 non–non-peer-reviewed publications and another type of languages except English. After that, we excluded 8 records based on the criteria and scope and again excluded records for duplicate 12 records. Finally, 1336 records met the eligibility criteria. Thus, in the "included" phase, the number of records included in the meta-analysis is presented. The VOS viewer (Van Eck & Waltman, 2011) and Bibliometrix tools (Aria & Cuccurullo, 2017) allowed for a more in-depth examination of citations and co-author relationships and were also applied to the data.

RESULTS

Country Collaboration

Table 1 shows that authors from 83 countries contributed to the literature on CPS in architecture from 2007 to 2022 and published 1336 papers. The authors' country of employment during research, which can be different from their country of birth or citizenship, was considered for this analysis. From a geographic standpoint, the highest contributions were from China (826), the USA (538), Germany (186), Spain (175), and the UK (167), as shown in Table 1. Furthermore, only three developing countries, India, Brazil, and Pakistan, were identified as some of the 20 most productive countries. Figure 3 depicts the collaboration between countries based on co-authorships using the VOS viewer tool. For this purpose, the minimum number of publications was set as five documents per country and a minimum number of ten citations.

Table 1. Country collaboration on CPS in architecture research

Rank	Country	Frequency	Rank	Country	Frequency
1	China	826	11	France	74
2	USA	538	12	Sweden	73
3	Germany	186	13	Saudi Arabia	56
4	Spain	175	14	Brazil	53
5	UK	167	15	Portugal	51
6	India	150	16	Pakistan	50
7	Italy	132	17	Greece	47
8	South Korea	122	18	Japan	44
9	Australia	82	19	Finland	38
10	Canada	74	20	Netherlands	33

