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Analysis of Climate-Oriented Researches in Building

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Abstract: Many factors and aspects of the construction and operation of buildings depend on climatic parameters and climatic zones, so these will be fundamental for adapting and mitigating the effects of climate change. For this reason, the number of climate-oriented publications in building is increasing. This research presents an analysis on the most-cited climate-oriented studies in building in the period 1979–2019. The main themes, the typologies of these investigations and the principal types of climatic zoning used in these studies were analysed through bibliographic and manual analysis. A broad spectrum of themes directly and indirectly related to climate and climatic zones and buildings was demonstrated. It was found that 88% of all climate-oriented investigations, to one degree or another, are within the scope of the general topic of energy conservation. A thorough understanding of all climate-dependent aspects will help in designing dwellings appropriately in different climate zones. In addition, a methodology that facilitates the establishment of a typology of climate-oriented research is presented. This typology can be used in future research in different scientific areas. It was also revealed that the climate zones of the National Building Codes of China, the USA and Turkey prevailed in the studies analysed.

Keywords: climate-oriented; buildings; building construction; climate zones; climate change; bibliometric

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1. Introduction

The construction industry, in general, and the building industry, in particular, are characterised by a high level of consumption of resources and emissions, which greatly impacts the environment [1,2]; 40% of the total energy consumption and one-third of the total greenhouse gas (GHG) emissions are associated with the construction and operation of buildings [3–5]. These GHGs, mostly CO_2, are emitted throughout the entire life cycle of buildings, although typically, the operation phase accounts for the majority of energy consumption and emissions compared to the construction and demolition phases [6–8]. It can be said that, currently, the construction industry is responsible for at least one-third of the anthropogenic effect of planetary climate change. Furthermore, global GHG emissions associated with building construction are expected to double by 2050 [9].

Given this problem, numerous investigations have been developed on this subject. Thus, scientific production in the field of buildings and climate change has been increasing in recent years, in addition to becoming more interdisciplinary. Among the published aspects is the development of methodologies that allow the use of current meteorological data for the energy simulation of the dwellings [10,11], as well as the development of works that are aimed at improving the hierarchy of climatic zones in buildings [12,13], so as to reduce the construction of inefficient houses from an energy point of view, and that take into account the urban, mesoclimatic and microclimatic conditions for buildings [14–18].

In the context of the evolution of knowledge about the climate system, as well as a knowledge evolution about the anthropogenic impact on the climate, research on minimising energy consumption in building construction by optimising the use of materials and GHG emissions has begun [19–21].

The development of climate change projections has sparked interest in conducting research on the change of climate zones for buildings in future climate conditions [22,23]. Furthermore, papers have been published on the analysis of changes in the total energy consumption of housing, as well as on the possible evolutions of changes in energy consumption for the cooling and/or heating of dwellings in different parts of the world [24–28]. In addition, other research has dealt with changes in the climate values of heating degree-days (HDD) and cooling degree-days (CDD) in the future [29,30]. Likewise, studies have been carried out on the analysis of adaptation techniques [31,32] and mitigation [33,34] in relation to climate change. The concern about climate change by researchers, public administration and society in general has promoted new research on the development of state standards and programs to control the negative effects of the building construction industry on the environment and policies to mitigate the effects of climate change [35–37].

Generally, all studies in building carried out based on climatological parameters, or in the context of climate change effects, can be identified as climate-oriented. Furthermore, for the most part, studies in building are characterised by pronounced localism, as it is generally implemented on a country, region or city scale. To a large extent, this situation is due to the research focus on the final consumer (government of countries, regions, municipal authorities, local construction companies, etc.). This is a substantial factor, as local building experts have a clear understanding of the particular characteristics of the region in which they work, conduct research and carry out applied projects. However, this may be a limiting factor if we consider the development of certain unified global techniques and methodologies. The climate factor clearly emerges from localism, which in turn affects the development of climate-oriented scientific works in building.

The studies mentioned above are directly linked to climate, with topics on climate zones for buildings, meteorological data for energy simulations and change in energy consumption under conditions of global climate change. However, there are also works that are indirectly related to climate, that is, studies that do not directly address climate research, but whose results or methodologies depend on climate or climate zones. For example, research on the composition and structure of the substrate of green roofs, where the authors show that the dependence on the optimal composition and structure of the substrate for better bioproductivity of the plants, is ultimately affected by the climatic zones [38], the selection of the best hybrid cooling system to minimise energy consumption and building emissions shows how each climate zone corresponds to a technically different optimal system [39], studies on passive building cooling have shown the importance of the climate zone with respect to the various techniques used [40] and the neutral temperature of the adaptive thermal comfort model and its relation to the minimum mortality temperature have a clear regional dependence [41].

For the above reasons, the dependence of the objectives, methodologies and/or results of studies on climate is based on the dependence on climate parameters and their variability, both temporal and geographical. In addition, a certain set of climatic parameters (at certain intervals) characterises some climatic zones. Therefore, the term climate-oriented is directly related to climate zones. Thus, in the works mentioned above, it can be seen that many aspects of building construction depend on climatic zones, specialised building zones or bioclimatic zones. Therefore, an understanding of all topics, parameters, techniques and methods of building according to climate zone will help in optimally designing buildings in different parts of the world.

Due to the large number of publications dealing with construction from a climate or climate-oriented point of view, either directly or indirectly, the main objective of this work is to establish a scientific map of climate-oriented studies in building, through a bibliographic and manual analysis of the most-cited publications in the period 1979–2019, and to identify the main topics, the typologies of these investigations and the main types of climatic zoning used in these studies and the principal climate zones in which the investigated works were implemented.

