Mapping two decades of smart home research: a systematic scientometric analysis

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Mapping Two Decades of Smart Home Research: A Systematic Scientometric Analysis

Abstract: Technological advancements such as information and communication technologies (ICTs), artificial intelligence (AI), internet-of-things (IoT), and the increasing popularity of the smart city and smart living movements during the last couple of decades boosted the developments in the smart home domain. Although the number of smart home related research has been expanding rapidly, there is still a lack of systematic analysis of the evolution of this research domain. This study helps to generate an understanding of the historical vicissitude, state-of-the-art and emerging trends, and the existing smart home research clusters. The study applies a scientometric method to analyse the published scholarly research (n=17,153) over the last two decades, from 2000 to 2021. The scientometric analysis findings reveal that: Smart home literature has experienced steady growth during the last two decades; Smart home research has mainly clustered around ICT for home automation, home information management, AI for home automation, domestic energy management, IoT for home automation, and home-based healthcare areas; IoT is seen as the most popular technology to realise fully functioning smart homes; Limited evidence exists on the urban perspective and social issues of smart home technology; Smart homes are seen potentially as a strong driver of the smart city agenda.

Keywords: smart home; home automation; home innovation; domotics; internet-of-things (IoT); artificial intelligence (AI)

1. Introduction and Background

Due to the technological advancements taking place in recent decades—especially developments in the smart urban technology domain (Lee et al., 2008; Metaxiotis et al., 2010)—, today the digital technology uptake in homes has become a common practice (Oliveira et al., 2020; Yigitcanlar et al., 2020a). Initially, the home is a private space, which provides occupants with a residence and allows them to act out the different roles and carry out their daily activities within this space (Marikyan et al., 2021). With the advance of wireless technology, this 'truly revolutionary paradigm shift' brings new possibilities to the home domain (Zhao et al., 2018). Wireless technology provides a barrier-free means of multimedia communication between people and domestic appliances and supports the advance of further innovations, such as smart homes (Goldsmith, 2005). Later, the emergence and development of the internet-of-things (IoT) have given smart homes more intelligent and more interconnected abilities to automate the home (Almusaylim & Zaman, 2019). Besides, with the integration of multifarious technological innovations and smart homes—e.g., ubiquitous computing, augmented reality, artificial intelligence (AI)—the concept of smart home has been evolved from the domotics to the smart home, later to the IoT, and more recently to the smart living (Solaimani et al., 2015; Yigitcanlar et al., 2020b). Nowadays, the smart home has arisen as the cornerstone of providing residents with security, convenience, comfort, energy efficiency and entertainment and enhancing their lifestyle and domestic life (Sovacool & Del Rio, 2020; Li et al., 2021).

The origin of the concept of smart homes dates back to the 1970s with the release of X10, a home automation platform that sends digital information through radio frequency bursts onto a home's existing electrical wiring (Kravchenko et al., 2017). Nevertheless, there were not many comprehensive examples of smart homes technologies until 1984. In the 1980s, the term 'intelligent building' was first used by United Technology Corporation (UTC) in the US. The 'building systems', a subsidiary of UTC, applied this concept to CityPlace Building in Hartford, Connecticut, to carry out a partial renovation project. The CityPlace Building is the world's first architectural project that integrated information technology into a building by adopting the computer system to monitor and control the air-conditioning, elevators, lighting, and other equipment of the entire building and providing information services such as e-mail, voice communication, and intelligence materials (Marcus, 1983; Omar, 2018). Since then, the idea of integrating information technology into the building has evolved from conception into practical application, which started the 'smart city or smart living' era of buildings (Mohammadi & Hammink, 2016; Yigitcanlar et al., 2019).

To date, apart from the original vision of providing users with convenience and comfort through general home automation services in daily living, the practical applications of smart homes are extended to the various domains of people's lives, such as security, energy, and healthcare (Chan et al., 2008; Alaa et al., 2017; Marikyan et al., 2019). In the home security domain, smart homes detect environment change with embedded sensors to identify potential threats and take autonomous actions based on the built-in response programs, which aims to maintain the safety of residents and their living environment (Dahmen et al., 2017; Pandya et al., 2018). In the domestic energy domain, smart homes provide remote monitoring and management functions to allow and assist users in optimising the household's daily energy consumption, which is purposed to improve household energy efficiency and reduce consumption (Fan et al., 2017; Ford et al., 2017). In the home-based healthcare domain, smart homes offer ambient assisted living (AAL) by creating a home-based care platform, which can assist healthcare decisions made and provide users with daily assistance via different smart devices (Choi et al., 2019; Sapci & Sapci, 2019). Besides, smart homes are widely applied to create an enjoyable, comfortable, aesthetically elegant, and safe living environment, which provides residents with the 'pleasance', i.e., "the sensory, effective and satisfying dimensions of everyday life" (Strengers & Nicholls, 2017; Strengers et al., 2020, p.6).

Nonetheless, even the smart home is widely practised in various domains of people's lives, there is still no broad consensus on what the smart home really represents, and what its future development trends are. As Solaimani et al. (2015) and Sovacool & Del Rio (2020) indicated, people's immensity and diversity of attention on smart homes or smart living developments and increasing market size had caused an ever-growing but a dispersed body of literature. During the last few decades, expanding practical applications in different fields have given the smart home numerous extensional definitions or visions across different perspectives from disciplinary, practice or conceptualisation-orientation to domain-orientation (Marikyan et al., 2019; Sovacool & Del Rio, 2020). Dahmen et al. (2017) highlighted that the smart home should provide a secure and healthy living environment to the residents and can warn and protect them and their homes from any kind of threats. Bennett et al. (2017) signified that the smart home should undertake the role of "improving the health and well-being of its occupants and assisting in the delivery of healthcare services" (Bennett et al., 2017, p.2). Mekuria et al. (2019) denoted that the smart home is used to control the operations of the domestic environment and can automatically accommodate and meet occupant's needs via a variety of AI techniques. Vlachokostas (2020) believed the smart home is the core of sustainable management of energy resources that has the potential to reduce resource consumption and ease the environmental burden. Against a backdrop of the booming growth of IoT, Almusaylim & Zaman (2019) considered that the smart home achieved the interconnection of all domestic things and linked home and external environment via the internet, which is an essential component in IoT applications.

Although several review studies of smart home technologies have been published, most of the previous studies were limited in terms of reviewing a certain perspective—e.g., business domain (Solaimani et al., 2015), user perspective (Marikyan et al., 2019), benefits and risks (Sovacool & Del Rio, 2020), IoT domain (Choi et al., 2021), and adoption domain (Li et al., 2021). Hence, systematic quantitative analyses regarding the research clusters and evolution of smart homes are still lacking in the extant literature. The systematic quantitative analysis as a valuable method for evaluating scientific production not only can identify the contribution and underlying influence of the researchers and practitioners in the field but also provide a macroscopic overview of existing literature (Ellegaard & Wallin, 2015; Guo et al., 2019).

This study applies a scientometric method to analyse the scholarly research published during the last two decades, aiming to generate a deeper understanding on the historical vicissitude, state-of-the-art and emerging trends, and research clusters of smart home research. Apart from offering a clear and up to date summary of authors, publications, countries, organisations, and publishing sources in the smart home field, the core contribution of this study is to identify the knowledge structure of smart homes from its colossal scale of literature, which may help to solve the incoherence exists within the existing literature. Finally, this study points out that embedding IoT to expend the benefits are the emerging trends in smart home research. Exploring the role of advanced technological innovations from the urban and social perspectives of smart home technology could be the future research direction, which helps in shaping our cities and societies' future.

The rest of the paper is organised as follows. Section 2 presents the research methodology. Section 3 discusses the main results of the study with reference to the general observations, academic influence analysis, research clusters of the smart home literature, the historical vicissitude, and the emerging trends of smart home research. Section 4 provides the discussion of results, and Section 5 concludes the paper.

2. Methodology

This study undertakes a scientometric analysis of existing smart home literature to address the research question of: What are the research clusters, the historical vicissitude, state-of-the-art and emerging trends in the smart home research? Based on the previous studies conducted by Sheikhnejad & Yigitcanlar (2020) and Faisal et al. (2021), the scientometrics technique can assist to produce a clear knowledge connection map to provide the visualisation of qualitative data, which can provide researcher with a deeper understanding of the research clusters.

A smart home literature database was built based on the keyword search results on bibliographic repositories. This study selected Elsevier's Scopus repository to carry out the search task. Scopus is a comprehensive and high-quality database including over 75 million records, 24,600 active titles and 194,000 books, which also offers a series of advanced search and analytical tools to reduce the difficulty and complexity of subsequent retrieval and analysis. Another benefit of using Scopus is that it allows files exporting in multiple formats to compatible with mainstream scientometric analysis software.

The research objective was framed to investigate the research trends, clusters, and interconnection of smart home literature. Therefore, 'smart home', 'home automation' and 'domotics' were chosen as the main keywords for the search task. Besides, a fuzzy format— '*' —was included in the query string to obtain more comprehensive literature data. The final query string of the search task was determined as: TITLE-ABS-KEY ("smart home*" OR "home automation" OR "domotics").

The search task of literature data was conducted in April 2021 by covering the publications between January 2000 and March 2021. Excluding a small number of publications with information absence—i.e., undefined document type and undefined author—the search resulted in selecting a total of 17,153 publications from Scopus repositories, including conference papers, articles, conference reviews, book chapters, and grey literature. The full records of the resulted publications, including citation and bibliographical information, abstract and keyword, funding details and other information, were then exported in the format as 'CSV', to be compatible with the selected data analysis software, i.e., VOSviewer.

