Review of Artificial Intelligence Techniques inGreen/Smart Buildings.

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Review of Artificial Intelligence Techniques in Green/Smart Buildings.

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Abstract The many benefits offered by green or smart buildings have led to an increase in their construction. In turn, this growth has been accompanied by a rapid evolution of research on this topic. Thus, given the specialist interest, research on the use of artificial intelligence in this type of construction has been gaining space. This topic, although still novel, due to its current and future importance requires a literature review to identify the main actors, evaluate the past and establish future lines of research. The results based on 174 manuscripts detected in Web of Science and Scopus databases allow us to establish the main authors, institutions, countries and journals as well as the seminal papers in this field. Furthermore, through a keywords co-occurrence analysis this study identifies some of the topics that have received most interest in the past as well as some promising future research trends. This bibliometric study analyzes the relationship between the main clusters DML&B (Deep - Machine Learning and Building Constructions) by means of a detailed description of the fundamental concepts identified in the content analysis. It is complemented by a temporal keyword analysis focusing on the economic, social and environmental benefits obtained through green or intelligent buildings. Consequently, this research contributes to the literature by providing an overview

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of the past and current status of this field, as well as by opening future research lines.

Keywords Green Buildings · Smart Buildings · Sustainability · Machine Learning · Deep Learning · Bibliometric

1 Introduction

Green or sustainable buildings are buildings that, as part of their design, construction or operation, reduce or eliminate related negative effects and can create a positive impact on our climate and natural environment [40](WorldGBC 2015), i.e. their impact on the environment and human health is taken into consideration during their conception and construction [42]. Green or sustainable buildings must have specific features such as efficient use of resources (energy, water, materials and land); use of renewable energy; pollution and waste reduction measures; & good indoor environmental air quality to improve health, comfort, and productivity, among others.

The construction of green or sustainable buildings has seen a significant increase in recent years worldwide. This sharp increase is due to the multiple benefits of these types of buildings. These benefits can be grouped into the following three categories:

1. Economic benefits. The economic benefits of green buildings are numerous, the most relevant being lower energy costs as well as health and productivity benefits, water efficiency, lower construction costs and job creation (European Commission [14]; Delphi Group [12]; [16]).
2. Environmental benefits. The most significant beneficiary of green or sustainable buildings is the climate and natural environment. They can reduce negative impacts on the environment generated by non-green buildings by using less water (potable water savings of 10%-50% every year compared to conventional buildings) energy (between 20-40% less energy), generating fewer greenhouse gas emissions, and using natural resources.
3. Social benefits. Green or sustainable buildings have been shown to bring about positive social change because many green building benefits are connected to the health and wellbeing of the people who work in green offices or live in green homes. Green buildings foster healthier, happier and more productive lives [40](WorldGBC 2015).

Smart or intelligent buildings, in contrast, are technologically oriented as they rely more on information technology (IT) than green buildings [43]. Smart or intelligent buildings are those buildings in which the facilities and systems (air conditioning, lighting, electricity, security, etc.) are subject to integrated as well as automated management and control in order to increase energy efficiency, comfort and security. Smart buildings successfully merge building management and IT systems that can dynamically optimize system performance and simplify facility operations [43].

With regard to the methodologies used to control smart or intelligent buildings, some proposals are largely based on the definition of a simple logical inference using the values of various measuring and presence sensors [1] [24] [28]. Other methodologies use techniques of Bayesian inference (A Bayesian network) to predict user behaviour patterns [18]. An example is given by [19] in which authors put forward a method capable of predicting energy consumption per capita.

In addition, iDorm is seen as an adaptive system (able to learn from user interaction and thus predict future needs) using embedded agents [17]. These agents use incremental synchronous learning (ISL) based on fuzzy logic. In the research of [13], the use of Markov chains is proposed to establish the likelihood of occupation of certain areas. In a similar vein [28] present a comparative study of different methods and techniques to control smart buildings.

There are also studies in which the authors propose implementing an adaptive loop control system as a component-based system [30] where the control loop can be reconfigured at runtime to incorporate new knowledge dynamically. In the study of Cetina [9] the authors apply dynamic software product lines in the domain of smart homes. It is worth drawing attention to the remarkable potential of artificial intelligence (AI) in sustainable design [3]. Comfort is described in terms of thermal comfort, lighting levels, indoor air quality, and acoustic levels. AI can control comfort levels through an intelligent energy management system, enabling maximum energy efficiency to be attained. Fuzzy logic is a key element in smart buildings and a fuzzy decision-making approach to select the most suitable construction method for Green Buildings was developed by Sunita [34]. A primary task in sustainable projects is the selection of an appropriate construction method based on an analytical tool to evaluate the applicability of a prefabricated or an on-site construction method.

An adaptive architecture at runtime for green buildings was presented by Rodríguez-Gracia [31]. The presented solution was used to equip the domotic system of the CIESOL green building with the ability to adapt to energy (between 20-40% less energy) user behaviour by integrating machine learning algorithms for decision making into the domotic system. This achieves an improvement in the system's energy efficiency and increases user comfort by adapting the system to the preferences of the user, thus freeing the latter from having to control the components involved in the system.

Analysis of scientific publications is an essential component in the research process, as it is a useful tool for analyzing the process of generation and evolution of knowledge, evaluating scientific quality and the impact on the academic world [4]. Given the relevance of the use of Artificial Intelligence techniques in Green/Sustainable Buildings, we can predict its analysis in the scientific literature through bibliometric analyses. In order to identify the main elements of a research topic, it is first necessary to pinpoint the most productive agents in the research field such as authors, institutions, or countries. According, the main driving force behind a field of research can be identified [6]. However, in recent years bibliometric analyses have been published in the scientific literature that refer only to the analysis of scientific production for green or sustainable buildings without determining any relationship to the technolgy applied (Table1). A bibliometric analysis of green buildings and smart buildings in conjuntion with artificial intelligence covers a research gap in the scientific literature.

In short, this literature review shows that rapid progress has been made in research on green and smart buildings, and hence on sustainable buildings. This rapid progress has generated broad and diverse knowledge on this topic, making it necessary to carry out a review study in this field, which will enable previous research to be evaluated and future lines of investigation to be established. To the

Table 1 Bibliometric studies on green buildings. (Source:own elaboration)

Title	Authors	Journal / Year	Database used / time	Research formula
Detection and introduction of emerging technologies for green buildings in Thailand	Visessonchok T. Sugiyama M. Sasaki H. Sakata I.	Int. J. Energy Technology and Policy, 12 (1). 2016	Web of Science 1900 -2013	(eco* **OR** energy efficien* **OR** low energy **OR** smart **OR** sustainab* **OR** low carbon **OR** low emission **OR** green) **AND** building*
Visualized analysis of knowledge development in green building based on bibliographic data mining	Liu X. Wang M. Fu H.	The Journal of Supercomputing, 1-17. 2018	Web of Science 2005 -2010	("green building*" **OR** "high-performance building*" **OR** "sustaina* building*" **OR** "green construction*" **OR** "high-performance construction*" **OR** "sustaina* construction*")
A Bibliographic Analysis of Water Efficiency among Green Building Rating Tools: LEED and ESGB	Zhou W.W. Wu D.J. Cheng X.X. Luo C.W. Tan F.X. Zhang Z. L.	Applied Ecology and Environmental Research 17(5):11639-11653. 2019	Web of Science Direct Engineering Village Scopus 2001- 2017	LEED, ESGB, green building, assessment methods, sustainable building, energy efficiency, water efficiency, environment protection, indoor environment quality, sustainable site
A bibliometric review of green building research	Zhao X. Zuo J. Wu G. Huang C.	Architectural Science Review, 62(1), 74-88. 2019	Web of Science 2000 -2016	green building* **OR** sustainab building*
A scientometric analysis and visualization of global green building research	Darko A. Albert P.C. Chan Xiaosen Huo De-Graft Owusu-Manub	Building and Environment, 149, 501-511. 2019	Scopus 1990 -2018	green building, green construction, sustainable building, sustainable construction, green technology, high-performance building, and high-performance construction
Mapping Knowledge in the Economic Areas of Green Building Using Scientometric Analysis	Xiao X. Skitmore M. Li H. Xia B.	Energies, 12(15), 3011. 2019	Web of Science 1990 -2019	("energy-saving building" **OR** "green building" **OR** " sustainable building" **OR** "energy- e_cient building" **OR** " energy-saving construction" **OR** "green construction" **OR** " sustainable construction" **OR** "energy-e_cient construction" **OR** "energy-saving hous*" **OR** "green hous*" **OR** "sustainable hous*" **OR** "energy-e_cient hous*") **AND** ("economic" **OR** "cost" **OR** "benefit" **OR** "value" **OR** "price" **OR** "incentive" **OR** "investment" **OR** "payment" **OR** "capital" **OR** "financial")

best of our knowledge, there is no review study such as that which is to be carried out in this work. As such, the aim of this research is to provide a literature review of artificial intelligence applied to new building techniques, particularly sustainable buildings, identifying core themes from existing research and establishing future research lines.