2. Materials and Methods

2.1. Bibliometric and Bibliographic Methods

In recent years, different methods of bibliometrics have been widely used to analyse the development of different fields of science. Bibliometrics is divided into two main areas:

- Performance analysis, where several scientific producers are evaluated using bibliographic data and applying bibliometric index (h-index, hg-index, etc.).
- Analysis of science maps, where the structural and dynamic aspects of the field of science and its temporal evolution are studied, while also analysing the intellectual connections and their evolution in the field of knowledge [42].

To study a scientific map, it is necessary to create and analyse bibliographic networks. In the study of Moral-Munoz et al. [42], a description of the main types of bibliographic networks is presented, including the following:

- Co-citation networks—two publications can be considered as co-cited if a third publication quotes both. The strength of the co-citation relationship will depend on the number of publications citing both publications together (Figure 1). Papers A and B are associated because they are co-cited in a reference list of papers C–E. Therefore, the greater the number of co-citations, the stronger the co-citation relationship [42,43].
- Bibliographic coupling networks—in this case, two publications are bibliographically coupled if both publications cite a third (Figure 1). Papers A and B are bibliographically coupled because they have common cited paper C–E in their reference list. A higher number of references shared by two publications indicates a stronger bibliographic coupling between them [42,44,45].

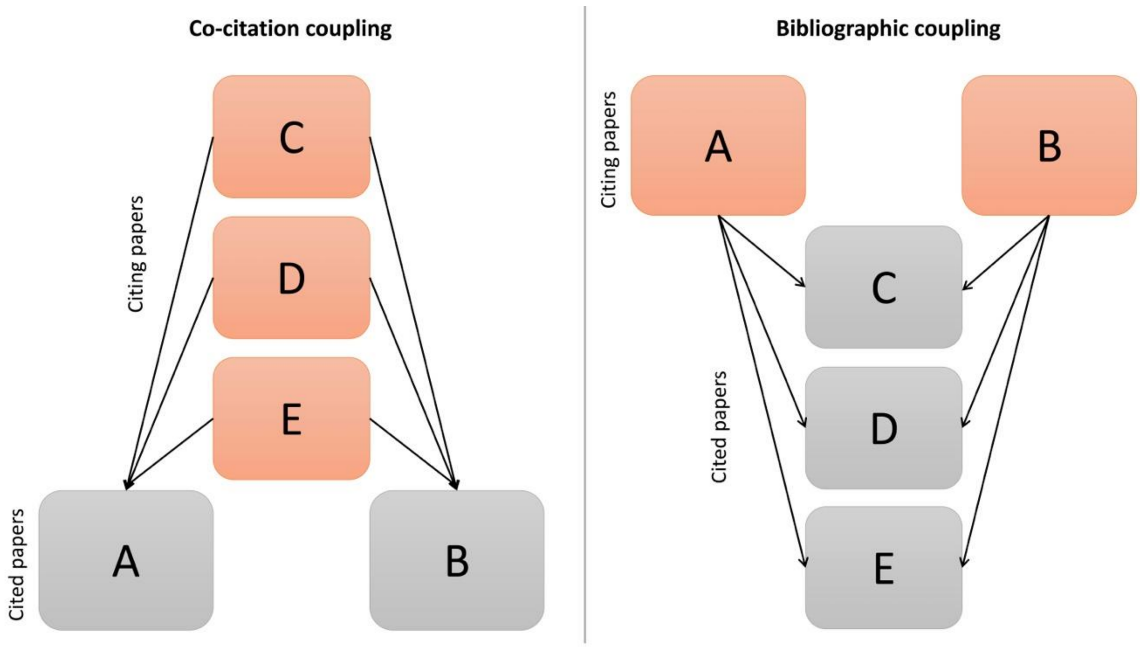

Figure 1. Bibliographic and co-citation coupling difference.

Small and Koenig, in 1977, clustered journals based on the bibliographic coupling method, demonstrating good results in comparison with the manual classification method [45]. In addition, the claim that the bibliographic coupling method is capable of grouping documents of similar research types has been confirmed in Jarneving's research [46]. Furthermore, in the work of Boyack and Klavans [46], the use of bibliographic coupling showed better results in the clustering process, compared to co-citation analysis and direct citation analysis. For these reasons, in this paper, it was decided to use this methodology for science mapping analysis.

2.2. Data Collection

This work is based on the main articles on climate-oriented studies in building. Papers published on the Web of Science (WOS) up to the end of 2019 were analysed. To find the articles, the following formula was used in "advanced search":

TS = ("climate zone" and "building") OR TS = ("climatic zone" and "building") OR TS = ("climate zones" and "building") OR TS = ("climatic zones" and "building") OR TS = ("climate zone" and "buildings") OR TS = ("climatic zone" and "buildings") OR TS = ("climate zones" and "buildings") OR TS = ("climatic zones" and "buildings") OR TS = ("climatic zoning" and "building") OR TS = ("climatic zoning" and "buildings").

The search included all languages and all types of documents for all years of operation of the WOS (until the end of 2019). Citation Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH and ESCI.

The initial sample drawn from WOS included a total of 1403 documents. First, manually, the abstracts and keywords of all publications were reviewed, and publications not related to the building scientific field were excluded. After this additional manual examination of publications, a total of 1280 documents remained. These 1280 documents covered the publication period from 1979 to 2019.

To select the publications with the most significant impact, 10% of the most cited papers were used (with more than 35 citations in WOS at the end of 2019). After applying this filter, 128 articles were selected covering the period from 1995 to 2018.