VOSviewer is a data analysis software developed by Leiden University's Centre for Science and Technology Studies, one of the most popular bibliometric network construction and visualisation tools. To date, VOSviewer has been widely used for scientometrics research in various fields, e.g., remote sensing technology (Viana et al., 2017), thermal comfort and building control (Park & Nagy, 2018), and autonomous vehicle (Faisal et al., 2020). This study applied VOSviewer as a tool to analyse the developed smart home literature database to produce a series of visual diagrams, e.g., co-authorship networks map, citation-based networks map, and co-occurrence networks map, and to achieve the qualitative data visualisation, i.e., literature data.

Finally, the repeated validations of results were undertaken to ensure the reliability and validity of the analysis, including duplicate screening of initial data, rerun test of software, and random selective tests of outputs. The limitations of this study, which may affect the result of the analysis, are the following: (a) The selected bibliographic repository and search keywords may not cover all publications relevant to the research objective; (b) The allowed fuzzy search may increase the possibility of irrelevant publications in the database, and; (c) The result of the analysis may be affected by the author's unconscious bias.

3. Results

3.1. General Observations

As described above, the developed smart home literature database covers 17,153 pieces of literature published from January 2000 to March 2021 across 354 countries, including 33,495 authors, 7,350 organisations, and 5,783 publishing sources (Table 1).

Table 1. Statistical information on the data

Data source	Elsevier's Scopus bibliographic repositories
Covered period	From January 2000 to March 2021
Covered countries	354
Number of publications	17,153
Number of authors (including corresponding authors and co-authors)	33,495
Number of organisations	7,350
Number of publishing sources	5,783

Based on the statistical charts, the number of smart home-related publications increases over time (Figure 1), where an exponential growth has been observed since 2015 (n=1,071) and has almost doubled in 2018 (n=2,114). Besides, the number of publications between 2015 and 2021 accounts for nearly 70% of total publications in the database. This growth trendline indicates that smart home has obtained a great interest from the industry and academia in the last five years, and consistent with the viewpoints of Almusaylim & Zaman (2019) regarding the growth of smart home was closely related to the advance of IoT. The main types of selected publications are conference papers (59%) and articles (31%). Other grey literature such as reviews, book chapters only accounts for 10% of the total number of publications (Figure 2). The major subject areas of selected publications are computer science (37%), engineering (26%), and mathematics (10%) (Figure 3). The US (n=2,152), China (n=1,991) and India (n=1,809) are the top three productive countries, which respectively accounts for 12.5%, 11.6%, and 10.5% of total publications (Figure 4).

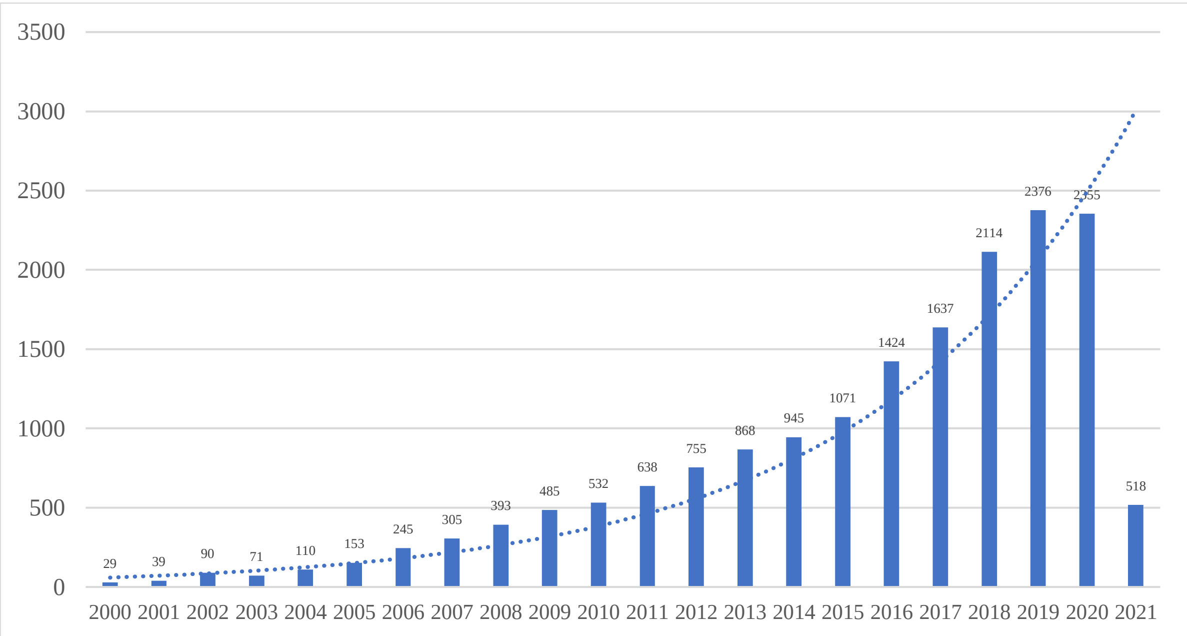


Figure 1. Growth trend of the smart home literature

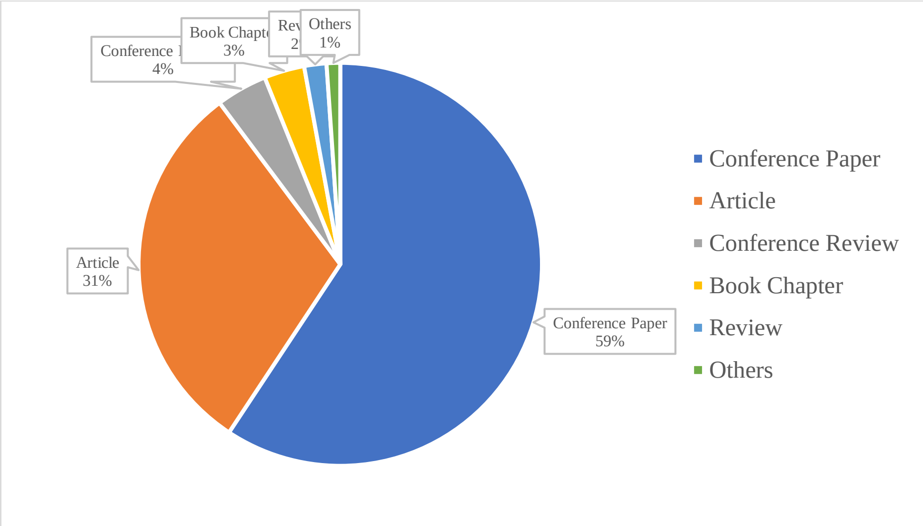


Figure 2. Document type of the smart home literature

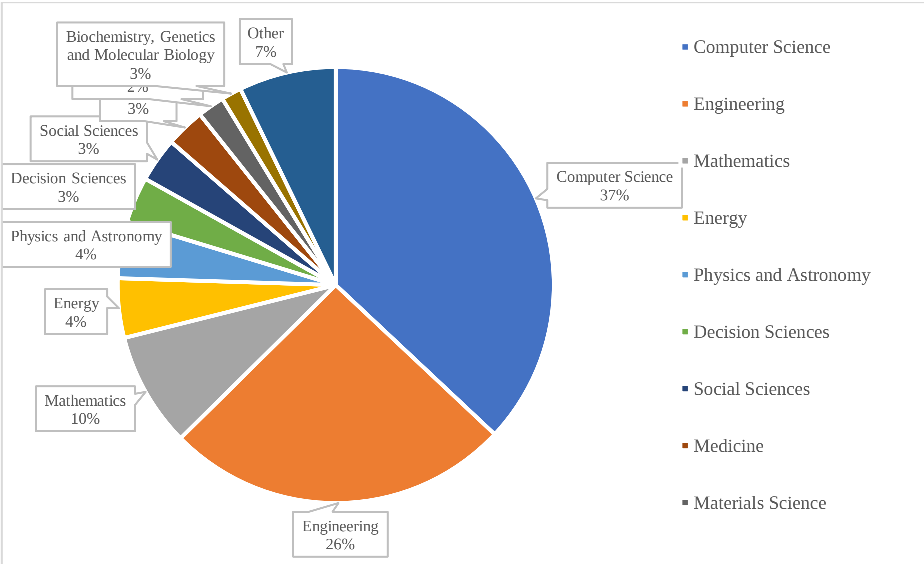


Figure 3. Subject area of the smart home literature

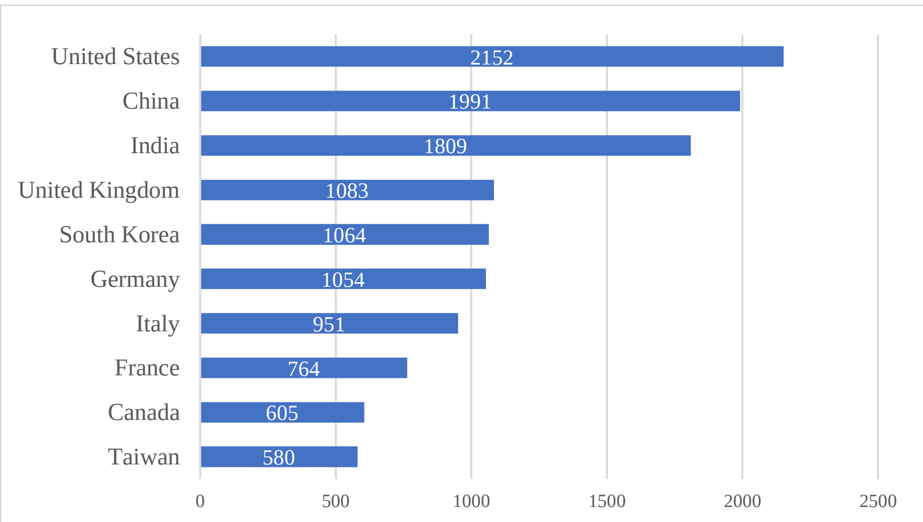


Figure 4. Top-ten productive countries in smart home literature

Bouchard, B., Javaid, N., and Bouzouane, A. are the top three most productive (first) authors in smart home research and contributed to 0.51%, 0.50%, and 0.47% of the selected smart home literature, respectively. Thereinto, two of the top three most productive (first) authors are affiliated with the same organisation – the Université du Québec à Chicoutimi in Canada. Particularly worth mentioning is nearly half (n=5) of the top-ten most productive (first) authors, namely the 1st, 3rd, 7th, 8th, and 9th rank authors, are from the Canadian organisations—i.e., the Université du Québec à Chicoutimi (n=2), the Laboratoire d'Intelligence Ambiante pour la Reconnaissance d'Activités (LIARA) (n=2), and the Université de Sherbrooke (n=1). Table 2 lists the top-ten most productive (first) authors and shows their affiliated organisations and contribution shares.