As a main contribution of this study, it can be highlighted that it extends previous review works by widening the research period, using the two main scientific databases (WoS and Scopus), including the analysis of smart buildings (not only focusing on green buildings) and presenting a new vision of the field by using bibliometric analysis as a literature review technique. This research therefore provides an exhaustive review of the literature on the use of artificial intelligence in green and smart buildings, which will allow academics and professionals to have access to an organized and synthesized vision of the research, while expanding their knowledge in this field and discovering future lines of research.

The work is structured as follows. First, the methodology to carry out this research is presented. Then, the results and discussion section are divided into descriptive analysis and content analysis for better illustration. The content analysis will focus on the analysis of keywords related to the economic, social and environmental benefits of sustainable construction. Finally, some conclusions, future lines of research, implications and limitations are proposed.

2 Materials and methods

As suggested in previous bibliometric studies [8] [6] [36], this research follows these five steps (Figure 1):

1. definition of the field of study;
2. database selection,
3. research criteria adjustment,
4. codification of recovered material and
5. examination of the information.

Definition of the field of study. As stated in the introduction section, there is a need to provide academics and professionals with a literature review on artificial intelligence applied to new building techniques, particularly green and smart buildings. Consequently, the field of study will be “the relevance of the use of Artificial Intelligence techniques in Green/Smart Buildings”.

Database selection. To reduce the risk of omitting relevant manuscripts during the search, this work used the two major scientific databases, i.e., Web of Science (WoS) and Scopus. It is true that Scopus encompasses approximately 84% of articles that can be found in WoS; however, this data may vary according to the area of study. Likewise, the Scopus database includes more indexed journals than WoS [27], therefore the use of both databases enables the consideration of a broader framework of documents.

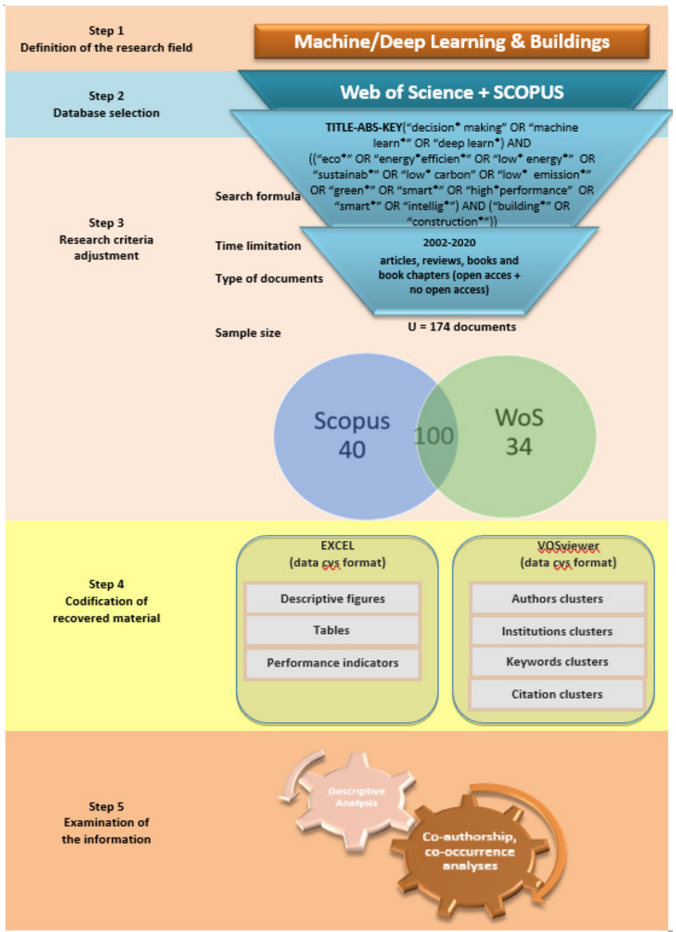


Fig. 1 Five steps bibliometric analysis methodology.

Research criteria adjustment. In an effort to be as unrestrictive as possible, a wide range of keywords were used for the search. The following parameters were employed to retrieve the search: "TITLE-ABSTRACT-KEYWORD ("decision* making" OR "machine learn*" OR "deep learn*) AND (("eco*" OR "energy*efficien*" OR "low* energy*" OR "sustainab*" OR "low* carbon" OR "low* emission*" OR "green*" OR "smart*" OR "high*performance" OR "smart*" OR "intellig*") AND ("building*" OR "construction*"))". In terms of the search period, once again, to avoid being restrictive and to keep the data as up-to-date as possible we decided to include documents published up to December 2020; i.e. the search was conducted in January 2021 and the selected study period was from 2002 to 2020 since the first paper was published in 2002. On the other hand, as to the type of documents included and excluded for this research, we have included original articles, book chapters, books, review articles and full proceedings articles published in double-blind review journals. This means that, in maintaining our policy of not being too restrictive, we have only excluded abstract proceedings. One hundred

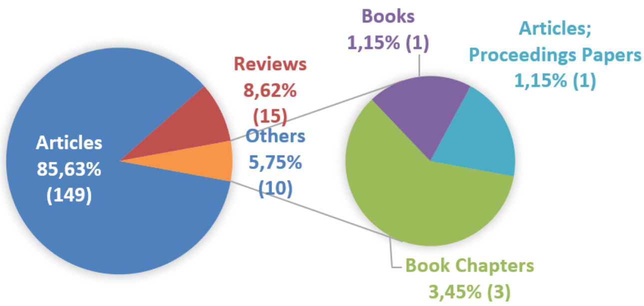


Fig. 2 Type of publication (2002-2020). Source: own elaboration with Web of Science and Scopus databases (2020).

thirty four documents were located in the Web of Science database and 140 in Scopus. After excluding the duplicated documents, the final sample consisted of 174 manuscripts, covering both in the database literature.

Codification of recovered materia. Data was downloaded from both databases (WoS and Scopus) in csv and ris formats and codified using Excel (version 2013). The combination of these two tools allowed the coding of data for the calculation of performance indicators (e.g., h-index), the identification of productivity indicators, the elaboration of tables, the illustration of descriptive graphs, and the processing of data prior to the use of bibliometric software.

Examination of the information. As mentioned in the fourth step, the examination of part of the information (e.g., calculation of performance indicators or the identification of productivity indicators) was carried out using Excel (e.g., calculation formulas). However, given the focus and main objective of this research, a decision was made to use one of the most powerful bibliometric software programs (VOSviewer, v1.6.9) for the illustration, visualization and discovery of scientific maps [39] [38]. VOSviewer is a widely used bibliometric tool for creating spatial representations that facilitate the understanding and interpreting of linking networks between keywords, authors, institutions, countries and journals [8] [10].

3 Descriptive Analysis

Bibliometric analyses are very helpful in understanding the literature structure of a scientific discipline. These types of studies provide a complete picture of the main characteristics of the production in a specific field of study. Table 2 illustrates a summary of the data used to perform this study. Likewise, Figure 1 shows a breakdown of the types of publications considered for this research. As can be seen,86% (149) of documents correspond to articles, 9% (15) correspond to review articles, and 5% (10) correspond to the sum of book chapters, books, and proceedings papers Figure 2.

Table 3 shows the evolution and the main characteristics (citations, journals, countries) of articles related to the search. As can be seen, the documents have

Table 2 Summary of data. (Source: own elaboration with Web of Science and Scopus data (2020).