2.3. Clustering Tools and Methodology

In the first stage of data processing, the Bib Excel tool was used to transform the .txt file of the WOS to a Citation Network File (with a number of commonly cited papers in references for each pair of articles). Of the 128 articles that made up the database, only 114 presented common references and therefore formed the basis of our cluster analysis.

To analyse the Citation Network File, it was processed in the program Gephi, version 0.9.2 [47]. Gephi is open-source software for graphics and network analysis, which provides the possibility of visualisation and research of all types of complex networks and systems, dynamic and hierarchical graphics. Gephi was implemented for a bibliometric analysis of research in different fields of science, applying different methods for analysis [48–50]. Note that Gephi is the most reliable software for scientific map analysis [42]. In this research, a 114×114 matrix was formed in Gephi with common references numbers for each pair of papers.

For clustering of the article network, a modularity cluster detection algorithm was used. The cluster definition algorithm is heuristic, based on modularisation optimisation and was first published in 2008 by Blondel et al. [51]. This algorithm (or Louvain's method [51]) has several advantages, such as the ease and speed of implementation and the ability to analyse large and weighted networks. In comparison with other methods, Blondel's algorithm showed better results for the definition of clusters [51,52]. The general methodology of this research is presented in Figure 2.

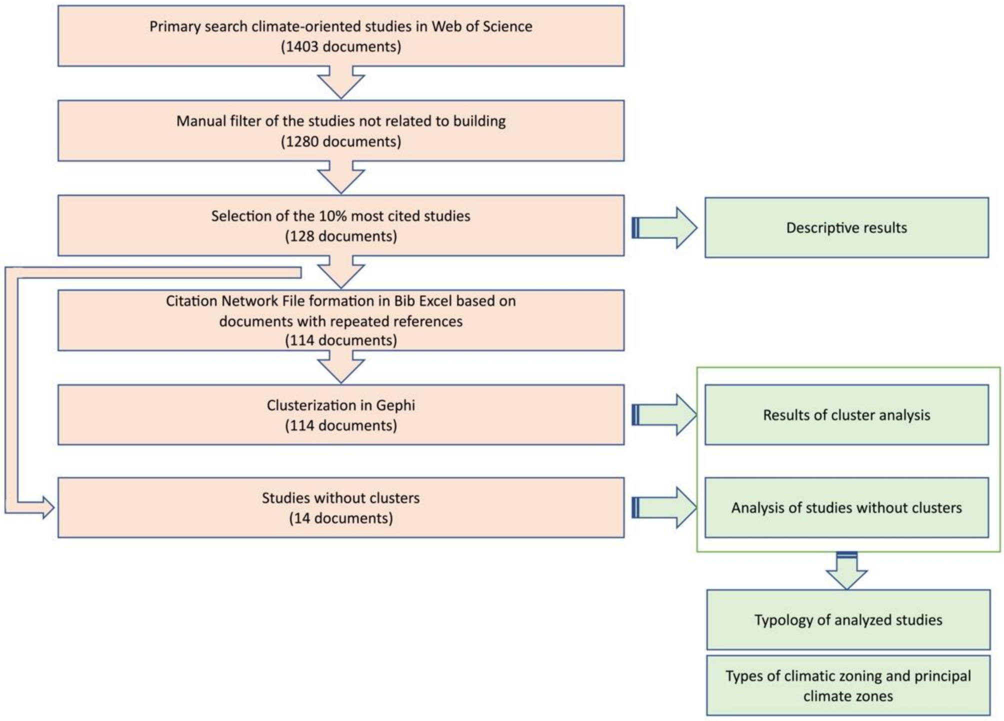

Figure 2. The general methodology of the present research.

The scope of the present research to identify the scientific map of climate-oriented publications can be summarised as follows:

- Only WOS publications were used.
- Ten percent of the most frequently cited papers were analysed.
- A bibliographic coupling method was used for clustering.
- Works published from 1995 to 2018 were analysed.

3. Results and Discussion

3.1. Descriptive Results

The time trend of the 128 publications used in this paper, all with more than 35 citations, is presented in Figure 3. It shows an upward trend, with a maximum number of documents published in 2012. The first work was published in 1995, and in the following 15 years (period: 1995–2011), 60 papers were published, while in a more recent period of only seven years (2012–2018), a similar number has been published, specifically 68 articles. The typology of the works studied includes 112 full research articles, 10 reviews, four article proceeding papers, one review book chapter and one editorial; these results once again highlight the intensive research being carried out on the subject under study in the present work.

Note that the earliest studies were related to the analysis of the effect of climate change on variations in the energy consumption of buildings [53], as well as to the analysis of the method of energy conservation by improving the thermal envelope of buildings [54]. The maximum of mean number of citations in Figure 3 in 2002 is associated with the publication of one of the fundamental articles on adaptive thermal comfort [55]. Noted that in the period up to 2005, principal studies related to the study of microorganisms in the indoor air were conducted [56,57]. Furthermore, in 2005, some of the main works on the study of cool roofs as energy saving techniques were published [58,59]. In 2008, a study on Fanger's thermal comfort analysis was published [60]. In 2014, work on the pairing of indoor thermal comfort and an analysis of the energy saving potential was published [61]. The most recent work analyses the reduction of carbon emissions from office buildings as a result of the effective building energy efficiency policy in China [62]. In general, over the past decades, the dominant theme of most of the papers under study has been energy saving in buildings. At the same time, this topic has gradually absorbed new emerging topics, for example, the topic of adaptive thermal comfort has been integrated into the energy saving concept. Urban heat island mitigation techniques, systems optimisation, building envelope optimisation techniques and emission reduction techniques have also become progressively more complex. Meanwhile, the analysis of microorganisms in the indoor air has remained outside the general topic of energy saving.