Table 2. Top-ten most productive authors (first author)

Rank	Author	Affiliated organisation	Country	Count	Share
1	Bouchard, B.	Université du Québec à Chicoutimi	Canada	88	0.51%
2	Javaid, N.	COMSATS University Islamabad	Pakistan	85	0.50%
3	Bouzouane, A.	Université du Québec à Chicoutimi	Canada	81	0.47%
4	Cook, D.J.	Washington State University Pullman	US	63	0.37%
5	Nugent, C.	Ulster University	UK	61	0.36%
6	Mukhopadhyay, S.C.	Macquarie University	Australia	58	0.34%
7	Giroux, S.	Université de Sherbrooke	Canada	53	0.31%
8	Gaboury, S.	Laboratoire d'Intelligence Ambiante pour la Reconnaissance d'Activités (LIARA)	Canada	51	0.30%
=9	Bouchard, K.	Laboratoire d'Intelligence Ambiante pour la Reconnaissance d'Activités (LIARA)	Canada	50	0.29%
=9	Vacher, M.	Universite Grenoble Alpes	France	50	0.29%
10	Chen, L.	Ulster University	UK	40	0.23%

The top three most productive organisations in smart home research are the Ulster University from the United Kingdom (UK), the COMSATS University Islamabad in Pakistan, and the CNRS Centre National de la Recherche Scientifique in France (Table 3). The types of the organisations on the list are educational institution (n=9), governmental institution (n=5), and joint research institution (n=1), which reflects the fact that not merely the academia but also the governmental organisations have attached importance to smart home research.

Table 3. Top-ten most productive organisations

Rank	Organisation	Type	Country	Count	Share
1	Ulster University	Educational institution	UK	129	0.75%
2	COMSATS University Islamabad	Educational institution	Pakistan	127	0.74%
3	CNRS Centre National de la Recherche Scientifique	Governmental institution	France	117	0.68%
4	Università Politecnica delle Marche	Educational institution	Italy	106	0.62%
5	Electronics and Telecommunications Research Institute	Governmental institution	Korea	102	0.59%
=6	Université du Québec à Chicoutimi	Educational institution	Canada	101	0.59%
=6	Universite Grenoble Alpes	Educational institution	France	101	0.59%
7	Chinese Academy of Sciences	Governmental institution	China	96	0.56%
=8	Massey University	Educational institution	Auckland	94	0.55%
=8	Washington State University Pullman	Educational institution	US	94	0.55%
=9	Ministry of Education China	Governmental institution	China	93	0.54%
=9	Consiglio Nazionale delle Ricerche	Governmental institution	Italy	93	0.54%
=10	Vellore Institute of Technology	Educational institution	India	86	0.50%
=10	King Saud University	Educational institution	Saudi Arabia	86	0.50%
=10	Laboratoire d'Informatique de Grenoble	Joint research institution	France	86	0.50%

The most productive publishing source is Lecture Notes in Computer Science, a book series type source published by Springer Nature, and accounts for 5.46% of total smart home publications (Table 4). This source specialises in the areas of computer science (general computer science) and mathematics (theoretical computer science). Since 1973, it has unwoven commitment to report the latest words from all areas of computer science and information technology research, development, and education. Based on the top-ten most productive publishing sources list (n=11), over 90% of sources (n=10) are specialised in the areas of computer science and engineering. Combined with the preceded analysis of publications' distribution by subject area (Figure 3), it somehow reflects that existing research has predominantly focused on the technical characteristics of smart homes.

Table 4. Top-ten most productive publishing sources

Rank	Publishing source	Subject area	Type	Count	Share
1	Lecture Notes in Computer Science	Computer science, Mathematics	Book series	937	5.46%
2	ACM International Conference Proceeding Series	Computer science	Conference proceeding	343	2.00%
3	Advances in Intelligent Systems and Computing	Computer science, Engineering	Book series	303	1.77%
4	Sensors Switzerland	Multiple subjects	Journal	259	1.51%
5	IEEE Access	Engineering, Computer science, Materials science	Journal	197	1.15%
6	Communications in Computer and Information Science	Mathematics, Computer science	Book series	170	0.99%
7	Lecture Notes in Electrical Engineering	Engineering	Book series	156	0.91%
8	Applied Mechanics and Materials	Engineering	Book series	126	0.73%
9	IEEE Transactions on Consumer Electronics	Engineering	Journal	123	0.72%
=10	Ceur Workshop Proceedings	Computer science	Conference proceeding	117	0.68%
=10	International Journal of Smart Home	Computer Science	Journal	117	0.68%

3.2. Academic Influence Analysis

3.2.1. Citation Analysis by Publication

Wireless communications, by Goldsmith (2005), is the most influential publication with significantly high citations. It provides a comprehensive introduction of wireless technology—e.g., the underlying theory, design techniques and analytical tools, and focusing primarily on the core principles of wireless system design. The author's opinion is that wireless technology is a 'truly revolutionary paradigm shift', which provides the barrier-free means of multimedia communication between people and devices and supports the advance of further innovations, such as smart homes, telemedicine, and automated highways (Goldsmith, 2005).

Edge computing: vision and challenges by Shi et al. (2016) ranked second on the top ten most-cited publications. It focuses on edge computing, a new computing paradigm pushed by the proliferation of the IoT and a series of successful cloud services. The authors indicate that cloud computing is not efficient enough to support the increasingly huge amounts of data generated by people's daily life in today's post-cloud era, but edge computing has the potential to address most of the restrictions of cloud computing.

A review of wearable sensors and systems with application in rehabilitation by Patel et al. (2012) is the third most-cited publication. It summarised the wearable technology development in the first decade of research and focusing on practical applications. The authors believe that integrating technical innovations into healthcare services may address the socio-economic burden created by the increased medical expenses in today's aging society.

Table 5 lists the top-ten most influential research publications and shows the author, publication year, research focus and citations. Based on Table 5, the most influential publications have mainly focused on the technical domain and the practical application of smart homes, such as information and communication technologies, IoT related matters, and healthcare-related applications. Thereinto, half (n=5) of the listed publications (n=10) focus on advancing information and communications technologies, e.g., wireless communication technology, edge computing, Blockchain, and context-aware middleware. This reflects that information and communication technologies are the most influential research themes of smart homes. IoT related publications (n=4) occupies 40% of the listed publications (n=10), which means that this emerging topic had attracted significant interest from researchers and became one of the influential research clusters of smart homes. Besides, healthcare is one of the influential research orientations in smart home research, especially in healthcare-related applications, e.g., realising or providing remote monitoring, telemedicine, or other healthcare services by smart home devices. Based on the lists, 30% of the publications (n=3) are focus on this orientation.

Table 5. Top-ten most-cited publications

Rank	Publication Title	Authors and year	Research focus	Citation
1	Wireless communications	Goldsmith A. (2005)	Wireless communication systems	7,871
2	Edge computing: Vision and challenges	Shi W. (2016)	Cloud computing, IoT, Bandwidth, Time factors, Mobile handsets, Data privacy, Smart homes	2,294
3	A review of wearable sensors and systems with application in rehabilitation	Patel S. (2012)	Wearable sensors and systems, Home monitoring, Telemedicine, Smart home	1,133
4	Wearable sensors for human activity monitoring: A review	Mukhopadhyay S.C. (2015)	Monitoring, Biomedical monitoring, Wearable sensors, Wireless sensor networks, Temperature measurement, Wireless communication	702
5	IoT security: Review, blockchain solutions, and open challenges	Khan M.A. (2018)	IoT security, Blockchain, IoT protocols, Network security, Data security	686
6	A service-oriented middleware for building context-aware services	Gu T. (2005)	Context-aware middleware, Pervasive computing, Context-aware services, Network services, Context model, Context ontology	681
7	Coordinated scheduling of residential distributed energy resources to optimize smart home energy services	Pedrasa M. (2010)	Energy resources, Smart homes, Density estimation robust algorithm, Processor scheduling, Costs, Scheduling algorithm, Energy management, Particle swarm optimization, Stochastic processes, Smart grids	632
8	Blockchain for IoT security and privacy: The case study of a smart home	Dorri A. (2017)	Smart homes, Security, Cloud computing, Privacy, IoT, Conferences, Online banking	628
9	A review of smart homes-Present state and future challenges	Chan M. (2008)	Smart home, Elderly people	623
10	A review of Internet of Things for smart home: Challenges and solutions	Risteska Stojkoska B. (2017)	IOT, Smart home, Holistic framework, Smart grid	492

3.2.2. Citation Analysis by Organisation

University of New South Wales in Australia, the Comsats Institute of Information Technology in Pakistan, and the University of Waterloo in Canada are the top three most-cited organisations in smart home research. Based on the top ten most-cited organisations listed in Table 6, nearly half of the organisations are from the US (n=4), the rest are from Canada (n=2), Australia (n=1), China (n=1), New Zealand (n=1) and Pakistan (n=1). Besides, most organisations (n=9) are classified as educational institutions; only one (Microsoft Research) is an entrepreneurial research institution. The results reveal that academia, especially the educational institutions from North America, has significantly influenced the development of smart home research.