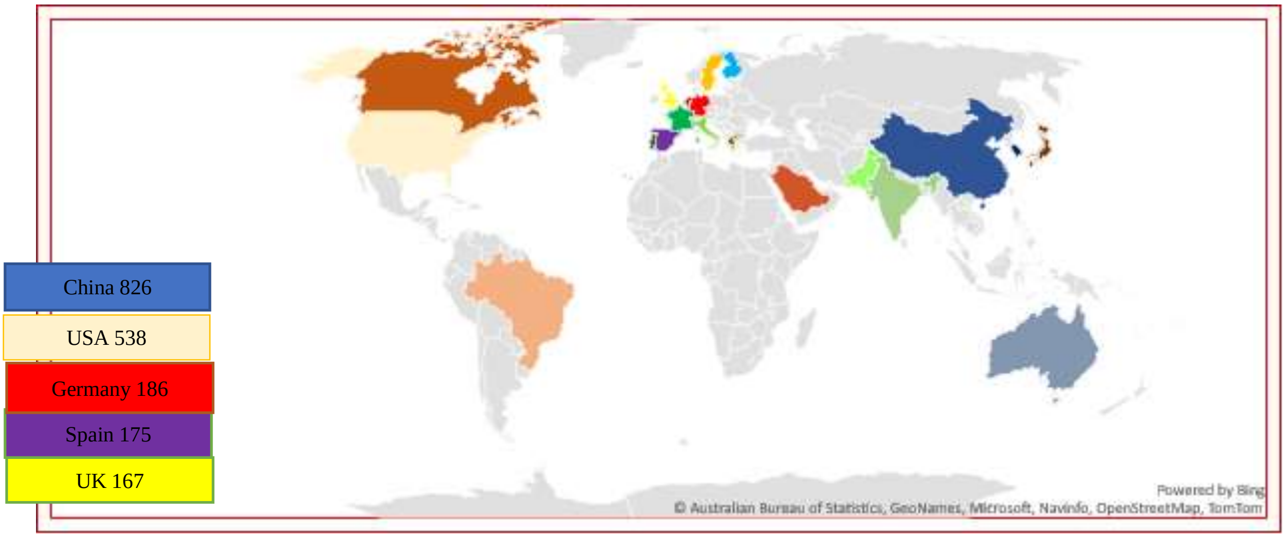

Figure 3. Map of top 20 countries' collaborations

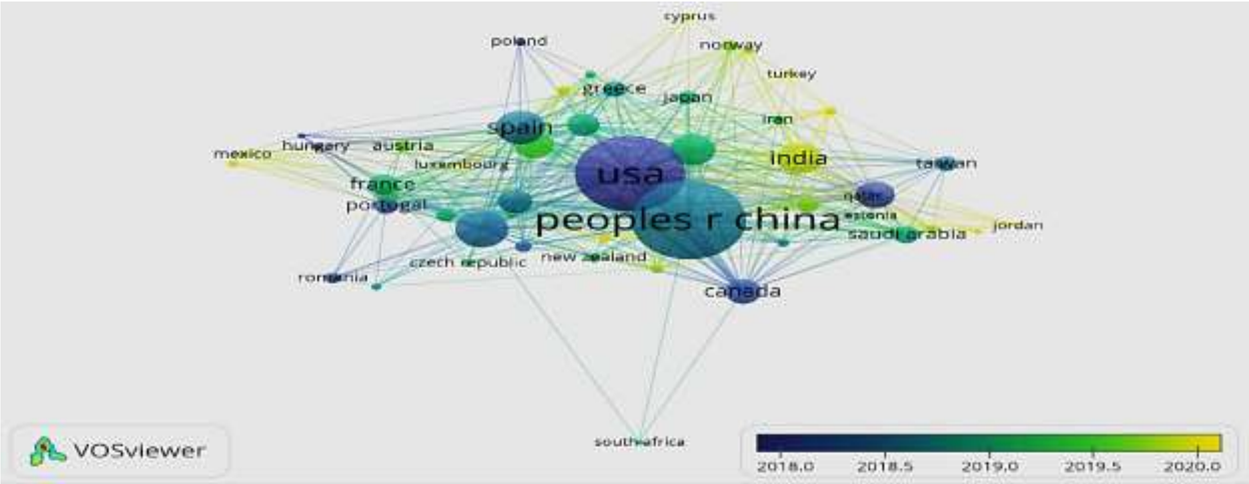

Figure 4. Co-authorship analysis of countries using VOS viewer

In Figure 4, the strength of global cooperation is represented by the line thickness between countries (Jeong & Koo, 2016). The size of the circle denotes the scope of global cooperation. Of the 83 countries, 51 met the threshold for the country, as shown in Figure 2. The map has six country clusters, 432 links, and a total link strength of 1141. It also shows that China and the USA had the most paper collaborations in the CPS in architecture research.

Institution's Collaboration in the World

As shown in Table 2, the South China University of Technology (China) published the most articles on CPS in architecture, followed by the King Saud University, KSA, and the Shanghai Jiao Tong University, China. It can be seen that in the top 10 worldwide institutions with the most CPS in architecture publications, both private and public institutions are highly represented. However, the public institutions were more prolific than their private counterparts. Furthermore, public institutions like the South China University of Technology and King Saud University produced a substantially higher number of articles than others. Only one private university, Northeastern University, USA, made it to the top 10 universities list by publishing 18 articles.

Table 2. The top institution articles contributing to the world

Rank	Affiliation	Articles	Nation	Ownership	Discipline
1	South China University of Technology	28	China	Public	Engineering
2	King Saud University	25	Saudi	Public	Multidisciplinary
3	Shanghai Jiao Tong University	25	China	Public	Multidisciplinary
4	Polytechnic University of Madrid	25	Spain	Public	Multidisciplinary
5	Huazhong University of Science and Technology	21	China	Public	Engineering/Medical
6	Technical University of Munich	20	Singapore	Public	Multidisciplinary
7	Zhejiang University	20	China	Public	Multidisciplinary
8	South China University of Technology	19	China	Public	Multidisciplinary
9	Northeastern University	18	USA	Private	Multidisciplinary
10	Tsinghua University	18	China	Public	Multidisciplinary

Evolution of Scientific Production

The evolution of the number of articles related to CPS in architecture between 2007 and 2022 is shown in Figure 5. The first article was published in the Web of Science database in 2007 and was entitled "Hyperion-Next-Generation Battlespace Information Services". It can be seen that from 2007 to 2022, the number of documents progressively increased from 2010 to 2021. Further, 2009 has no publications, and the largest number of articles was published in 2021 (n=272).