The papers included in this study collect a total of 8777 citations in WOS, of which 24.6% are concentrated in ten of them, as shown in Table 1. As can be seen, this generally involves research related to interior thermal comfort, the search of optimal thermal insulation and the use of renewable energy to improve the energy performance of houses.

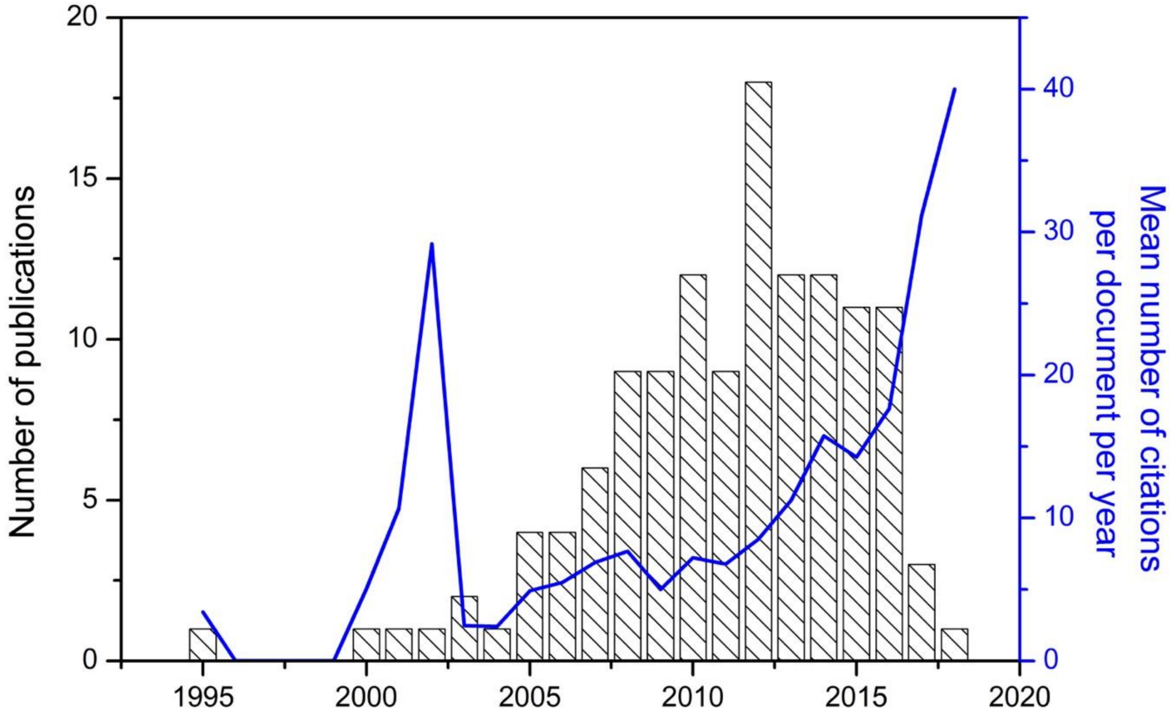

Figure 3. Temporal evolution of analysed publications.

The 128 publications analysed were produced by 359 authors. Table 2 presents the authors with the most significant impact, the total number of citations, the number of publications of each author used in this study and the main work of each author. Three-hundred-and-thirteen of the identified authors participated in only one publication, and the average citation value per author was 80. Most of the analysed studies are concentrated in China (24%) and the USA (20%), with the rest of the countries being in the minority (7% from Greece, 6% from Spain, 5% from Australia and the remaining 38% from 22 other countries); in fact, the five authors with the largest number of publications belong to Chinese institutions (Lam J.C, Yang L., Jing Y.Y, Li D.H.W. and Wang J.J.), which comprise 2847 of the 8777 citations.

Table 1. The most-cited bibliography used in the analysed researches.

Title of Publ.	Authors	Journal	Type	Year	Tot. Cit.	Tot. Cit./Year	Ref.
Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	De Dear R.J.; Brager G.S.	Energy and Buildings	Article proceedings paper	2002	496	29.2	[55]
Thermal comfort and building energy consumption implications—A review	Yang L.;Yan H.Y.; Lam J.C.	Applied Energy	Review	2014	308	61.6	[61]
Solar air conditioning in Europe—an overview	Balaras C.A.; Grossman G.; Henning H.M.; Ferreira C.A.I.; Podesser E.; Wang L.; Wiemken E.	Renewable & Sustainable Energy Reviews	Review	2007	241	20.1	[63]
Forty years of Fanger's model of thermal comfort: comfort for all?	Van Hoof J.	Indoor Air	Review	2008	220	20.0	[60]
The adaptive model of thermal comfort and energy conservation in the built environment	De Dear R.; Brager G.S.	International Journal of Biometeorology	Article	2001	192	10.7	[64]
Zero energy buildings and sustainable development implications—A review	Li D.H.W.; Yang L.; Lam J.C.	Energy	Review	2013	182	30.3	[65]
Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey	Bolatturk A.	Applied Thermal Engineering	Article	2006	150	11.6	[66]
Impact of climate change on energy use in the built environment in different climate zones—A review	Li D.H.W.; Yang L.; Lam J.C.	Energy	Review	2012	128	18.3	[67]
Energy performance of building envelopes in different climate zones in China	Yang L.; Lam J.C.; Tsang C.L.	Applied Energy	Article	2008	122	11.1	[68]
Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings	Hoyt T.; Arens E.; Zhang H.	Building and Environment	Article	2015	119	29.8	[69]

Table 2. Principal authors of the analysed researches.