Table 6. Top-ten most-cited organisations

Rank	Organisation	Type	Country	Citation
1	University of New South Wales	Educational institution	Australia	695
2	Comsats Institute of Information Technology	Educational institution	Pakistan	636
3	University of Waterloo	Educational institution	Canada	578
4	Carnegie Mellon University	Educational institution	US	568
5	Washington State University	Educational institution	US	489
6	Carleton University	Educational institution	Canada	487
7	University of California	Educational institution	US	486
8	Microsoft Research	Entrepreneurial research institution	US	473

9	Massey University	Educational institution	New Zealand	443
10	Zhejiang University	Educational institution	China	383

3.2.3. Citation Analysis by Country

Table 7 lists the top-ten most-cited countries and shows the citations, total link strength, and average publication year (APY). Based on Table 7, receiving significantly high citations has made the US the most influential country in smart home research. China and the UK are ranked second and third by similar citation numbers. The total link strength represents the total strength of the links of a country with other countries. For example, the US has 6,616 total link strengths, which means compare with Australia (1,837), the US has a wider academic relationship (in citation) with other countries.

Table 7. Top-ten most-cited countries

Rank	Country	Citations	Total link strength	APY
1	US	47,185	6,616	2015
2	China	17,381	5,054	2016
3	UK	15,955	4,927	2015
4	South Korea	12,225	3,852	2014
5	Italy	10,986	2,505	2014
6	France	10,493	2,549	2014
7	Canada	9,422	2,956	2015
8	India	8,863	2,292	2017
9	Germany	8,282	2,587	2014
10	Australia	6,626	1,837	2016

Notes: Minimum number of documents of a country is 10; Minimum number of citations of a country is 5; Of the 354 countries, 79 meet the threshold; APY: average publication year

Figure 5 displays the citation network map by country, where the circle represents the country, and the size of the circles represents the citation numbers of countries' publications. The line between each circle represents the academic relationship between pairs of countries; a shorter line between two circles represents a closer academic relationship between two countries. The colour of circles was used to classify the clusters to which they belong based on the citation relations that were referred to as scientific communities, i.e., the countries belonging to the same scientific community were deeply linked in the citation (Van Eck & Waltman, 2017).

Based on Figure 5, although the top three high cited countries are showing belong to three different citation communities, these three countries still kept extremely close links in citations with each other. Besides, the composition of citation communities does not show any distinct regional characteristics, e.g., all from the same continent. These indicate that in the last two decades, smart home research was not dominated by a single subject or group, but the academia around the world all kept a level of interest and academic communication on this topic.

Figure 6 shows the (average) publication year visualisation of citation network map by countries, where the colour of circles represents the chronological order of the average publication year from early (dark coloured) to recent (light coloured) years. Based on the map, Spain, Finland, and France from Europe; South Korea and Taiwan from Asia; and New Zealand from Oceania are the countries that produced research on the smart home. India, Pakistan, Jordan from Asia are the countries that produced start smart home research most recently.