Data	Deep and Machine Learning in Building Constructions DML&B
Number of documents	174
Number of citations	1,453
Number of keywords	1,015
Number of journals	106
Number of authors	587
Number of institutions	287
Number of countries	50
Study time	2002 - 2020
Data sources	Scopus - Web of Science

Table 3 Main characteristics of the data used. (Source: own elaboration with Web of Science and Scopus data (2020). A: number of articles published per year; C: number of citations per year; C/A: average number of citations per article (citation total since 1992/total of articles since 1992); AU: number of authors per year; AUA: number of authors that published at least 1 article in a specific year; JA: number of journals that published at least 1 article in a specific year; IA: number of institutions that published at least 1 article in a specific year; and COA: number of countries that published at least 1 article in a specific year)

Year	A	C	C/A	AU	AUA	IA	JA	COA
2002	1	49	49.00	2	2	1	1	1
2005	1	16	16.00	2	2	1	1	1
2008	1	136	136.00	2	2	3	1	1
2011	1	0	0.00	1	1	1	1	1
2012	2	12	6.00	6	6	2	2	2
2013	1	3	3.00	4	4	1	1	1
2014	1	8	8.00	3	3	3	1	3
2015	3	2	0.67	9	9	5	3	4
2016	9	99	11.00	39	35	13	9	5
2017	9	93	10.33	25	21	11	9	5
2018	28	462	16.50	112	103	63	21	22
2019	51	440	8.63	203	200	103	38	34
2020	66	457	6.92	259	232	121	48	29
	174	**1,777**	**10.21**					

increased from one in 2002 to 66 in 2020. It should also be noted that almost 93% of the articles have been published in the last five years (2016-2020). Likewise, more than 87% of citations have occurred in articles published in the last five years, denoting the continued interest in developing this field. Figure 3 complements Table 3 by illustrating the evolutionary trend in articles and citations for this field. It reveals that the manuscripts published in 2008 received the best average citation per article (C/A=136), followed by 2002 with 49.00 and 2018 with 16.50. Moreover, analyzing the total number of authors (AU) per year (in this indicator, an author who has published more than one article may count more than once) indicates that an increasing number of authors are publishing on the subject being studied.

Likewise, to refine this indicator, we calculated the number of different authors that published at least one article in a specific year (AUA), i.e. even if an author has published more than one article, it counts as only one. For example, in 2020, 232 different authors published at least one paper on this field. Reinforcing these

Table 4 Top ten most productive journals. (Source: own elaboration with Web of Science and Scopus data (2020).)

Rank	Journal	A	C	C/A	1st A	Last A	h-index
1	ENERGY AND BUILDINGS	13	138	10.61	2016	2020	6
2	IEEE INTERNET OF THINGS JOURNAL	9	135	2.55	2016	2020	5
3	IEEE ACCESS	9	23	15	2019	2020	3
4	APPLIED ENERGY	8	158	19.75	2017	2020	6
5	ENERGIES	6	31	5.16	2018	2020	4
6	BUILDING AND ENVIRONMENT	5	145	29	2017	2020	4
7	JOURNAL OF CLEANER PRODUCTION	4	54	13.5	2017	2020	3
8	SENSORS	4	13	3.25	2019	2020	2
9	SUSTAINABLE CITIES AND SOCIETY	4	24	6	2012	2020	3
10	APPLIED SCIENCES-BASEL	3	20	6.66	2019	2020	2

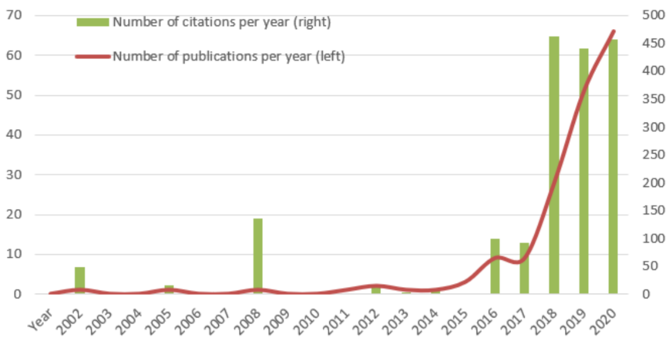


Fig. 3 Number of citations and publications per year (2002-2020). (Source: own elaboration with Web of Science and Scopus data (2020))

ideas, Figure 4, shows that an increasing number of authors, countries, institutions and journals are publishing on DML&B.

Table 4 shows the 10 most productive journals about DML&B from 2002 to 2020, these being *Energy & Building* with 13 articles, *IEEE Internet of the things Journal* and *IEEE Access* with 9 documents in both of them. However, looking at the average citations per article, the two most important journals were *Building & Environment* (29 citations per article) and *Applied Energy* (19.75 citations per article). Regarding the h-index of each journal, it can be seen that the *Energy & Buildings* and *Applied Energy*, both with a value of 6, are the highest ranked journals. Finally, it is remarkable that only in the last five years did all these journals begin publishing about green & smart buildings, denoting that this field truly is booming.

As stated in Table 5, there is no single most productive author; Zheng S.Q. and Zhou Y.K. stand out with 7 articles, 72 citations and the highest h-index, 5. However, it should be noted that the authors with the highest number of citations and highest average number of citations per article are Cheng J.C.P. and Zhou Y.X. It is worth nothing that, these ten authors have only started publishing in the last four years (2017-2020) and eight of them have published at least one article in the last year (2020). It should also be noted that five of the ten authors are

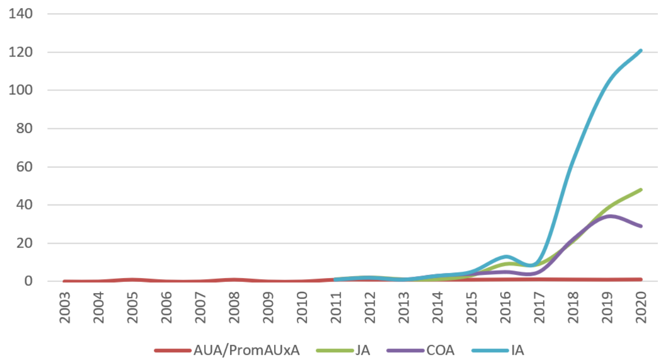


Fig. 4 Number of authors, institutions, countries and journals per year (2000-2020). (Source: own elaboration with Web of Science and Scopus data (2020)). AUA: Number of authors that published at least 1 article in a specific year; JA: Number of journals that published at least 1 article in a specific year; COA: Number of countries that published at least 1 article in a specific year; IA: Number of institutions that published at least 1 article in a specific year

Table 5 Ten most productive authors. (Source: own elaboration with Web of Science and Scopus data (2020).)

Rank	Authors	A	C	C/A	1st A	Last A	h-Index	Country	Affiliation
1	Zheng SQ	7	72	10.29	2019	2020	5	Peoples R China	City Univ Hong Kong
2	Zhou YK	7	72	10.29	2019	2020	5	Peoples R China	Hong Kong Polytech Univ
3	Zhang GQ	5	58	11.60	2019	2020	4	Peoples R China	Hunan University
4	Spanos CJ	5	59	11.8	2018	2019	3	United States	Univ Calif Berkeley
5	Ma J	4	59	14.75	2017	2020	4	Peoples R China	Hong Kong Univ Sci & Technol
6	Zou H	4	41	10.25	2018	2020	2	United States	Univ Calif Berkeley
7	Cheng JCP	3	53	17.67	2017	2020	3	Peoples R China	Hong Kong Univ Sci & Technol
8	Zhou YX	3	41	13.67	2018	2019	2	United States	Univ Calif Berkeley
9	Zhang W	3	19	6.33	2018	2020	2	Singapore	Singapore Institute of Technology
10	Wen YG	3	19	6.33	2018	2020	2	Singapore	Nanyang Technol Univ

affiliated to Chinese universities and three to American universities. Once again, Asia (People's Republic of China and Singapore) and the United States stand out in this study area.

[2] state in their work that it is not only of interest to analyze the productivity of researchers, but also the collaborative networks that are formed, both intra-institutional and inter-institutional, or intra-national and inter-national. For these purposes, considering three or more scientific works in common (Figure 5), it is possible to detect the following three scientific networks of different collaborations (Table5):

1. Network 1 (interinstitutional & international): The scientific network with the greatest scientific productivity (seven documents) is intrainstitutional and intranational in its origins, located in Peoples R. China and led by two of the most productive authors that figure in Table 4, Zheng S.Q. and Zhou Y.K., affiliated with City University Hong Kong and Hong Kong Polytechnology University, respectively. This network then grew with the adition of two new members (five documents), Zhang GQ from the University of Hunan and Spanos C.J. from the University of California at Berkeley (United States), transforming the network into an inter-national one. Finally, the inclusion of Zou H from University of California - Berkeley broadened the North American branch.
2. Network 2 (interinstitutional & intranational): In importance it is followed by the inter-institutional and intranational network (three documents) located in Singapore and comprising Zhang W. from the Singapore Institute of Technology and Wen Y.G. from Nanyang Technology University.
3. Network 3 (interinstitutional & international): this network comprises Amayri M. affiliated to Concordia University (Canada) and Bouguila N. from Grenoble Institute of Technology (France).