Author	Last Affiliation (5 October 2019)	Num. Publ.	Sum. Cit.	Year of the First Publ.	Title of More Cited Publ.	Ref.
Lam J.C.	City University of Hong Kong, Kowloon, Hong Kong	8	983	2008	Thermal comfort and building energy consumption implications—A review	[61]
Yang L.	Xi'an University of Architecture and Technology, Xi'an, China	7	904	2008	Thermal comfort and building energy consumption implications—A review	[61]
Jing Y.Y.	North China Electric Power University, Baoding, Baoding, China	4	268	2010	Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	[70]
Li D.H.W.	City University of Hong Kong, Kowloon, Hong Kong	4	424	2011	Zero energy buildings and sustainable development implications—A review	[65]
Wang J.J.	North China Electric Power University, Baoding, Baoding, China	4	268	2010	Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	[70]
Balaras C.A.	National Observatory of Athens, Athens, Greece	3	379	2000	Solar air conditioning in Europe—an overview	[63]
De Dear R.	The University of Sydney, Sydney, Australia	3	326	2001	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55	[55]
Hong T.Z.	Lawrence Berkeley National Laboratory, Berkeley, United States	3	158	2013	Commercial building energy saver: an energy retrofit analysis toolkit	[71]
Mago P.J.	Mississippi State University, Starkville, United States	3	137	2009	Analysis and optimisation of the use of CHP-ORC systems for small commercial buildings	[72]
Tsang C.L.	City University of Hong Kong, Kowloon, Hong Kong	3	251	2008	Energy performance of building envelopes in different climate zones in China	[68]
Ucar A.	Firat Üniversitesi, Elazig, Turkey	3	169	2009	Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey	[73]
Wan K.K.W.	City University of Hong Kong, Kowloon, Hong Kong	3	195	2008	Building energy efficiency in different climates	[74]

3.2. *Results of Cluster Analysis*

Next, an analysis of the results of the Citation Network processing in Gephi, as well as the clustering, was carried out, identifying the main directions of scientific development in climate-oriented studies in building. As clustering was based on common references, Table 3 shows the analysis of the most commonly used references in the analysed studies. In total, 114 analysed studies cited 4172 publications. At the same time, work published in ASHRAE Transaction [75] is presented in the references of 12 analysed studies.

Table 3. Most used articles in the references of analysed studies.

Year	Journal/Book	Title of Publ.	Num. of Rep.	Ref.
1998	ASHRAE Transactions	Developing an adaptive model of thermal comfort and preference	12	[75]
2008	Applied Energy	Energy performance of building envelopes in different climate zones in China	9	[68]
1998	Energy and Buildings	Thermal adaptation in the built environment: a literature review	8	[76]
2011	Building and Environment	Future trends of building heating and cooling loads and energy consumption in different climates	8	[77]
2002	Energy and Buildings	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55	7	[55]
1970	Book	Thermal comfort. Analysis and applications in environmental engineering.	7	[78]
2002	Energy and Buildings	Extension of the PMV model to non-air-conditioned buildings in warm climates	7	[79]
1998	ASHRAE Transactions	Understanding the adaptive approach to thermal comfort	7	[80]
2005	Renewable Energy	Energy policy and standard for built environment in China	7	[81]
2003	Applied Energy	Towards sustainable energy buildings	6	[82]
2009	Energy and Buildings	Analysis and optimisation of CCHP systems based on energy, economical and environmental considerations	6	[83]
2008	Energy and Buildings	Integration of distributed generation systems into generic types of commercial buildings in California	6	[84]
2012	Applied Energy	Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications	6	[85]
2010	Applied Energy	Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	6	[70]
2010	Energy	Environmental impact analysis of BCHP system in different climate zones in China	6	[86]
2011	Applied Energy	Influence analysis of building types and climate zones on energetic, economic and environmental performances of BCHP systems	6	[87]

The map of bibliographic coupling clusters obtained from Gephi analysis (Figure 4) made it possible to identify the following nine clusters, in addition to the general outline of the relationship between Citation Network works:

- Cluster 1—Mitigation of the effects of UHI and cooling of buildings (with the following principal topics: Building cooling, UHI mitigation techniques, Outdoor thermal comfort, General energy saving techniques and Indoor thermal comfort in UHI conditions).
- Cluster 2—Indoor air microorganisms.
- Cluster 3—Combined heating, cooling and power systems.
- Cluster 4—Economic and energy optimisation of the thermal insulation.
- Cluster 5—Indoor thermal comfort.
- Cluster 6—Energy optimisation of school buildings.
- Cluster 7—Infiltration and air leakage.
- Cluster 8—Windows and façade optimisation.
- Cluster 9—Energy simulation, conservation and meteorological data (with the following principal topics—Simulation of energy consumption, Multiparametric and multi-objective optimisations, Schedule occupancy optimisation, Heat and energy recovery ventilators, HVAC systems optimisation, Indoor thermal comfort models implementation for energy simulation, Climate change and energy consumption, Building climate zones and Meteorological data for simulation).