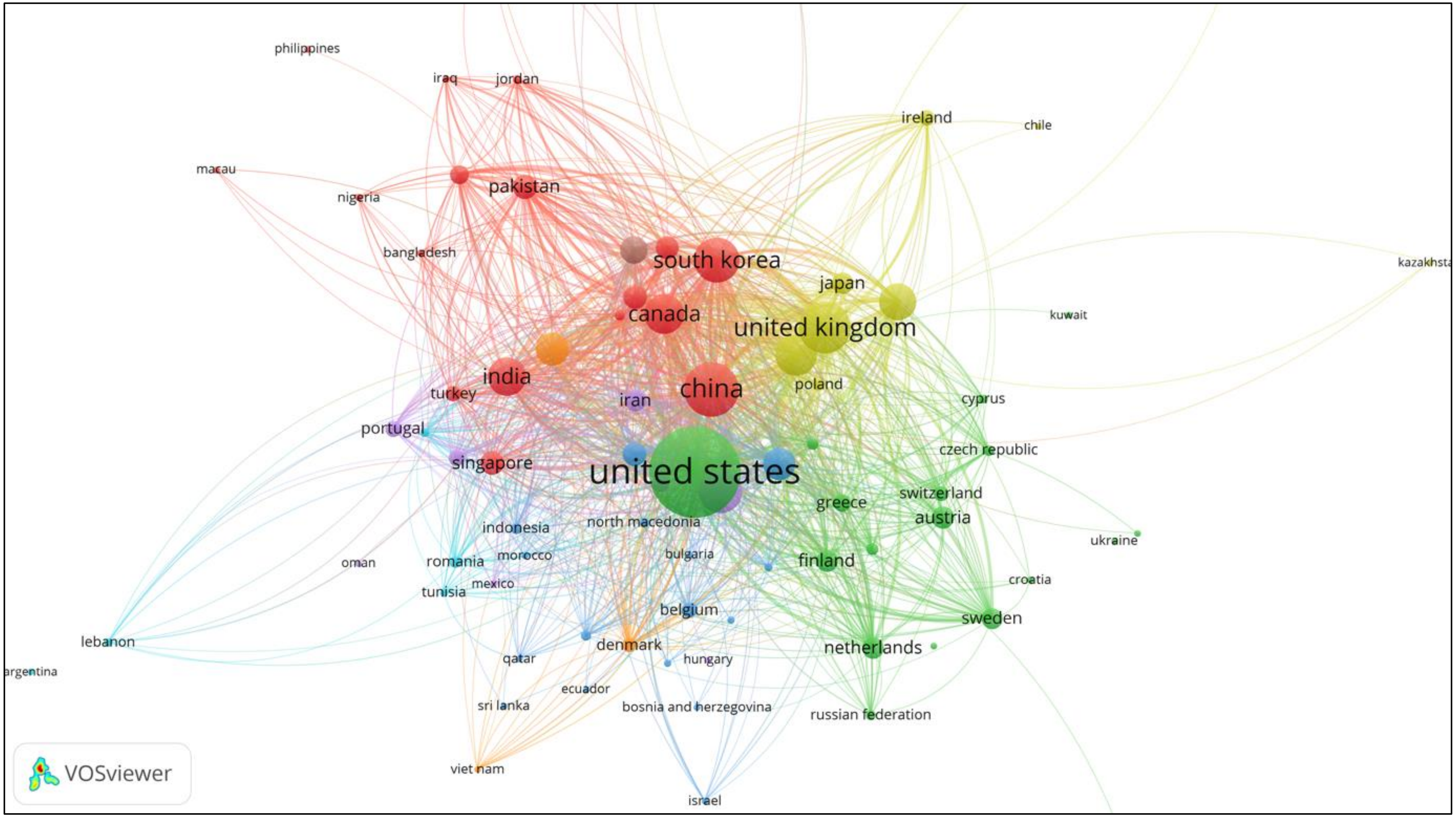


Figure 5. Citation network map by countries

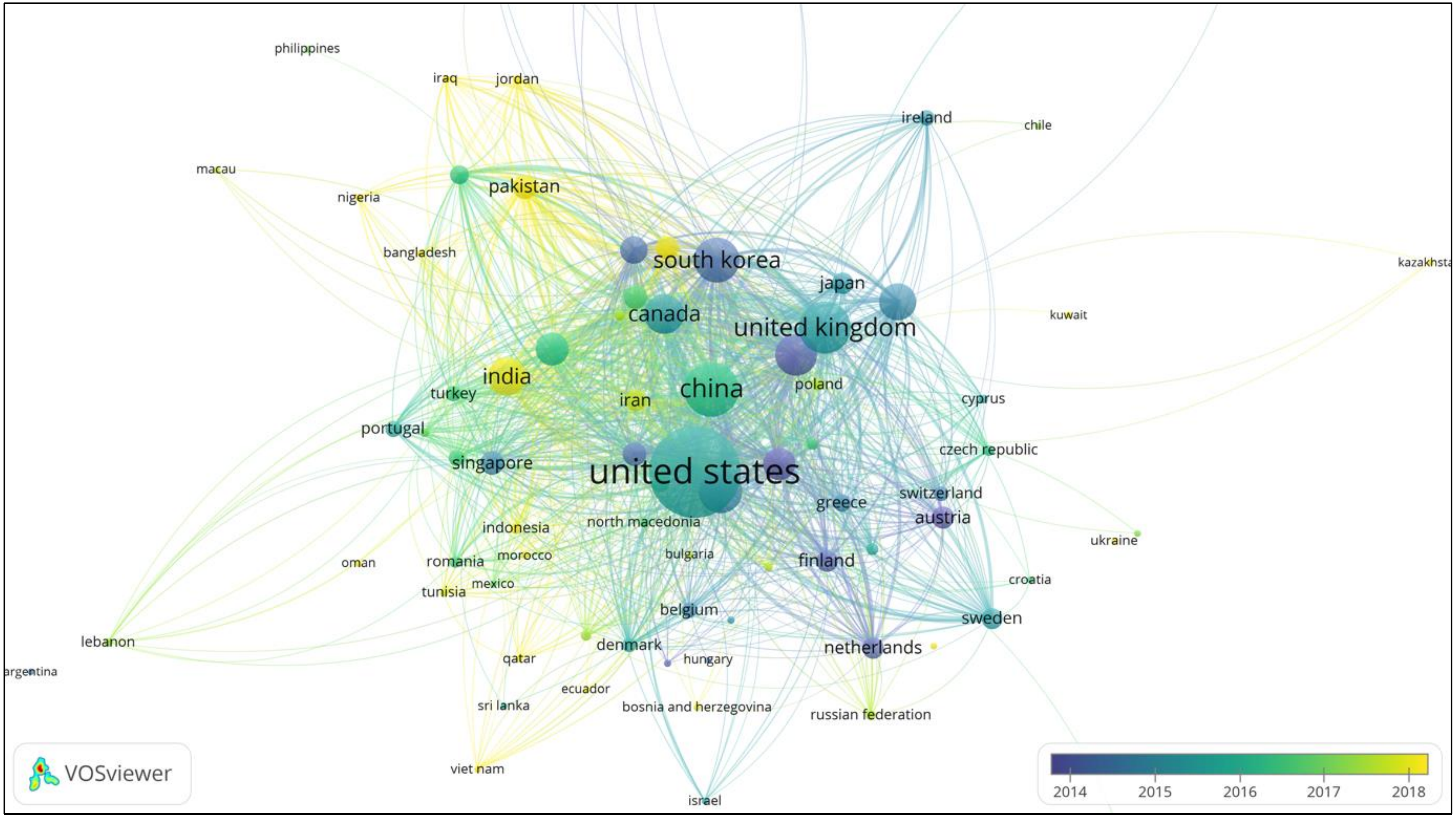


Figure 6. Citation network map by countries and publication year

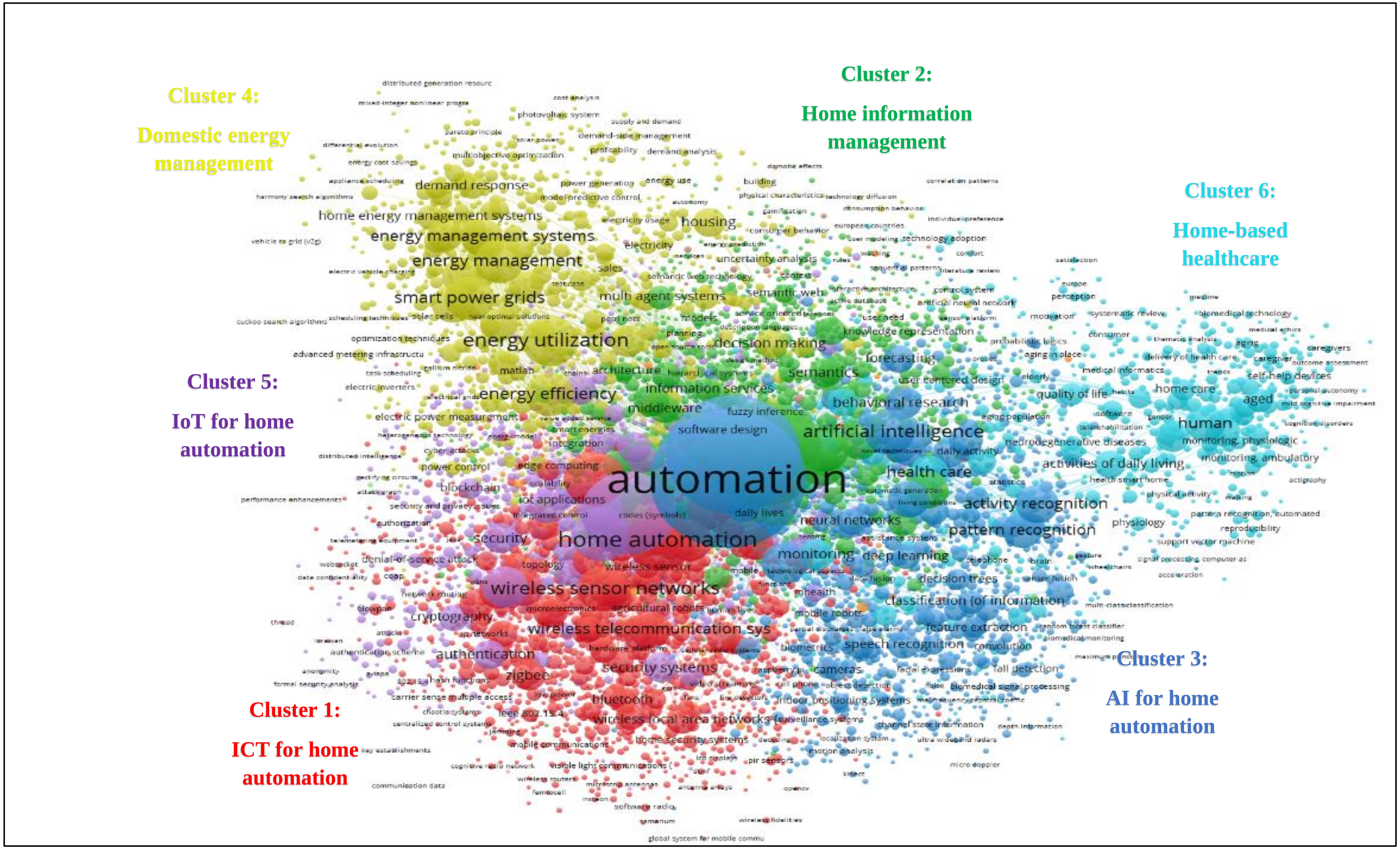


Figure 7. Smart home research clusters network map (by keyword occurrences)

3.3. Research Clusters of the Smart Home Literature

The research clusters were ascertained through the frequency and link strength analysis of 39,194 keywords extracted from the smart home literature database. Finally, 5,758 keywords met the threshold of at least five occurrences and were selected to be analysed. The analysis results indicated there were twelve clusters on the existing smart home research, and the main research clusters were identified and categorised into six groups as the following:

- Cluster 1: ICT for home automation—e.g., wireless sensor networks, telecommunication systems, internet protocols, and Zigbee.
- Cluster 2: Home information management—e.g., multi-agent systems, interoperability, ontology, and semantics.
- Cluster 3: AI for home automation—e.g., learning algorithms, learning system, activity recognition, and pattern recognition.
- Cluster 4: Domestic energy management—e.g., energy efficiency, energy utilisation, energy management, and smart power grid.
- Cluster 5: IoT for home automation—e.g., network security, blockchain, cryptography, and authentication.
- Cluster 6: Home-based healthcare—e.g., independent living, home care services, daily life activity, and monitoring ambulatory.

Figure 7 exhibits the research clusters network map, where each circle represents a keyword, and the size of the circle signifies the occurrence frequency of this keyword. The colour of circles manifests the research clusters of keywords and the distance between circles demonstrates the strength of correlation and similarity between the keywords. The map indicated that: (a) The distributions of Cluster 1 and 5 highly are overlapping, showing that these two clusters are closely connected; (b) Cluster 2 is distributed on the middle of the cluster network map, which takes on the role of connection with each cluster; (c) Cluster 3 contains various coloured circles from different clusters, which reflects that it has various connections with other clusters; (d) Clusters 4 and 6 are relatively independently distributed, which means these two clusters have weak ties with other clusters.

Table 8 provides a list of the top ten occurrence keywords and shows the average publication year, occurrences, links, total link strength, and subordinate clusters. The list excludes the search keywords and other alternative keywords—e.g., 'automation', 'intelligent buildings', 'home automation'. A set of exclusion criteria can reduce the redundancy on the list and help to identify the research trends of smart home research, i.e., identify the specific research clusters or extended research orientations. The most frequent keyword 'IoT' has the strongest total link strength, indicating that IoT had emerged in smart homes and had been the most popular trend that attracting significant interests from various organisations (Choi et al., 2021). Four out of the top ten occurrence keywords (the 3rd, 8th, 9th, and 10th rank keywords) are categorised as Cluster 4 – domestic energy management. The sum of the total link strength of these four keywords ranks second on the list, which reveals the existing smart home research kept a relatively strong connection with energy cluster. Besides, no keyword categorised to Cluster 6 is on the list, which means the Home-based healthcare cluster is not a popular extended research orientation for smart home research.

Table 8. Top-ten occurrence keywords in smart home literature (2000-March 2021)

Rank	Keyword	APY*	Occurrences	Links	Total link strength	Cluster
1	IoT	2018	4,683	7,411	56,486	5
2	Domestic appliances	2015	1,285	3,181	17,026	1
3	Energy utilisation	2016	1,083	2,721	15,186	4
4	Ambient intelligence	2017	895	2,791	10,521	2
5	AI	2015	868	2,785	11,288	3
6	Ubiquitous computing	2013	854	2,553	9,817	2
7	Wireless sensor networks	2014	844	2,554	11,520	1
8	Energy efficiency	2016	787	2,463	10,889	4
9	Smart power grids	2016	786	2,003	11,396	4
10	Energy management	2016	772	1,968	8,970	4

Notes: Minimum number of occurrences of a keyword is 5; Of the 39,194 keywords, 5,758 meet the threshold; APY: average publication year; Exclusionary – search keywords and other alternative keywords.

3.4. Historical Vicissitude of Smart Home Research

This sub-section identifies the historical vicissitude of smart home research based on the keyword occurrence density maps and the list of top-ten occurrence keywords. The keyword selection process excludes the search keywords and other alternative keywords, aiming to reduce the redundancy and to provide a more explicit understanding of the specific research clusters and extended research orientations of smart homes.