The Chinese network, Zheng S.Q. and Zhou Y.K. (network 1), shows the most recent scientific activity (Figure 6), together with the French-Canadian network (network 3).

Table 6 displays the main indicators of the ten most productive academic institutions on DML&B research from 2002 to 2020. As can be observed, Asian and American universities are the most important for the development of this field. Just one university, *Grenoble Institute of Technology* (France) is located outside both Asia and the United States. The *Nanyang Technological University* of Singapore is ranked top with 12 manuscripts. This is followed by the *Hong Kong Polytechnology University* of the People's Republic of China with 11 papers but with the highest h-index, 8. The *Western Michigan University* had the most citations (C), with 193 and the most average citations per articles (C/A) with 64.33. It is worth noting that 5 of the top-10 countries began publishing about DML&B 5 years ago (2015-2019). Finally, it is worth highlighting that the majority of academic universities have started publishing on this subject in the last four years (2017) with the exception of the *Carnegie Mellon University* in 2012.

The organizational networks that are investigating this topic (except those mentioned above) are not made up of consolidated teams but just come together for occasional joint research. The inter-organizational network formed at international level, which studies DML&B, can be divided into two main clusters, considering six or more scientific works in common (Figure 7). The red cluster is the most productive cluster, composed of Chinese institutions and linked through the Hong Kong Polytechnic University to the American green cluster. The red cluster is led by the research center with the second highest production at global level, the *Hong Kong Polytechnic University* from the People' s R. China (Table 6). This institution is directly linked with other Chinese universities (*City University of Hong Kong and Hunan University*) and intercontinentally with *Carnegie Mellon University* from the United States. Finally, the smallest blue cluster is formed by another inter-national network, the most productive organization, the *Nanyang Technology University* from Singapore and the *University of California – Berkeley* from the United States. In the time perspective, the Chinese universities are

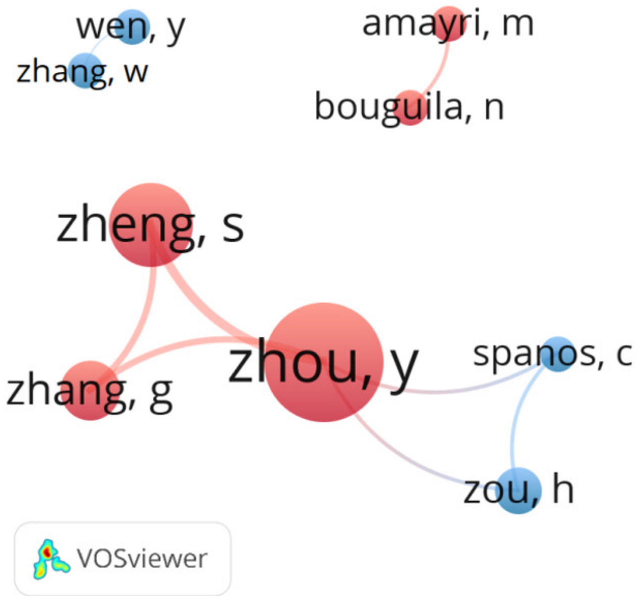


Fig. 5 Authors networks. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software (minimum 3 documents))

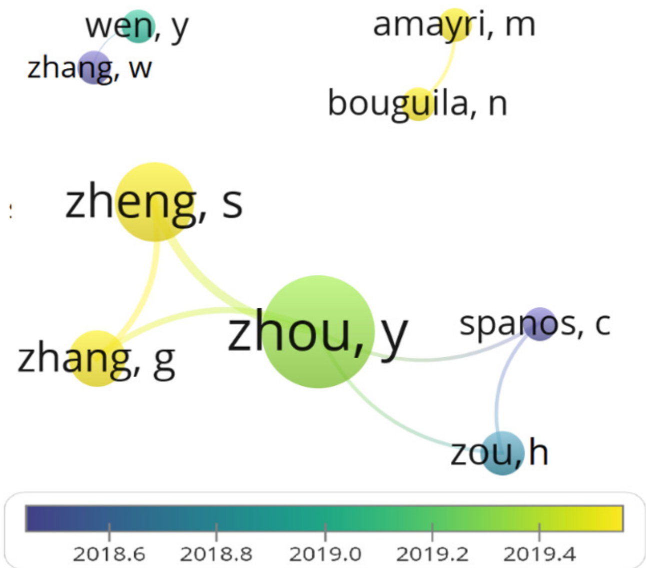


Fig. 6 Temporal evolution of authors networks. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software (minimum 3 documents))

Table 6 Ten most productive institutions. (Source: own elaboration with Web of Science and Scopus data (2020).)

Rank	Institution	Country	A	C	C/A	1st A	Last A	h-Index
1	Nanyang Technol Univ	Singapore	12	116	9.67	2017	2020	6
2	Hong Kong Polytech Univ	Peoples R China	11	121	11.00	2017	2020	7
3	Hunan Univ	Peoples R China	10	112	11.20	2019	2020	8
4	City Univ Hong Kong	Peoples R China	9	88	9.78	2019	2020	6
5	Univ Calif Berkeley	United States	7	157	22.43	2018	2020	4
6	Carnegie Mellon Univ	United States	6	12	2.00	2012	2020	1
7	Grenoble Inst Technol	France	4	12	3.00	2019	2020	2
8	Western Michigan Univ	United States	3	193	64.33	2018	2019	3
9	Shenzhen Univ	Peoples R China	3	54	18.00	2019	2020	3
10	Univ Houston	United States	3	10	3.33	2018	2020	2

reporting the most recent scientific activity (Figure 8), *City University of Hong Kong* and *Hunan University*.

Table 7 shows the key indicators of the 10 most productive countries in DML&B from 2002 to 2020. The *United States of America* stands out in first place with 50 manuscripts, followed by the *People's Republic of China* with 41 articles, and *Singapore* with 28. Of these 10 most productive countries, 4 are located in Asia, 4 in Europe, and 2 in North America, which shows that this is a topic of interest in various regions of the world. As another interesting characteristic, Table 7 also illustrates the population of each country which makes it possible to calculate the number of articles published per million inhabitants of each country (AP). Looking at this indicator, *Singapore* is the country with the best average with 3.19. On the other hand, *India*, had the lowest average, 0.01. The *United States* had the largest number of total citations (C) and average citations per article (C/A), with 705(14.10), followed by *the People's Republic of China* with 443(10.80), and *Singapore* with 443(9.00). Finally, Table 7 illustrates the first year (1st A) and the last year (Last A) that these countries published at least one article about the topic being researched. Countries such as the *United States* and *Singapore* have had early publications, in 2008 and 2012 respectively, while other countries such as the *United Kingdom, Canada* and *India* began publishing more recently, in 2018. In 2020, all the listed countries continued publishing on DML&B. Finally, looking at the h-Index indicator, we see that *the United States* is once again stands out in first place with 13, followed by *the People's Republic of China* with 12 and *Singapore* with 8, which highlights these countries as the most important for developing the subject being studied.

If we analyse the structure of the research at country level, taking into account eight or more documents in common, one cluster can be noted (Figure 9). The most productive country, the United States, leads the green group and it is directly related to the People's Republic of China and Singapore. The red group is the most numerous, made up mostly of Asian countries (South Korea and India), European countries (Spain and France), and Canada. Finally, the smallest blue