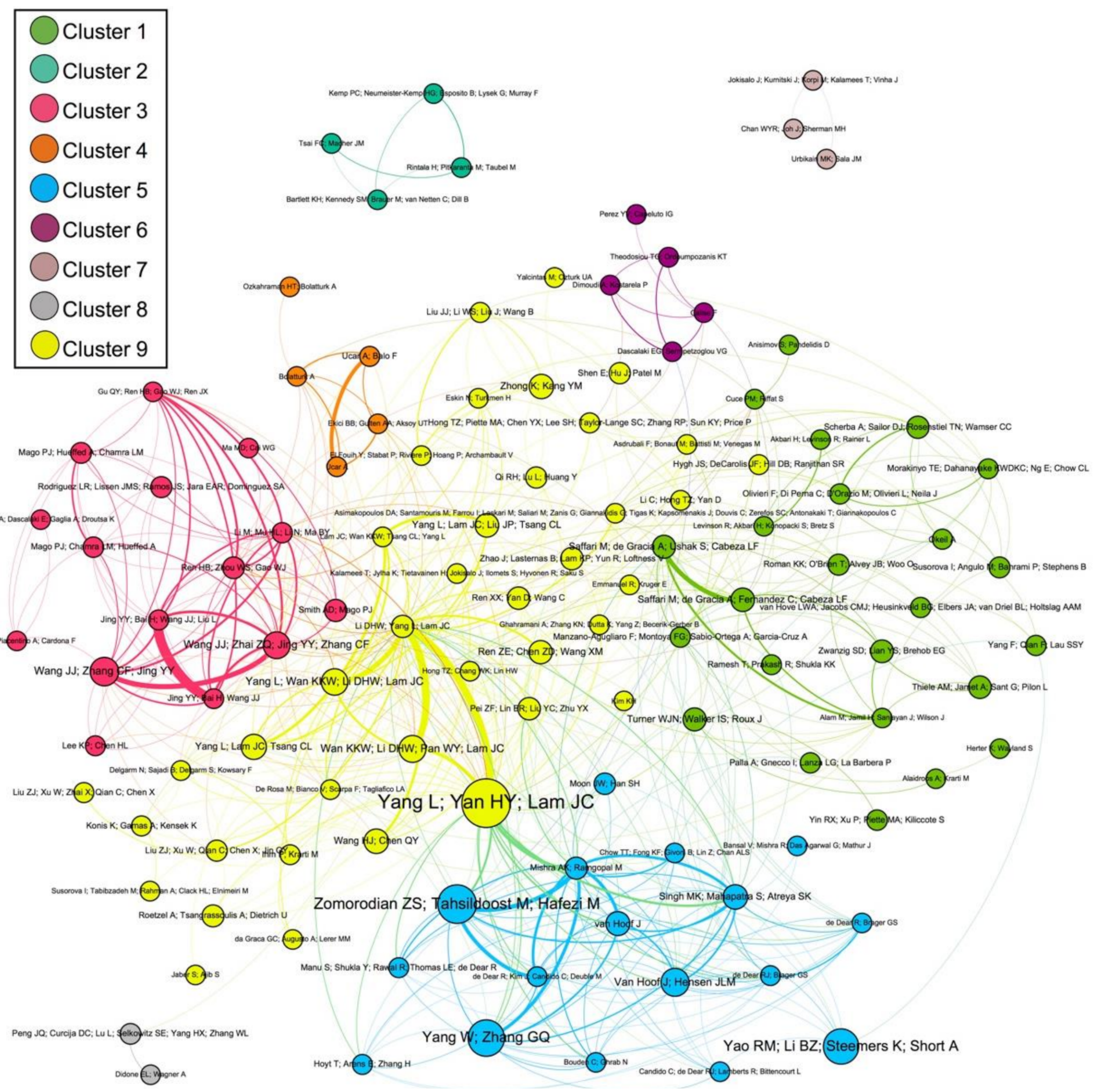

Figure 4. Map of bibliographic coupling clusters.

In this clustering, 114 publications have been used, with 517 interconnections (edges) of repeated references in each pair of papers, varying from one common reference to 41. Figure 4 shows that, of all the clusters identified, seven are connected to each other, and two are isolated; depending on the number of references in common, the thickness of the edge is greater if there are more references in common between two works. There is a greater number of common references in studies by the same authors, e.g., (Yang L; Yan HY; Lam JC) [61] and (Li DHW; Yang L; Lam JC) [67]. On the other hand, the size of the circle of each article depends on the degree of involvement of each work in the Citation Network of the study; thus, the work of (Yang L; Yan HY; Lam JC) [61] is grade 51, which means that 48 study network papers are used in his references, and three study network papers cite this work; instead, the research of (Ozkahraman HT; Bolatturk A) [88] is grade 1 and located on the periphery of the network, which means that only 1 study in the network uses this work in its references. Given that the present study used works with high citation numbers in the scientific environment, the main emphasis in the analysis of the results will focus on the clustering and the definition of the main themes of the studies, and not on how these works relate to each other in this research network.

In general, the seven clusters have a clear correspondence with one single scientific topic. However, Cluster 9 includes ten themes, due to its central position among other clusters; therefore, the themes of this cluster can overlap with the topics of other clusters. In addition, Cluster 1 includes five themes.

During the analysis of the publications, it was observed that most of the works are within an overall theme of energy conservation in the buildings. Outside the subject of energy conservation is the Indoor air microorganisms theme (Cluster 2). Moreover, the Indoor air microorganisms theme is isolated, just as most of the work of Indoor thermal comfort is outside the subject of energy conservation; this is because, although research has recently been carried out on the application of thermal comfort models in the process of energy simulation and for the evaluation of the energy efficiency of buildings, most of the studies in this cluster focused on the development of thermal comfort models. The topic of outdoor thermal comfort (Cluster 1) is also vaguely related to the topic of energy conservation. The economic and energy optimisation of the thermal insulation (Cluster 4) is difficult to relate completely to the topic of energy conservation, as the basis of the works on this theme is the methodology for finding an economic optimum between the insulation material and the economic costs of heating and cooling in buildings.