The outputs are interpreted as follows. First, on the density map of 2000-2005, the keywords of Clusters 1 and 2 are distributed in the adjacent areas as seen in Figure 8a. These keywords are closely linked to each other, which assemble the largest aggregation on the map. On the other hand, the keywords of Cluster 6 assemble in an area relatively far away from the aggregation of Clusters 1 and 2, having a weak connection with them. In this period, the most frequent keywords are from Cluster 1 (n=8) and occupy the majority of the top ten occurrence keywords list. The remaining keywords on the list are from Cluster 2 (n=2) (see Table 9).

Second, on the density map of 2006-2010, the largest aggregation is still composed of the keywords of Clusters 1 and 2 (Figure 8b). On the other hand, some keywords of Cluster 3 first appear on the map with higher density, i.e., AI and sensors, and then joined the largest aggregation on the map. Besides, the density of the keywords from Cluster 6 is increased but still maintains a weak tie with the largest aggregation. In this period, the keywords of Cluster 1 (n=4), 2 (n=3), and 3 (n=2) occupy the top ten occurrence keywords list (see Table 9).

Third, on the density map of 2011-2015, the keywords of Clusters 4 and 5 appear for the first time and the composition of the largest aggregation on the map has changed in the same period (Figure 8c). The keywords of Cluster 5 joined the largest aggregation, and the keywords of Cluster 3 leave the original aggregation and form a separate, individual aggregation. So far, four aggregations are displayed on the density map: the aggregation of Clusters 1, 2 and 5; the individual aggregation of Cluster 3; the individual aggregation of Cluster 4; and the individual aggregation of Cluster 6. The shares of cluster on the top ten occurrence keywords list are ranked as Cluster 1 (n= 3); Cluster 4 (n=3); Cluster 3 (n=2); Cluster 2 (n=1); and Cluster 5 (n=1) (see Table 9).

Finally, on the density map of 2016-March 2021, the keywords density distribution layout is entirely different from the previous layouts (Figure 8d) as it presents a spreading layout with the keywords of Cluster 5 as the hub, and all the other keywords link to the hub and extend outward. Nevertheless, the keywords of Cluster 6 are still distributed distantly with a weaker link to other clusters, as has been found previously. In this period, although the keywords of Cluster 4 (n=5) occupy half of the top ten occurrence keywords list, the total occurrence of Cluster 5 keywords (5,490) was much higher than Cluster 4 keywords (2,762) (see Table 9).

The results of keywords occurrence density (by period) analysis revealed that:

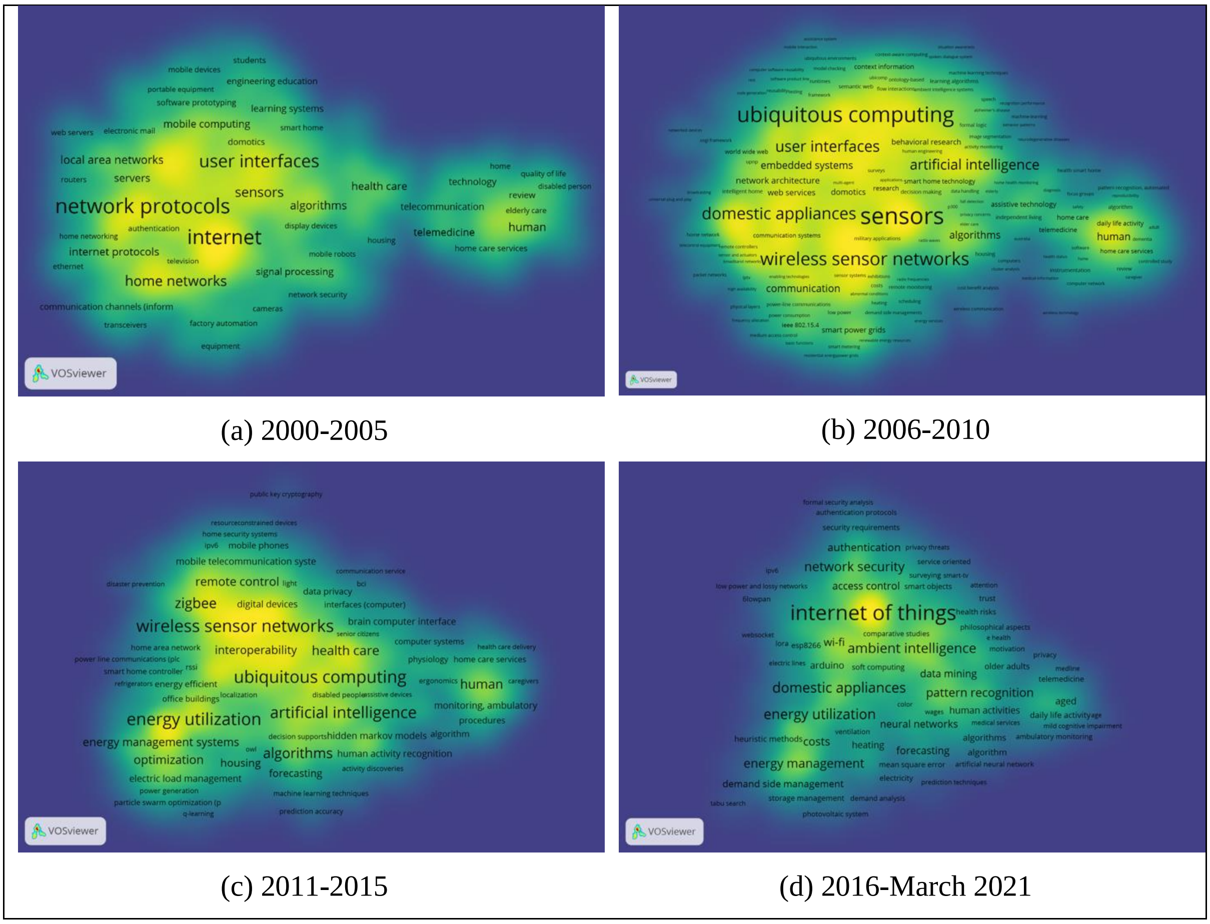
- ICT for home automation (Cluster 1) and Home information management (Cluster 2) are the earliest research clusters and the fundamentals of smart home research.
- Home-based healthcare (Cluster 6) is the first and the earliest extended research orientation of smart homes but has always maintained relatively weak links to other clusters.
- AI for home automation (Cluster 3), as an earlier research cluster of smart homes, has always been received with a certain degree of research enthusiasm by researchers over the past decade or more.
- Domestic Energy management (Cluster 4) has been the most popular extended research orientation of smart homes over the past decade.
- IoT for home automation (Cluster 5) is an emerging research cluster of smart homes, which rises based on the advances in ICT for home automation (Cluster 1). It has wide links with other relevant research clusters. In the past five years, the IoT for home

automation (Cluster 5) has replaced Domestic energy management's (Cluster 4) leading position and gradually evolved to the most popular research cluster in smart homes.

Cluster	Keyword	Occurrence per periods				Ranks per periods			
		2000-2005	2006-2010	2011-2015	2016-Mar 2021	2000-2005	2006-2010	2011-2015	2016-Mar 2021
1	Domestic appliances	52	139	289	805	3	5	5	2
1	Home networks	32	-	-	-	8	-	-	-
1	Internet	57	-	250	-	2	-	8	-
1	Network protocols	58	-	-	-	1	-	-	-
1	Personal communication systems	32	-	-	-	9	-	-	-
1	Remote control	32	-	-	-	10	-	-	-
1	Sensor networks	-	145	-	-	-	4	-	-
1	Telecommunication networks	33	-	-	-	7	-	-	-
1	Wireless networks	-	92	-	-	-	8	-	-
1	Wireless sensor networks	-	159	298	-	-	3	3	-
1	Wireless telecommunication systems	45	91	-	-	4	10	-	-
2	Ambient intelligence	-	-	-	677	-	-	-	4
2	Computer software	34	-	-	-	6	-	-	-
2	Middleware	-	92	-	-	-	9	-	-
2	Ubiquitous computing	-	215	303	-	-	1	1	-
2	User interfaces	45	117	-	-	5	6	-	-
3	AI	-	116	255	481	-	7	7	10
3	Sensors	-	196	278		-	2	6	-
4	Electric power transmission networks	-	-	-	515	-	-	-	7
4	Energy efficiency	-	-	-	519	-	-	-	6
4	Energy management	-	-	-	499	-	-	-	8
4	Energy utilisation	-	-	302	738	-	-	2	3
4	Smart grid	-	-	228	491	-	-	10	-
4	Smart power grids	-	-	293	491	-	4	9	-
5	IoT	-	-	231	4925	-	-	9	1
5	Network security	-	-	-	565	-	-	-	5

Notes:(2000-2005) Minimum number of occurrences of a keyword is 5; Of the 2,658 keywords, 212 meet the threshold;(2006-2010) Minimum number of occurrences of a keyword is 5; Of the 10,155 keywords, 824 meet the threshold;(2011-2015) Minimum number of occurrences of a keyword is 5; Of the 15,694 keywords, 1,685 meet the threshold;(2016-Mar 2021) Minimum number of occurrences of a keyword is 5; Of the 26,325 keywords, 3,532 meet the threshold; Exclusionary – search keywords and other alternative keywords.

Table 9. Top-ten occurrence keywords in smart home literature (ranks per 5-year periods)



(a) 2000-2005 (b) 2006-2010

(c) 2011-2015 (d) 2016-March 2021

Figure 8. Smart home keywords occurrence density map by periods

3.5. Emerging Trends of Smart Home Research

Based on the top ten occurrence keywords list created between 2000 and March 2021 (Table 8) and the rank list per 5-year periods - 2016 to March 2021 (Table 9), 'IoT' holds the top spot of both lists by an overwhelming advantage, namely, the most frequent occurrences and the strongest total link strength. It means that during the last two or three years, IoT as an emerging keyword has been extensively mentioned in numerous smart home publications.