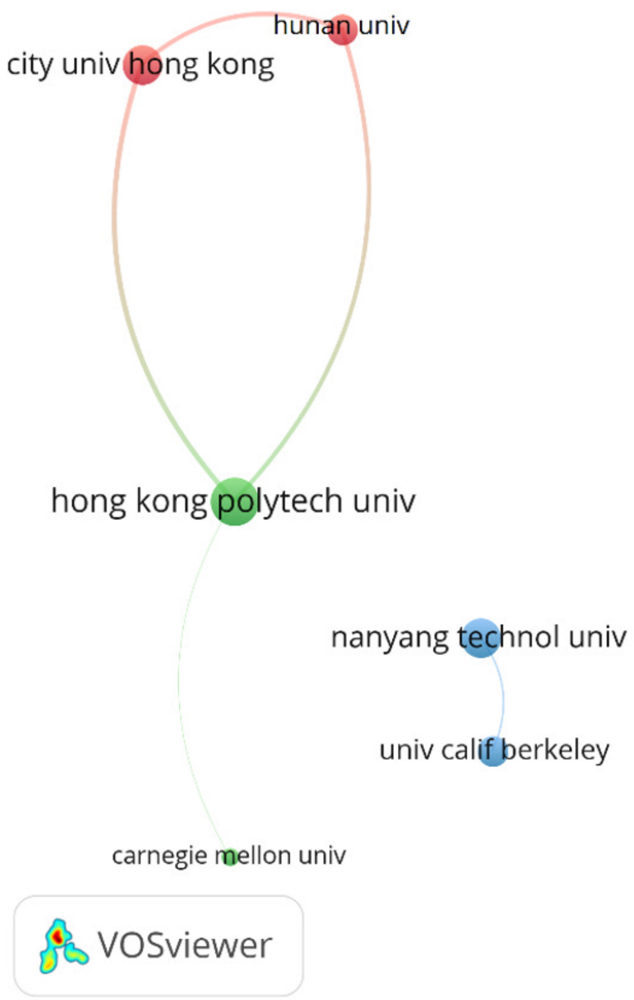


Fig. 7 Institutions networks. (Source: own elaboration with Web of Science and Scopus data (2019) processed with VosViewer software)

Table 7 Top ten most productive countries. (Source: own elaboration with Web of Science and Scopus data (2020).)

Rank	Country	A	P	AP	C	C/A	1st A	Last A	h-Index
1	United States	50	327,096,265	0.15	705	14.10	2008	2020	13
2	Peoples R China	41	1,420,062,022	0.03	443	10.80	2015	2020	12
3	Singapore	18	5,638,709	3.19	162	9.00	2017	2020	8
4	United Kingdom	13	66,959,016	0.19	35	2.69	2018	2020	5
5	South Korea	12	51,339,238	0.23	43	3.58	2012	2020	5
6	Spain	10	46,441,049	0.22	29	2.90	2017	2020	4
7	Canada	9	37,279,811	0.24	24	2.67	2018	2020	4
8	France	7	65,480,710	0.11	21	3.00	2014	2020	3
9	India	7	1,368,737,513	0.01	14	2.00	2018	2020	2
10	Italy	6	59,216,525	0.10	24	4.00	2013	2020	3

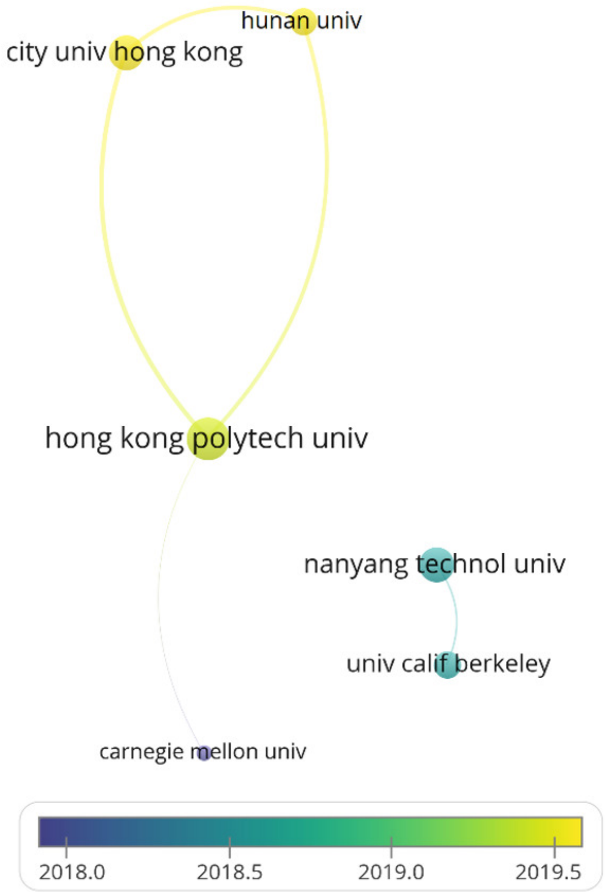


Fig. 8 Temporal evolution of organization networks. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software (minimum 6 documents))

group, comprising the United Kingdom and Italy, has a direct and strong association with the United States and the People's Republic of China. The country which shows scientific activity in the countries network (Figure 10) is the United Kingdom.

According to *Liao et al* (2018) [21], analysing the number of citations per article, reveals the quality of a manuscript. Table 8 therefore illustrates the ten most cited papers about DML&B research. The manuscript by *Brown H.S.* and *Vergragt P.J.* (2008) [5] ranks first with 136 citations, followed by the article by *Kim et al* (2018)[20] with 98 citations and then *Mohammadi et al* (2018) [26] with 80 citations. However, it is worth remarking that not only the number of citations is important. As such, in an attempt to diminish the relative advantage of the years that have passed since the publication of older articles (and have therefore had more years to be cited), the average number of citations per year (C/A) received by each of the manuscripts was calculated. When putting the 10 most cited articles on this subject under the magnifying glass of the indicator (C/A), it can be seen that the most representative articles are those from *Liu et al* (2019) [22] with 80 citations per year. Finally, it should be noted that only one journal (*Applied Energy*), possesses more than 103 citations.

A review of the published literature on Artificial Intelligence based short term load forecasting techniques is discussed in *Brown* and *Vergragt* (2008) [5] to demonstrate the current application of Artificial Intelligence techniques for effective load forecasting to achieve an approach towards the integration of smart grid and smart buildings. In *Kim et al* (2018) [20] indoor environmental quality (IEQ) simulation of conditions was carried out on “Green” and “Conventional” buildings to evaluate and compare the impacts on human higher-order cognitive function. This simulation clearly demonstrates better human cognitive function performances for ”Green” buildings than ”Conventional” buildings. Mohammadi et al (2018) [26] addressed. Finally, *Liu et al* (2019) [22] put forward an analysis and categorization of the existing environmental assessment tools.

4 Content Analysis

The 25 most frequently used keywords during the period 2002-2020 are shown in Table 9 in two different sub-periods. During the entire period, the most used keyword was *Machine Learning*. It appeared in 65 documents, i.e., in more than 37% of the published documents. Furthermore, it is the most used term in the second sub-period. Other most used terms in the whole period were *Smart building*, *Deep Learning*, *Internet of Things (IoT)* and *system*. Regarding the sub-period 2002–2015, and leaving aside smart building mentioned above, other relevant terms used were *artificial intelligence, energy consumption, simulation, energy, green building,* and *intelligent building*.

In the last sub-period, 2016-2020, some terms emerged at a quickening rate, such as *Machine learning, Deep Learning,* and *Internet of Things*. None of these terms appeared during the first sub-period, which demonstrates the recent use of Artificial Intelligence techniques to achieve *energy efficiency* in buildings. These AI techniques are applicable to *smart or intelligent buildings* where, through the implementation of a *learning machine*, the buildings can be equipped with the capacity to forecast energy and natural resource consumption, which allows us to increase *energy efficiency* and reduce operational costs. Finally, in recent years, governments and regulatory agencies around the world have sharpened their focus on smart *or intelligent* buildings based on the *Internet of Things* concepts [25].

Furthermore, other keywords displaying greater consolidation from the first sub- period to the second one were *intelligent buildings* and *energy conservation.* From the first sub-period to the second, research on intelligent or smart buildings arose in response to the need for *energy conservation* through *energy efficiency in buildings*, especially in office buildings where it is a primary goal for companies to reduce energy consumption and maintenance costs. In intelligent or smart buildings, building automation is a centralized and automatic system that controls a building's energy systems and is used to improve the comfort of its users and to reduce energy consumption and operating costs.