It can be said that the definition of clusters using Gephi and the bibliographic coupling method showed good results for identifying peripheral and isolated topics. However, in the case of centrally located topics and overlapping topics, additional manual analysis of the content of the clusters is required. Therefore, a detailed analysis of each cluster will be presented below.

3.2.1. Cluster 1—Mitigation of the Effects of UHI and Cooling of Buildings

The first cluster includes a total of 24 investigations (Table S1). These include general methodologies for energy conservation in buildings, techniques for mitigation the various effects of urban heat islands (UHI), the improvement of outdoor thermal comfort in UHI conditions and techniques for reducing energy consumption for cooling in buildings.

The first and oldest works of this cluster were focused on the idea of energy conservation. They analysed the application of cool-roof energy conservation techniques for non-residential and commercial buildings in different cities and in different climate zones, showing energy simulation results [58,59]. Subsequently, studies appeared that focus on the search for optimal bioclimatic architectural strategies [89] as well as the optimal design of residential building envelop systems [90], all of this with the general aim of reducing energy consumption in housing and improving indoor thermal comfort.

Mitigation techniques were developed, ranging from cool-roofs, green roofs and green façades, to the application of phase change materials (PCM) for building envelopes and the search of the optimal PCM for different cities and climate conditions. These generally show an evolution from field studies of the thermal effect and the radiation balance of various UHI mitigation techniques to complex computational simulations of the energy saving potential, considering indoor thermal comfort. Thus, in 2010, a paper was published on the search for optimal building shapes [91] with the main purpose to mitigate the effect of UHI using simulation with the ENVI-Met tool, which showed that the shape of buildings can improve ventilation in the streets, and the use of green-roofs, will help mitigate the effect of UHI. In this respect, research on techniques for mitigating the effect of UHI was subsequently carried out. Thus, in 2011, based on Energy Plus simulations in six ASHRAE climate zones in the USA, it was determined "that white and green-roofs are effective strategies for UHI mitigation" [92]. In Italy, based on field experiments and computer simulation, a numerical model for calculating the thermal resistance of green roofs was presented [93]; finally, numerical models were developed for calculating the thermal resistance of green façades [94]. Continuing with the application of UHI mitigation techniques in countries such as the USA and Australia [95], the use of PCMs in building envelopes, which can generate potential annual energy savings of 17–23%, is emerging [96]. In this regard, it has become clear that "PCM performance highly depends on the weather conditions, emphasising the necessity to choose different PCMs at different climate zones" [97]. More recent work focuses on finding optimal PCM melting temperatures for different cities and climate zones [98], as well as combining the use of PCM with indoor thermal comfort models in energy simulations [99].

This cluster also includes two publications that address the study of outdoor thermal comfort in UHI conditions, as well as the development of methods to mitigate the thermal and energy effects of UHI [100,101]. In both investigations, the authors point out the importance of the urban wind environment for outdoor thermal comfort in two cities located in different climate zones. By 2017, estimates were already being made of the effect of green roofs on outdoor/indoor temperature and cooling demand under four different climate conditions and urban densities with ENVI-met and Energy Plus tools [102]. In this sense, studies have evolved from focusing solely on the dwelling to an analysis of buildings with an aspect of interaction with the urban environment, e.g., on the scale of streets and neighbourhoods.

Additionally, because the effect of the increased energy consumption of buildings in UHI conditions is a problem generally in cities with hot climates and mostly related to cooling, this cluster presents research on energy reduction techniques for cooling. In 2010, two studies were published by different scientific groups in California on economic methods for energy conservation. In these cases, the critical-peak pricing effect [103] was studied in the case of cooling energy for residential housing. Furthermore, the optimisation of HVAC system operation settings (pre-cooling strategies) [104] for the minimisation of energy consumption in commercial buildings was analysed. In addition, the use of pre-cooling strategies was also used for residential buildings [105].

3.2.2. Cluster 2—Indoor Air Microorganisms

The second cluster, with four papers, deals with Indoor air microorganisms and includes studies on the presence of bacteria, fungi and microbes inside the office, school and residential buildings, as a consequence of the variability of these microorganisms, which is related to climatic zones and ventilation techniques, as well as solutions to reduce their presence.

Initially, airborne fungi species and culturable bacteria content analysis research focused on office buildings. In 2003, it was shown that an HVAC system helps to minimise the concentration of airborne fungi species in the indoor air of New York offices, whereas this is not the case in Perth [56]. In addition, the seasonal and climatic dependence on the content of culturable airborne bacteria in office indoor air of 100 office buildings in 10 US climate zones was revealed [57].

In another study, airborne bacterial concentration was analysed in 39 schools in Canada, showing a direct relationship between the concentration of airborne bacteria and the concentration of CO_2 in school classrooms, demonstrating the importance of implementing ventilation in school facilities in the climate zone studied [106]. Finally, in 2012, house dust microbial communities were investigated, and conclusions were drawn that residences located in a temperate climate zone showed higher dust microbial diversity than in tropical climate zone [107].

3.2.3. Cluster 3—Combined Heating, Cooling and Power Systems

The third cluster presents 15 investigations, listed in Table S2, dealing with climate-dependent optimisations and an analysis of energy saving potential of combined heating, cooling and power systems (CHCP).

Initially, the primary interest of the scientists was to investigate the energy effects of the use of CHCP systems in airport buildings due to a problem related to the high level of energy consumption in these types of buildings, while noting the good potential for energy savings from using these systems in more southerly climatic zones [108]. Thus, in the oldest study of the cluster, the problem of using systems with the right power in the aspect of energy conservation in airport buildings was raised. Systems optimisation measures at Greek airports could result in potential energy savings of 15–20% for the southern climates and 35–40% for the northern climates [109].