In the publication year (average) visualisation of the research clusters network map (Figure 9), the circle and its size represent the keyword and its occurrence frequency, respectively. The line between each circle represents the academic relevancy between pairs of keywords; a shorter line between two circles represents closer academic relevancy between the two keywords. The colour of circles represents the chronological order of the keyword's average publication year from early (dark coloured) to recent (light coloured) times.

Based on the map, 'IoT' is denoted by a larger size circle with the lightest colour, which means this keyword only arose in very recent years but has already received significant interest from researchers. Within this cluster (Cluster 5 – IoT for home automation), other emerging keywords that have close academic relevancy with IoT are blockchain, edge computing, cyber-attacks, security and privacy issues, and smart city. This points out that with the emerging combination of IoT and smart homes, researchers did not just only focus on the technical advance, but also had started to be concerned about the potential issues posed by these emerging technologies, e.g., the issue of cyber security. Besides, the embedding of IoT provides smart homes with a direct link with smart cities, which may be one of the most promising research orientations and has a broad application view in the future.

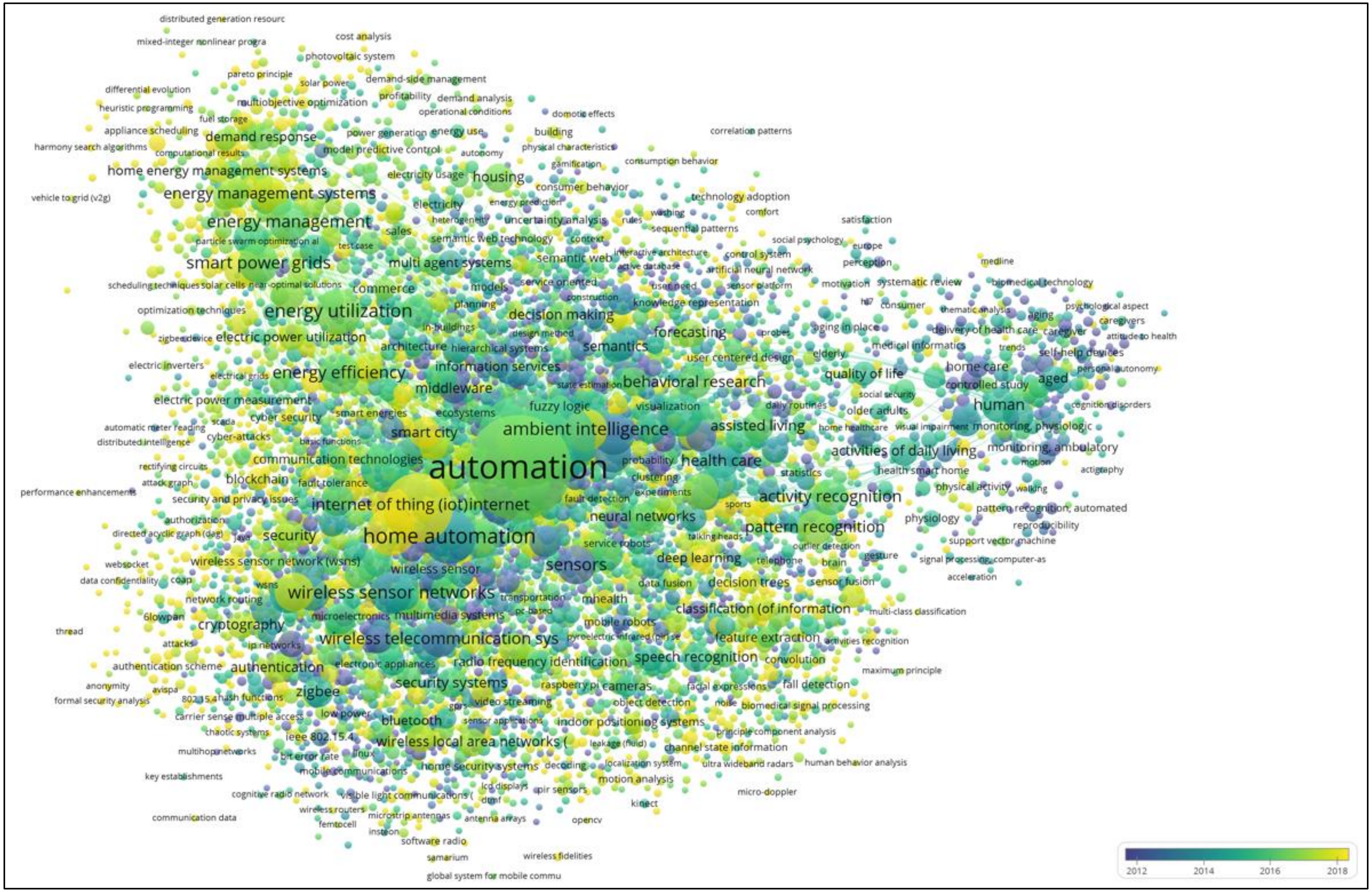


Figure 9. Smart home research clusters network map (by keyword occurrences and average publication per year)

The colours of circles categorised to the clusters of AI for home automation (Cluster 3) and Domestic energy management (Cluster 4) are relatively lighter and contain some circles with the lightest colour. It means these two clusters are the relatively new research orientations of smart homes, and more new research topics have emerged within these two clusters in recent years, such as ambient intelligence, machine learning, deep learning in Cluster 3; electric power transmission, demand side management in Cluster 4. An interesting finding is the aforementioned emerging topics all have a direct link with IoT, which means these new advances of other smart home research clusters maybe closely associated with the emergence of IoT. Furthermore, apart from the search keywords (smart home and its alternative), IoT is the only keyword that has direct links with all other clusters. Therefore, IoT has potential to become a new hub in smart home research by establishing the links between all clusters, which may contribute to the reintegration of existing dispersed smart home clusters.

4. Discussion

This study analysed 17,153 pieces of literature published between January 2000 and March 2021 with the aim of creating a clearer understanding of the historical vicissitude, state-of-the-art and emerging trends, and research clusters in smart home research. The growth trend of smart home literature shows that this research topic has obtained great interest from both public and private sectors in the last five years. The growth of smart homes has benefited from the booming of the IoT (Hui et al., 2017; Almusaylim & Zaman, 2019), and due to the increasing practical applications in diverse fields the smart home has attracted significant attention from the industry, academia, and governmental organisations in recent years. Besides, under the recent threats from climate change, uncertainties of energy supply, rapidly ageing society, and pandemic, the potential and significance of smart homes being the critical element of the possible solution has inspired a new wave of research worldwide (Li et al., 2021).

The US, China and India are the top three productive countries by contributing over a third of the total smart home publications. These three countries, however, have not dominated the top-ten productive (first) authors and organisations lists as the smart home as a global research topic is valued by researchers all over the world. Besides, no countries from Africa and South America get on any productive lists, i.e., productive countries, authors, or organisations, indicating that the smart home research or practical applications in these two continents may still be in their early days or there is less need there. From the perspective of academic influence analysis, based on the citation count, the US is the worthy leading country in the smart home field and is likely to have a greater impact on the field in future. Presumably, it's because the US has always been one of the world's technological innovation leaders for a long period in the past (Deutch, 2018).

Based on the subject areas of the literature suggested by Scopus, over 70% of the existing smart home publications were classified in the fields of computer science, engineering, and mathematics, where the most influential publications have chiefly focused on the technical domain and the practical application of smart homes. Moreover, over 90% of the top-ten most productive publishing sources specialised in computer science and engineering fields, The above results reflect that the existing knowledge structure of smart home research is more in favour of technical characteristics and advances. The research from other perspectives such as urban and social dimensions are still not widely undertaken.

The main research clusters of smart homes are: (a) ICT for home automation; (b) Home information management; (c) AI for home automation; (d) Domestic energy management; (d) IoT for home automation, and; (e) Home-based healthcare. This finding highlights that smart home research has not been restricted to its primary clusters but has broadened its research sight and developed some new extended orientations like the practical application in energy and healthcare fields to deepen the research in its primary clusters.

ICT for home automation and home information management are the earliest research clusters and have always been the major subjects of smart home research in the past two decades. Based on previous studies conducted by Chan et al. (2008), Mussab et al. (2017), Marikyan et al. (2019), and

Sovacool & Del Rio (2020), the core operating mechanics of smart homes can be interpreted as an array of sensors and information and communication technologies to acquire and manage the knowledge about its users and their surroundings and utilising this information to anticipate, respond and meet users' demands and needs. Therefore, the research and knowledge about ICT and information management can be regarded as the fundamentals of smart home research and have always been the most influential components of its knowledge structure.

Home-based healthcare is the first and the earliest extended research direction of smart homes research. The demands for healthcare services are increasing with the growth of the population and the extending of the average life expectancy of people (Majumder et al., 2017). The potential contributions of smart homes in the healthcare field are providing users with remote health monitoring, support, assistance, and improving the health care services delivery, which to achieve independent living and strengthen the quality of life, safety, and prospects for aging-in-place (Amiribesheli et al., 2015; Majumder et al., 2017; Li et al., 2021). However, the healthcare cluster has always maintained relatively weak links to other research clusters. This is possibly because the researchers have mostly focused on the specific aspects of smart homes but integrating various smart home applications in different fields and finally realising a fully functional and comprehensive smart home environment still requires profound research (Majumder et al., 2017).