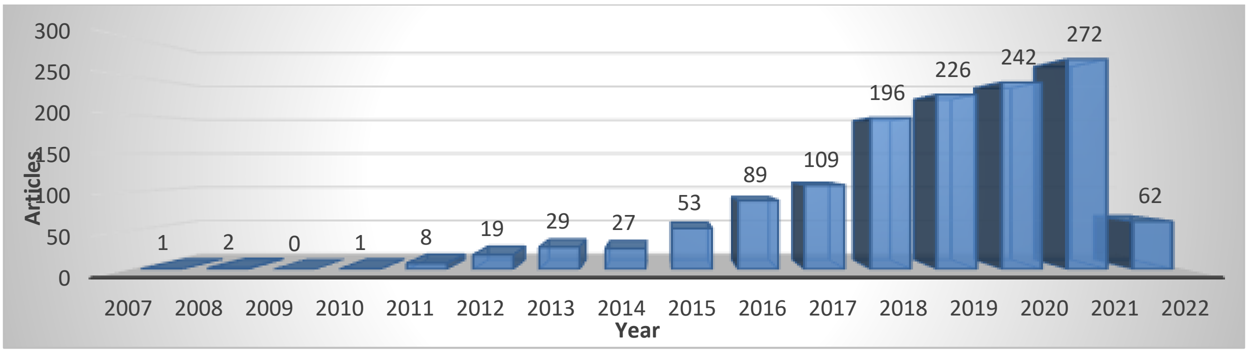

Figure 5. Quantity of papers by year

Author's Keyword Analysis

Co-word analysis identifies the relationships between concepts (words or topics) that appear in the same document title, keywords, or abstract (Liu et al., 2024; Xu et al., 2024). As a result of the co-occurrence of keyword analysis, VOSviewer was used to identify the most frequently used keywords in the 1336 documents in the sample.

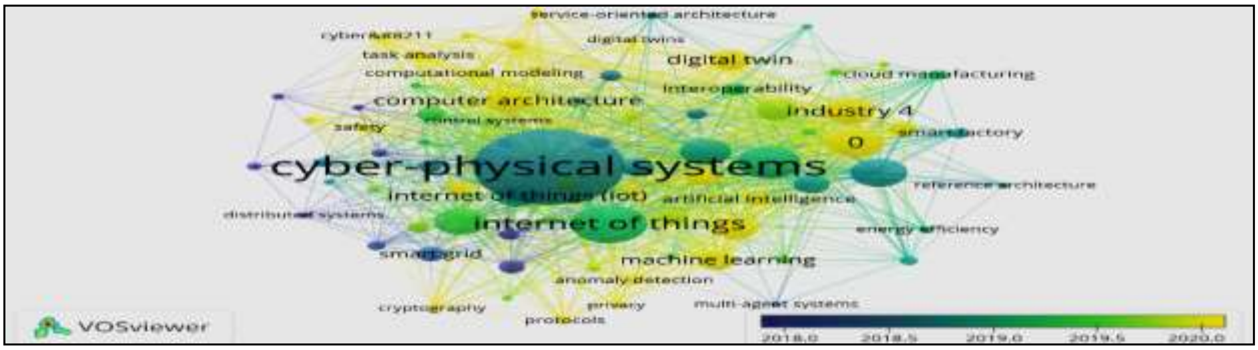

Figure 6. Density visualization of author keywords using VOS viewer.

The minimum number of occurrences of an author keyword was 10. A total of 4329 keywords met the threshold and are shown as 5 clusters in the map exported from the VOS viewer. In Figure 6, the font size of the keyword indicates the frequency of use of the keyword. The most frequently used keyword was 'cyber-physical systems' with 281 occurrences, followed by 'internet of t with 116 occurrences, and 'cyber-physical system' with 93 occurrences.

Most Citations Received by Authors

Table 3 presents the list of authors most frequently cited by research articles on CPS in architecture published during the study period. Wan JF, Li D, and Wang SY were the most cited, with 716 citations. These authors have discussed implementing smart factories in the industry. Wan JF, Li D, Wang SY, and Zhang DQ claimed the second-highest number of citations received for their article entitled 'Towards Smart Factory for Industry 4.0: A Self-Organized Multi-Agent System with Big Data Based Feedback and Coordination'.