Complementing Table 9, Figure 11 shows the relation networks between keywords (co-occurrence analysis), which help to identify important knowledge areas

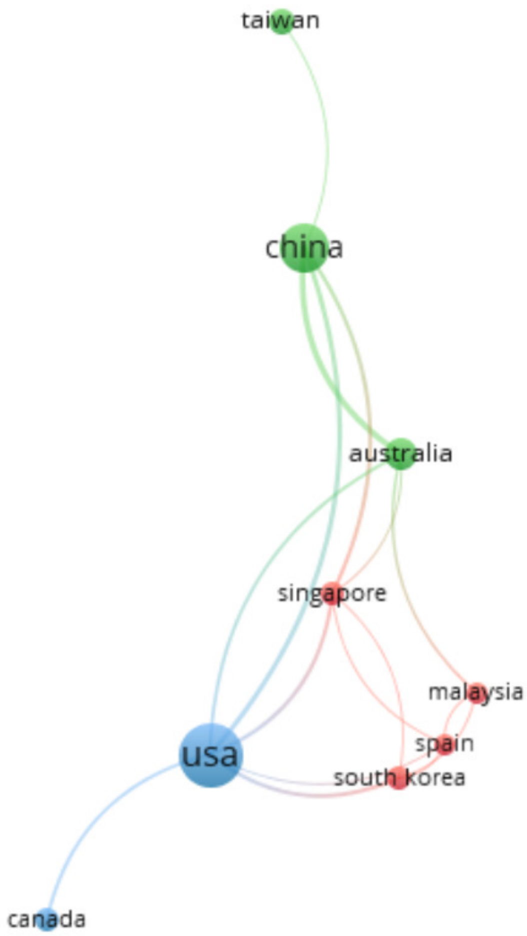


Fig. 9 Country networks. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software.(minimum 8 documents))

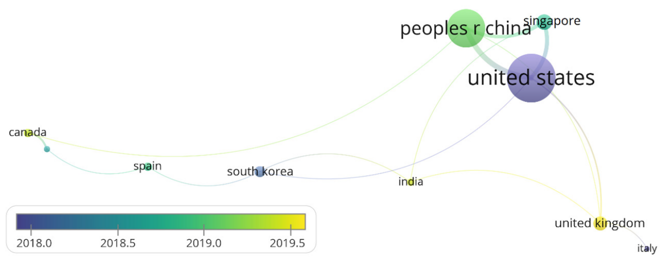


Fig. 10 Temporal evolution of country networks. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software.(minimum 8 documents))

Table 8 Ten most cited articles. (Source: own elaboration with Web of Science and Scopus data (2020).)

#	Title	Author/s	Journal	C	Year	C/A
1	Bounded socio-technical experiments as agents of systemic change: The case of a zero-energy residential building	Brown, HS; Vergragt, PJ	TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE	136	2008	11.3
2	Personal comfort models - A new paradigm in thermal comfort for occupant-centric environmental control	Kim, J; Schiavon, S; Brager, G	BUILDING AND ENVIRONMENT	98	2018	49.0
3	Semisupervised Deep Reinforcement Learning in Support of IoT and Smart City Services	Mohammadi, M; Al-Fuqaha, A; Guizani, M; Oh, JS	IEEE INTERNET OF THINGS JOURNAL	93	2018	46.5
4	Intelligent Edge Computing for IoT-Based Energy Management in Smart Cities	Liu Y., Yang C., Jiang L., Xie S., Zhang Y.	IEEE Network	80	2019	80.0
5	Using machine learning techniques for occupancy-prediction-based cooling control in office buildings	Peng, YZ; Rysanek, A; Nagy, Z; Schluter, A	APPLIED ENERGY	63	2018	31.5
6	Institutional barriers to sustainable construction	van Bueren, EM; Priemus, H	ENVIRONMENT AND PLANNING B-PLANNING & DESIGN	49	2002	2.7
7	A hybrid model approach for forecasting future residential electricity consumption	Dong, B; Li, ZX; Rahman, SMM; Vega, R	ENERGY AND BUILDINGS	49	2016	12.3
8	Assessment of deep recurrent neural network-based strategies for short-term building energy predictions	Fan, C; Wang, JY; Gang, WJ; Li, SH	APPLIED ENERGY	42	2019	42.0
9	A Novel Approach for Evaluation of Projects Using an Interval-Valued Fuzzy Additive Ratio Assessment (ARAS) Method: A Case Study of Oil and Gas Well Drilling Projects	Dahooie, JH; Zavadskas, EK; Abolhasani, M; Vanaki, A; Turskis, Z	SYMMETRY-BASEL	39	2018	19.5
10	A Novel Ensemble ELM for Human Activity Recognition Using Smartphone Sensors	Chen, ZH; Jiang, CY; Xie, LH	IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS	39	2019	39.0

in this research field. Figure 11 illustrates five clusters of keywords; there is heterogeneity between each cluster but homogeneity within them.

Of the five clusters, two stand out for containing the main keywords of the research. The yellow cluster contains "smart building" as a central node and the red cluster contains "machine learning" and "green building".

Machine learning and Green building. In a green or sustainable building, the a primary target is energy efficiency. By means of decision-making systems based on machine learning, algorithms, this goal can be achieved and extended to include user comfort (which is also an objective of green buildings). These decision-making

Table 9 The most used keywords. (Source: own elaboration with Web of Science and Scopus data (2020).)

Rank	Keywords	2002-2020		2002-2015		2016-2020	
		A	**%**	**A**	**%**	**A**	**%**
1	**Machine learning**	65	37.36%			65	39.88%
2	**Smart building**	63	36.21%	1	9.09%	62	38.04%
3	**Deep learning**	34	19.54%			34	20.86%
4	internet of things	32	18.39%			32	19.63%
5	system	25	14.37%			25	15.34%
6	energy efficiency	23	13.22%			23	14.11%
7	neural network	21	12.07%			21	12.88%
8	building	21	12.07%			20	12.27%
9	prediction	19	10.92%			19	11.66%
10	artificial intelligence	17	9.77%	1	9.09%	16	9.82%
11	artificial neural network	16	9.20%			16	9.82%
12	model	15	8.62%			15	9.20%
13	optimization	15	8.62%			15	9.20%
14	performance	15	8.62%			15	9.20%
15	thermal comfort	14	8.05%			14	8.59%
16	energy consumption	12	6.90%	1	9.09%	11	6.75%
17	simulation	12	6.90%	1	9.09%	11	6.75%
18	algorithm	11	6.32%			11	6.75%
19	design	11	6.32%			11	6.75%
20	energy	11	6.32%	1	9.09%	10	6.13%
21	**Green Building**	11	6.32%	1	9.09%	10	6.13%
22	**Intelligent Building**	11	6.32%	1	9.09%	9	5.52%
23	support vector machine	10	5.75%			10	6.13%
24	smart home	9	5.17%			9	5.52%
25	smart city	9	5.17%			9	5.52%
	Number of documents	174	8.87%	11		163	

systems will consist of learning machines that generate inference rules for the system's integrated as well as automated management and control. These inference rules will be executed in the system to achieve energy efficiency and user comfort inside smart buildings.

Smart building, Internet of Things, Smart city and Energy efficiency. Smart buildings and smart houses provide some of the main fields of application for Internet of Things technologies focused on energy efficiency (smart management of consumption of water, gas and electricity), user comfort and security systems [41]. On the other hand, the IoT connection in smart buildings and smart houses will be able to achieve the transition from current cities to future smart cities.

The remaining clusters (Figure 11), such as the violet cluster, are mainly relating to deep learning technique, e.g. sensors and their relationship with systems. The green cluster mainly invloves some general keywords focused on machine learning algorithms and Artificial Intelligence, such as Artificial Neural Networks, algorithms, big data, prediction and model. Finally, the most common keywords leading the blue cluster are building, performance, optimization and ventilation, i.e. this cluster is closely related to the yellow cluster.

Figure 12 shows the connection of different clusters and how they are linked to the main research formula keywords [11].

Smart buildings and Intelligent buildings. The red cluster mainly encompasses keywords related to "machine learning", associated with "intelligent buildings". Smart and intelligent buildings are different terms for the same definition. In previous decades, only the term smart buildings was used, but in recent years the two terms are becoming used more interchangeably.