AI for home automation is an earlier research cluster of smart homes, and researchers have always kept a certain degree of research enthusiasm to this cluster over the past decade or more. From a functional view, the first generation of smart homes (based on ICT technologies) provides users with a monitored, sensed environment and allows them to control actively or allows the system to be automatically activated by users' motions (Marikyan et al., 2019; Sovacool & Del Rio, 2020). With the advance of AI technologies, the second generation of smart homes applied elementary forms of AI-based devices. The embedding of AI offers smart homes with more intelligent attributes, such as providing daily tasks assistance via built-in programmes (Marikyan et al., 2019), anticipating users' needs to optimise the use of devices (Sepasgozar et al., 2020), automatically making appropriate decisions based on different situations (Mekuria et al., 2021). Therefore, the emergence of AI technologies has propelled the first burst of research in smart homes and developed into one of the indispensable components of its knowledge structure.

Domestic energy management is the most popular extended research orientation of smart homes over the past decade and kept a relatively strong connection with the existing smart home research. The researchers' significant interest in the energy domain may be due to the emerging threats of climate change, global warming, and uncertainties of energy supply that have fuelled their interest in innovative solutions (Marikyan et al., 2019; Li et al., 2021). As the vital component of the smart grid, the smart home has the potential to surmount several key issues regarding existing patterns of energy production and consumption (Perri et al., 2020). For example, promoting the integration and utilisation of renewable energy resources into the residential buildings, e.g., solar power (Zhou et al., 2016); optimising energy consumption via demand flexibility programs, e.g., demand-response (DR) (Badar & Anvari-Moghaddam, 2020); and supporting the new paradigm shift of domestic energy use—prosumer mode, i.e., converting passive energy consumers into active energy prosumers towards more efficient domestic energy use (Koltsaklis et al., 2021).

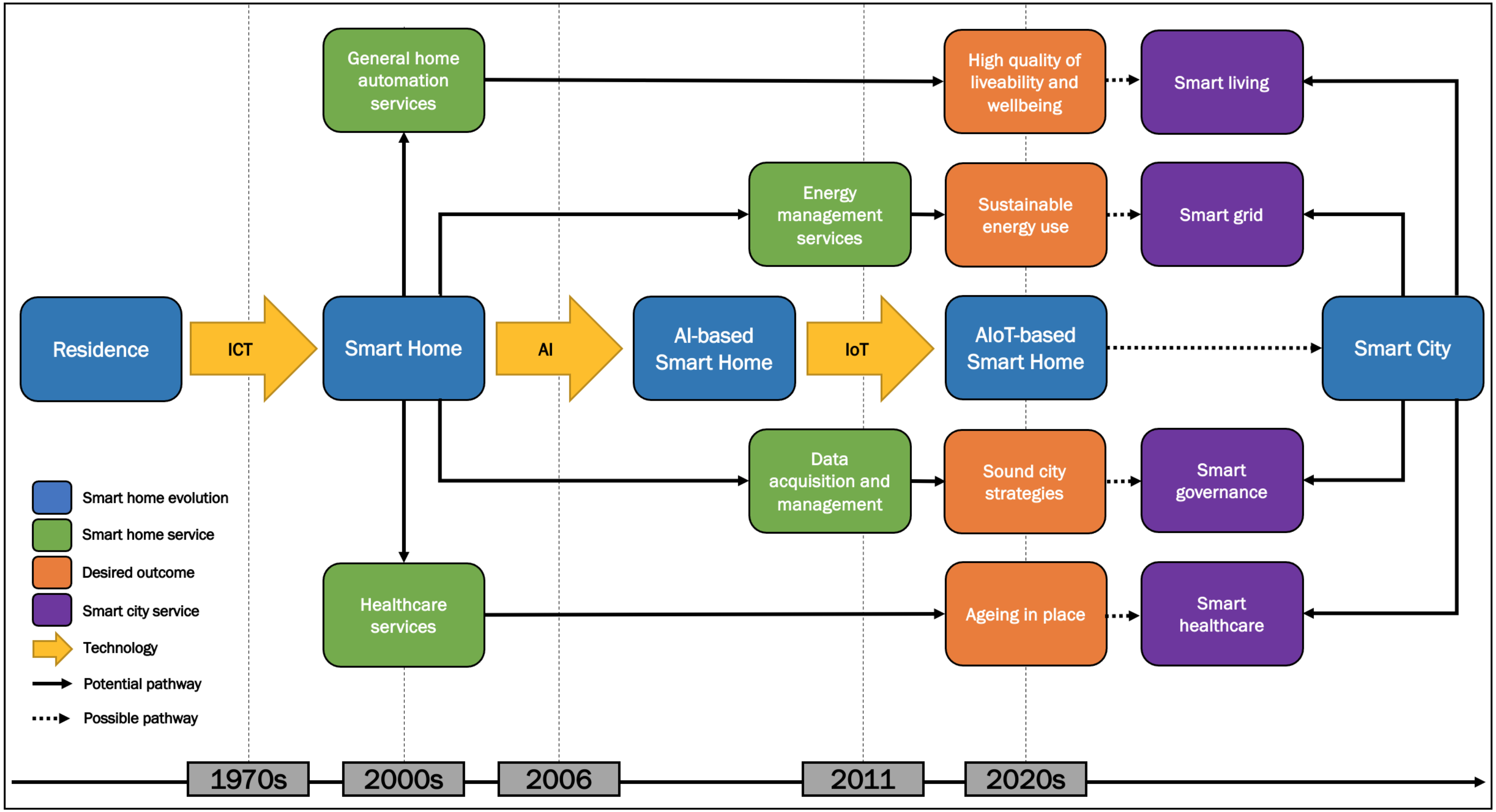


Figure 10. Evolution of smart home concept and related technologies and services

IoT for home automation is an emerging research cluster of smart homes, which has been rising based on the advance in ICT for home automation and having wide links with other smart home research clusters. In the past five years, the IoT for home automation has replaced domestic energy management's leading position and gradually evolved to the most popular research cluster in smart homes. Nowadays, the paradigms of IoT significantly influence the development of smart homes (Choi et al., 2021). The IoT added a new characteristic of 'interconnectedness' to the smart home, which means the third generation of smart homes can achieve a 'smart interconnection' between smart home devices, domestic appliances, and communication devices (Kim et al., 2019). The embedding of IoT can link the specific smart home applications together, e.g., general home automation, home-based healthcare, and domestic energy management, which has the potential to build a fully functional and comprehensive smart-home environment (Stolojescu-Crisan et al., 2021). Therefore, IoT will develop into the core of the smart home's knowledge structure in the future and undertake the key role of connecting other research clusters of smart homes.

The shift from basic residence to the smart home and smart living is an emerging trend in the residential sector. As the most basic building block of the city, the smart home has strong potential to support the digital transformation of urban development, i.e., shifting from the traditional city to the smart city (Lynggaard & Skouby, 2016; Hui et al., 2017; Kim et al., 2021). The third generation of smart homes (based on AI and IoT technologies) can provide residents with comprehensive home automation services to achieve the desired outcomes for smart cities in the form of enhancing liveability, sustainability, and wellbeing (Yigitcanlar & Kamruzzaman, 2019; Yigitcanlar et al., 2021).

In the home domain, smart homes provide residents with personalised life services to improve their quality of life, which play a key role in achieving smart living. In the energy domain, smart homes as a key component of smart grids have the potential to support the affordable low-carbon energy transition. In the healthcare domain, smart homes can support aging-in-place, which can maximise residents' wellbeing and provide a promising and cost-effective solution for the public health sector in the context of the rapidly ageing society and pandemic era.

Additionally, the study has found that smart home is the best venue assisting in acquiring various types of urban data, including personal data, energy data, and public health data (Hui et al., 2017). These digital data can assist policymakers and planners via a 'bottom-up approach' to develop the sound smart city strategies and improve the quality and implementation of city policies, and finally reach the goal of smart governance (Yigitcanlar et al., 2022). Figure 10 shows the evolution of smart home concept and related technologies and services in a timeframe form and shows the potential of smart homes to support the smart city agenda.

5. Conclusion

This study conducts a systematic scientometric analysis based on 17,153 smart home-related published papers over the last two decades. Apart from providing a clear and up to date summary of the extant literature, this study uncovered the coherent knowledge structure of smart homes and its evolution process from the colossal scale of publications. The study finds that the existing practices of smart homes are applied to general home automation, energy management, and healthcare domains. Since the 1970s, the smart home has undergone three major generation changes with the progressive embedding of advanced diachronous technologies, including ICT, AI, and IoT (also including AIoT). The latest generation of smart home has prospects to realise a fully functional and comprehensive smart living environment.

In sum, the study findings disclosed that: (a) Smart home literature has experienced steady growth during the last two decades; (b) Smart home research has mainly clustered around ICT for home automation, home information management, AI for home automation, domestic energy management, IoT for home automation, and home-based healthcare areas; (c) IoT is seen as the most popular technology to realise fully functioning smart homes; (d) Limited evidence exists on the urban perspective and social issues of smart home technology, and; (e) Smart homes are seen potentially as a strong driver of the smart city agenda.

Lastly, this study not only provides a retrospective analysis of the smart home field, but also explored the prospect of smart homes from a macroscopic angle, i.e., the perspective from home to city. The smart home has strong potential to support the smart city agenda as the desired outcomes achieved by a series of smart home services are expected to realise the common vision of the smart city. Nevertheless, so far, the existing smart home research was in favour of more technical characteristics and advances than the urban and social dimensions. Therefore, further research is needed to focus more on exploring the role of advanced technological innovations such as smart homes in shaping our cities and societies' future.

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