Table 3. Most citations received things by authors

Rank	Author	Sources	DOI	Citations
1	Wan JF	International Journal of Distributed Sensor Networks	10.1155/2016/3159805	716
2	Li D	International Journal of Distributed Sensor Networks	10.1155/2016/3159805	716
3	Wang SY	International Journal of Distributed Sensor Networks	10.1155/2016/3159805	716
4	Wan JF	Computer Networks	10.1016/j.comnet.2015.12.017	559
5	Li D	Computer Networks	10.1016/j.comnet.2015.12.017	559
6	Wang SY	Computer Networks	10.1016/j.comnet.2015.12.017	559
7	Zhang DQ	Computer Networks	10.1016/j.comnet.2015.12.017	559
8	Wan JF	IEEE Sensors Journal	10.1109/JSEN.2016.2565621	365
9	Li D	IEEE Sensors Journal	10.1109/JSEN.2016.2565621	365
10	Wang SY	IEEE Sensors Journal	10.1109/JSEN.2016.2565621	365

Sources Impact

Table 4 shows that the 1336 documents were published in 297 journals. The IEEE Access has been the most productive journal with 104 published papers, followed by the Sensors with 66 papers, and the IEEE Internet of Things Journal with 40 papers published. The impact factor values of the Proceedings of the IEEE and IEEE Internet of Things Journal are among the highest. Table 4 also shows the number of citations the articles published in the most popular journals received. It can be seen that IEEE Access received the most citations. Furthermore, the eight journals were in the first quartile.

Table 4. Sources' impact on CPS in architecture

Rank	Element	Papers	Citation	h-index	Impact Factor	Quartile	Pub. Year
1	IEEE Access	104	3823	24	4.48	2	2015
2	Sensors	66	922	16	10.2	1	2008
3	IEEE Internet of Things Journal	40	2238	13	12.37	1	2014
4	Future Generation Computer Systems-The International Journal of Science	38	1227	17	9.11	1	2016
5	IEEE Transactions on Industrial Informatics	37	1468	20	11.22	1	2010
6	Journal of Manufacturing Systems	26	1087	15	10.88	1	2015
7	Applied Sciences-Basel	23	100	5	2.679	3	2017
8	Proceedings of the IEEE	20	1127	13	45.17	1	2012
9	International Journal of Advanced Manufacturing Technology	19	306	10	3.55	1	2016
10	International Journal of Computer Integrated Manufacturing	19	361	14	3.7	1	2017

The Hirsch index (also known as the h-index) is a metric used to assess educational institutions' and researchers' influence and performance. If h papers out of a scientist's total number of papers have at minimum h citations each, and his or her remaining papers have been cited no more than h times every, the scientist has an h-index (Engqvist & Frommen, 2008). The Hirsch index concurrently determines the effectiveness and long-term significance of the research. The journal of IEEE Access had the highest number of citations (n=3823) and had an h-index of 24.

As seen in Figure 7, based on the top 10 sources, IEEE Access Sources published the maximum number of articles from 2007 to 2021, followed by Sensors and IEEE Internet of Things Journal. Most documents were published in 2021 from all top 10 sources.

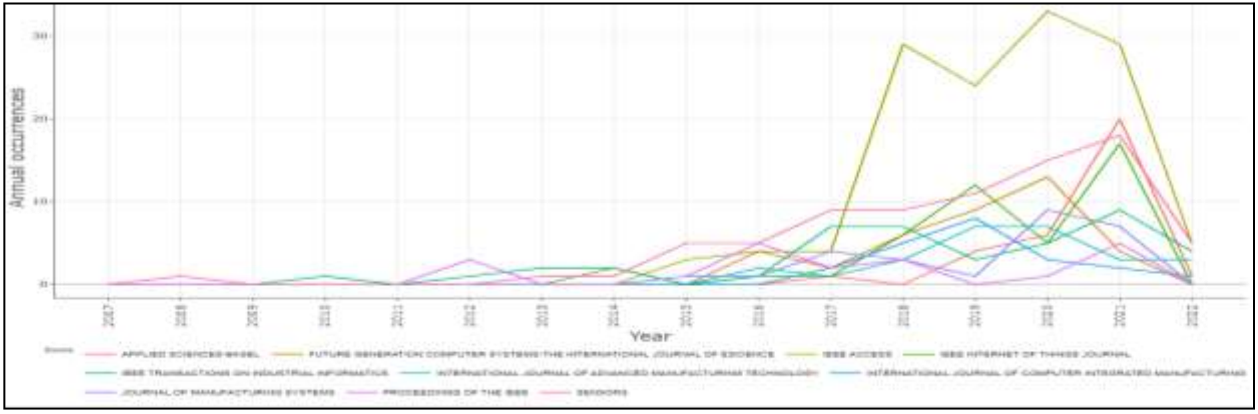

Figure 7. Annual output of sources (top 10) from 2007 to 2022

Importance of CPS in Architecture

The importance of CPS in architecture lies in its ability to enhance the performance, efficiency, and sustainability of buildings while improving the safety, comfort, and satisfaction of building occupants. As such, the integration of CPS is becoming increasingly critical in the design, construction, and management of facilities in the 21st century (Monostori et al., 2016; S. Wang et al., 2016). CPS has become increasingly important in the field of architecture due to the numerous benefits they offer, including:

Improved Efficiency

CPS can help improve buildings' efficiency by optimizing energy usage, reducing waste, and improving the management of building systems. This can lead to lower energy bills, reduced carbon footprints, and increased sustainability.

Enhanced Safety and Security

CPS can help improve building safety and security by monitoring the health of the building's structure, detecting potential hazards, and providing real-time alerts in emergencies. This can help prevent accidents, reduce damage, and save lives.

Improved User Experience

CPS can help create more user-friendly buildings by providing personalized experiences, adapting to user preferences, and providing real-time feedback. This can help enhance building occupants' comfort, productivity, and satisfaction (Kang et al., 2016).

Better Building Management

CPS can help improve the management of buildings by providing real-time data on building performance, enabling predictive maintenance, and facilitating remote monitoring and control. This can reduce costs, increase efficiency, and improve the overall performance of buildings (L. Wang et al., 2015).

Future-Proofing

CPS can help future-proof buildings by enabling them to adapt to changing user needs, environmental conditions, and technological advancements. This can help ensure that buildings remain relevant, sustainable, and efficient over the long term (Gerostathopoulos et al., 2016).

DISCUSSIONS

The present study presents the global status and trends in the literature on CPS in architecture. A bibliometric analysis was conducted on data extracted from the Web of Science database to identify the most prolific authors, sources, and countries active in the research area. VOS viewer software was used for graphical analysis and mapping of the clusters of countries and author keywords. The study results have identified China as the country leading in this research domain. Although there was a disparity between China's academic impact, quality, and the number of publications, China has been working hard to become a valuable contributor with outstanding research institutions such as the South China University of Technology and Shanghai Jiao Tong University.

This work presents the notion of cyber-physical systems and a model architecture. It argues that this definition and architecture not only satisfy every aspect of the CPS currently recognized but also unite the machine-only and human-only computation models currently in use (Khaitan & McCalley, 2014; Sony, 2020).

To the best of the authors’ knowledge, this is the first bibliometric study in the field of CPS in architecture. Our findings provide a foundation for scholars and policymakers to recognize the bibliometric indicators used in this study as indicators of research performance in CPS to inform future policies and funding decisions (Cardin, 2019). Finally, our research has revealed that bibliometric analysis is an effective method for mapping published literature on a specific topic and identifying research gaps in that field.

This study provides valuable insights into the literature on CPS in architecture. Cyber physical systems will exist in all industrial sectors, such as telecommunications and within the fourth industrial revolution (Panetto et al., 2019). Innovative production techniques will be made possible by CPSs, which will eventually become the norm in the sector (Wan et al., 2014). Improved agility, mobility, and affordability will result from self-configuring, self-adjusting, and self-optimizing output settings (Babiceanu & Seker, 2016). Every operational component of manufacturing, from design to manufacturing to supply chains to customer service and support, will be impacted (Alam & El Saddik, 2017).

CONCLUSIONS

The comprehensive systematic examination and analysis of sustainable architecture and the Role of Cyber-Physical Systems exposes a diverse landscape in which incorporating technology into architectural practices has enormous potential for increasing sustainability. The review of current research emphasizes CPS's vital role in addressing environmental issues, resource efficiency, and overall building performance. The review focuses on CPS' revolutionary potential in developing Sustainable Architecture. The convergence of technology and environmental consciousness provides a path for constructing smarter, more resilient, and environmentally friendly constructed environments. Research projects in the future might analyze real-world difficulties in industrial operations and suggest strategies to work with CPS in architecture. Future studies may also examine the main hazards connected with using cyber-physical systems to manage operations across various industries and sectors (Wan et al., 2014). Both scholars and practitioners can benefit from in-depth reporting on real case studies.

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