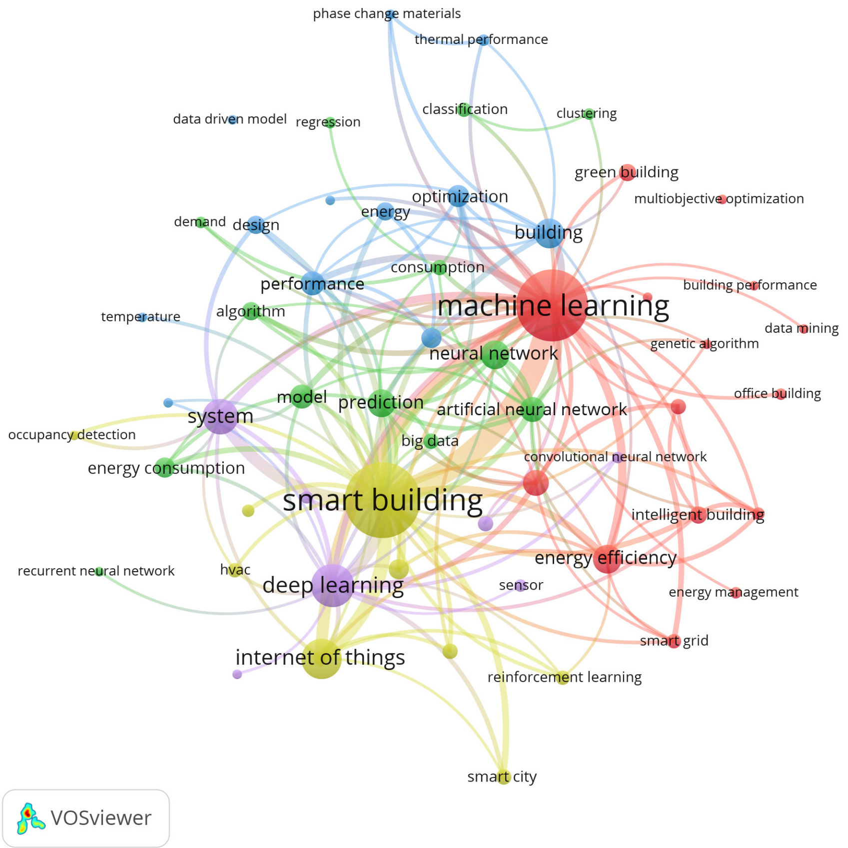


Fig. 11 Keywords clusters. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software)

Machine learning, Smart or intelligent building. Smart or intelligent buildings are those buildings whose facilities and systems (air conditioning, lighting, electricity, security, etc.) allow integrated as well as automated management and control in order to increase energy efficiency, comfort and safety. Smart buildings successfully fuse building management and control systems so that system performance can be dynamically optimized and facility operations can be simplified. From an Artificial Intelligence perspective, smart buildings are those in which energy management and the conservation system are integrated with Artificial Intelligence techniques. To be more precise, these techniques are methodologies that are based on machine learning algorithms. In other words, we can affirm that machine learning contributes via Artificial Intelligence to how smart or intelligent buildings are.

For its part, Figure 13 shows the temporal evolution of the use of keywords. This type of network allows us to analyze which keywords have been most used in the past as well as more recently, which in turn facilitates the identification of possible future lines of research. Although the first article identified according to the applied search formula [23] suggested that for the successful development of an

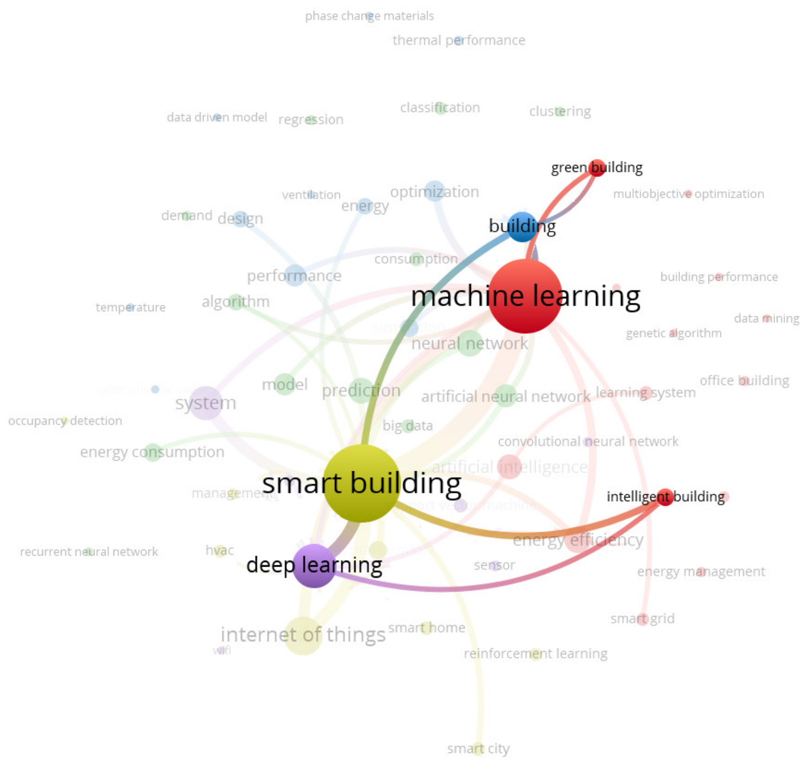


Fig. 12 Main connections between green and smart building clusters. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software).)

information -rich urban policy, more than just 'smart' buildings or the provision of Internet access were needed.

Deep learning is a subset of machine learning based on multi-layer neural networks [32]. Brown and Vergragt (2008) [5] introduced deep learning to analyze people's behavior and how to improve sustainability by means of technology and deep learning. In Mohammadi et al (2018)[26], deep reinforcement learning was applied to people indoor localization, because it is a fundamental problem for smart city services. Finally, in Fan et al (2019) [15] strategies for building energy predictions were addressed through the use of deep learning networks.

4.1 Temporal keywords analysis focus on Benefit categorization

Sustainable design and construction can provide economic, environmental and social benefits that are the result of careful consideration of resource use and how the buildings will affect the environment. According to a temporal analysis of keywords related to the categorisation of the different benefits provided by sustainable design and construction, environmental benefits were the first to be investigated. The keyword network characterised by terms associated with environmental ben-

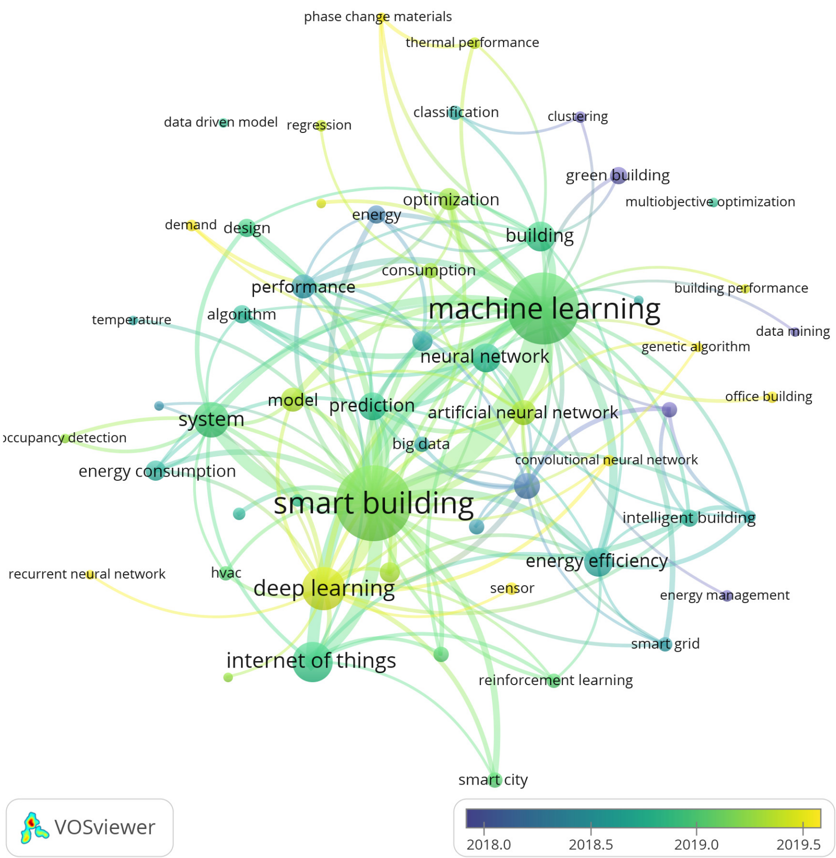
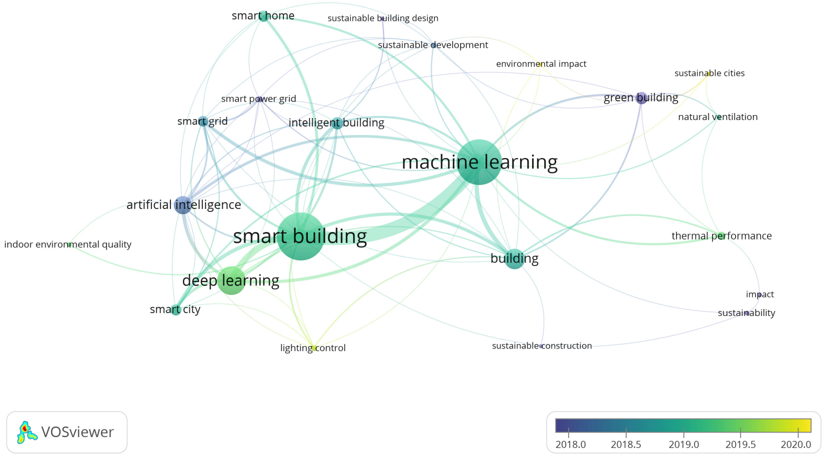


Fig. 13 Temporal evolution of keywords used. (Source: own elaboration with Web of Science and Scopus data (2020) processed with VosViewer software).

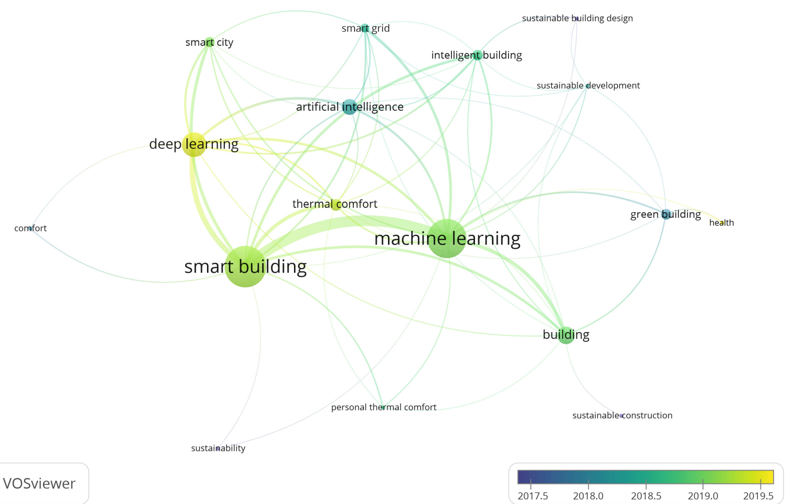
efits is predominantly blue-green, covering the period 2017-2018 (Figure 14(a)). Then, social benefits were manifested in the scientific outputs (2018-2019) with a yellowish-green network (Figure 14(b)). Finally, economic benefits are the most recently addressed topic, with a fully yellow grid from 2019 onwards (Figure 14(c)).

In the environmental benefit analysis shown in Figure 14(a), environmental impact relates directly to green buildings and sustainable development, together with sustainable building design. In contrast, indoor environmental quality and the lighting control are related to smart buildings. Finally, thermal performance is associated with green buildings and the application of machine learning techniques.

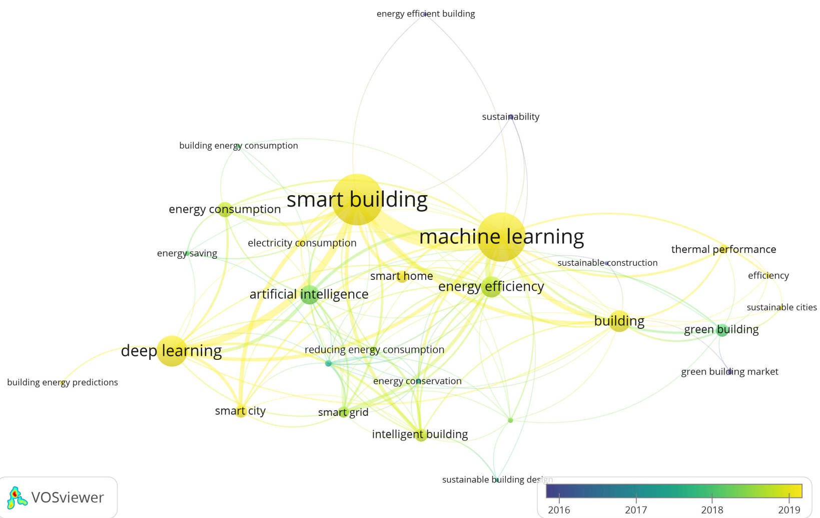
In the study focused on social benefits, Figure 14(b), the relationship between sustainable development and sustainable cities and green buildings stands out. Where the wellbeing of the people who work in green offices or live in green homes [40] highlights the direct relationship between green buildings and health. There is also the study of comfort, thermal comfort and personal thermal comfort, linked to artificial intelligence through the application of machine/Deep learning approaches, typical of smart buildings.



(a)



(b)



(c)

Fig. 14 Keyword analysis in Benefit categorization.

The analysis of keywords related to the economic benefits, Figure 14(c), highlights the study of electricity consumption, energy consumption, building energy consumption, to obtain energy efficiency and energy efficient buildings in order to obtain reduced energy consumption and energy saving. Coinciding with those exposed who exposed that the cost of energy consumption is perhaps the most immediate economic benefit in a green building design, due to the implementation of efficiency and consumption strategies that are fundamental parts of any green building. All these energy saving strategies are also intimately linked to the application of machine/Deep learning approaches, typical of smart and intelligent buildings, emphasising building energy predictions with Deep learning tools exclusively.

5 Conclusion

The purpose of this work is to highlight the evolution over the last two decades (2002-2020) of research topics related to the concepts of sustainable development and the construction of the latest generation of buildings. Given the relevance of the use of Artificial Intelligence in smart, intelligent, green buildings and in order to identify the main details of a research topic, to identify the most productive agents in the research field such as authors, institutions, or countries, a bibliometric analysis was carried out. To date, the bibliometric analyses that have been published in the scientific literature only refer to the analysis of the different types of state of the art buildings(ecological, energy-efficient, energy-saving, low energy, smart, sustainable, low carbon, low emission, green and high-performance buildings) without any relationship to the technology applied. In this regard, a bibliometric analysis of green and smart buildings regarding artificial intelligence tools used covers a research gap in the scientific literature. Finally, with respect to the main contribution of this study, it can be stated that it extends previous review works by widening the research period and encompassing the two main scientific databases (WoS and Scopus). Accordingly, the analysis covers almost all the entire sample universe of peer-reviewed documents. This review covers the entire universe of peer-reviewed articles, comprising 174 papers. If only the use of scopus or web of science had been taken into account, the universe of indexed articles would not have been fully covered, excluding between 20 and 23% of the documents.

At global level, the American scientists are the most productive researches, but at institutional level Singapore stands out (Nanyang Technol University), with strong links to the University of California Berkeley from the United States. Two of the five main contributing countries with high quality production in terms of this research topic being analyzed (United States, People's Republic of China, Singapore, United Kingdom and South Korea) are also the leaders of one international collaborative network (Peoples Rep. China & United States). This international research network with the greatest scientific productivity is led by two of the most productive authors (Zhou Y.K. and Zheng S.Q.), both from Hong Kong and affiliated to Hong Kong Polytech University and City University Hong Kong, respectively. This work has focused on the scientific publications from the last eighteen years, encompassing different disciplines, reflected in the knowledge areas covered by the top ten journals focusing on energy, environment, cleaner production, sensors and Internet of things. The growing scientific production focused on artificial intelligence applied to the new generation of buildings is thereby demonstrated.

Also, as result of this work, it can be observed that the number of publications referring to smart buildings and the different related areas have seen a sharp increase between 2017 and 2020. This conclusion leads us to anticipate a significant increase in the short term future, both in research and development, regarding the use of smart buildings as a very important tool with which to achieve sustainable development based on energy efficiency. At the time evolution of the scientific production about artificial intelligence applied to building construction, environmental benefits were the first to be analysed. Economic benefits are the most immediate benefits to be identified, but the latest to be the focus of attention. As per future lines of research, the bibliometric analysis presented in this work will be extended to a systematic review, expanding the search to "green building", "sustainable building", "smart building" and "intelligent building" and selecting the most relevant articles in order to detect the most pertinent AI techniques applied, leading to the identification of certain research gaps in this field. Other potential future research lines, we would like to explore are the thematic relationships within the fields of sustainable building and the application of Industry 4.0, through artificial intelligence, focusing on the analysis of technological production according to worldwide published patent databases. Industry 4.0 is an expanding interdisciplinary field in which interactions between science and technology (S&T) are increasingly intensifying with a strong link to sustainable development. The state of the art technology will show that in the field of sustainability in building construction oriented to Industry 4.0, some topics are exclusively in basic science, others only in the technological area, and also others interact between science and technology. Analysis of patentable subject-matter is gaining momentum in economic analysis and scientific research with the rapid growth of intellectual property applications worldwide. However, there does not seem to be a corresponding increase in patent research publications, especially in the category of scientometrics and information science.

6 Declarations

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6.4 Conflict of interest

The authors declare that they have no conflict of interests.

6.5 Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

6.6 Informed consent

Informed consent was obtained from all individual participants included in the study.

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