Subsequently, studies already focused on office buildings were addressed. Thus, in 2009, in the USA, a method was demonstrated to optimise a combined heating and power system (CHP) in this type of building, and in the context of three objectives: energy saving (ES), operation cost reduction (OCR) and environmental impact minimisation (EIM)—only for carbon emissions; it was shown that electricity and natural gas CHP system optimisation is dependent on climate zones and operational mode [110]. In the case of a building in Beijing, solar CHCP systems were considered, and the OCR optimisation objective was extended in the context of LCA methodology. Moreover, the EIM objective was extended to global warming, the chemical composition of precipitation and the respiratory effect of pollutants, and the results indicate that the energy saving and pollutant emissions reduction potentials of the FTL operation mode are better than that of the FEL mode [111]. The same authors of the previous study used a similar approach for multi-objective optimisation of the electricity and natural gas CHCP system in a commercial office building in Beijing. In this research, the optimal equipment size and operation mode was obtained. The authors found that "if energy benefits are paid more attention, following the thermal load (FTL) mode is the first choice, while if environment performance is more valuable, following the electricity load (FEL) mode is the good operation strategy" [112]. In the two papers presented above for Beijing, the authors note that their conclusions were obtained for the specific climatic conditions of this city.

In another investigation, the application of CHP systems with Organic Rankine Cycle (ORC) was analysed in small commercial office buildings in six climate zones in the USA. The authors show that the CHP–ORC system helps reduce the primary energy consumption cost and carbon dioxide emissions in comparison with the same building, operating solely with a CHP system in all climatic zones of study [72].

In the case of hotel buildings, optimisation methodologies aimed at three objectives (ES, OCR and EIM) were presented for CHCP systems. The authors concluded that CHCP systems are most relevant in the aspect of primary energy conservation and emission reduction in a cold climate with high heating energy needs [70]. On the other hand, in the USA, it proved effective in the hybrid method for operating a CHP system of a hotel building (which either follows the thermal or the electric demand), by comparing the energy simulation results of this method with FEL and FTL modes of operation strategies in 16 climate zones. It was shown that the choice of the CHP system operation method will depend on the climate zone for this type of building. Therefore, in all climatic zones, the efficiency of the system with the hybrid operational mode was greater than with FEL and FTL. However, the FEL operational mode is more suitable for warm climatic zones of ASHRAE (1A, 2A, 2B, 3A, and 3B) and FTL for cold climatic zones [113].

In the research of Wang et al., the authors developed and compared the use of optimal CHP systems for four types of buildings (hotel, school, office and hospital) in five cities in China, with different climates in the context of three objectives (ES, OCR and EIM). The authors concluded that energy demands depend on the type of building, which also affects the optimal design of the CHP. In general, throughout the year, the CHP system in office buildings consumes less energy, spends less and emits less CO_2 among the four categories of buildings. In terms of saving primary energy, CHP systems are optimal for severe cold climates; in terms of reducing carbon emissions, they are optimal for mild climates [87].

In 2012, the possibility of applying CHCP systems in a multi-storey residential building, under the climatic conditions of Shanghai City, was analysed. The authors summarised that, from an economic point of view, the introduction of these systems is not profitable for residential buildings and that a reduction in natural gas prices may make it possible to use these systems in such buildings [114]. On the other hand, in Spain, the design of the integrated hybrid solar thermal (PV) micro-CHP system was analysed and applied to an apartment building in five climate zones. In this paper, a discussion was presented on the problems of using micro-CHP systems in residential buildings, and it was concluded that CHP systems are optimal for cold climate zones [115].

The evolution of the application of CHCP systems for different types of buildings is remarkable. Initially, these systems were used for airport buildings and other types of public buildings. Recently, researchers have been analysing the possibility of applying these systems to residential buildings. In addition, it is significant that the timing and mode of operation of these systems depend on the type of building, climate zones and target (energy saving, economic or ecological) that is most desired with the use of CHCP systems.

3.2.4. Cluster 4—Economic and Energy Optimisation of the Thermal Insulation

In the fourth cluster, five studies are presented that develop a methodology for determining the optimum thickness of thermal insulation based on minimising the parameters that affect it.

Thus, the first paper presented a methodology for finding the optimal thickness of thermal insulation for exterior walls in a cold climate zone in Turkey. This methodology was based on an approach of minimising the economic costs of heating as well as the cost of thermal insulation [88]. Following the methodology of the previous study, subsequent work searched for the optimum thickness of the exterior wall insulation, considering the economic–energy balance using (i) heating degrees-days, (ii) the cost of the insulating material and (iii) the cost of fuel used to heat the house for a decade [66]. In subsequent studies, the methodology was extended by adding the search for the optimum fuel for different climate zones [73], as well as the search for the optimum thickness of the thermal insulation of the roof, evaluating also the effect of the thermal insulation on the environment, thus reducing CO_2 and SO_2 emissions [116] and, finally, extending the number of materials analysed for use as thermal insulation, determining, for each climate zone in Turkey, the optimum material and structure in the external walls [117].

3.2.5. Cluster 5—Indoor Thermal Comfort

The fifth cluster is composed of 17 papers on indoor thermal comfort, which generally deal with the concept of the adaptive thermal comfort model and its evolution over time, the conventional thermal comfort model and the potential for energy savings in the application of thermal comfort models in buildings. All studies of this cluster are presented in Table S3.

The adaptive thermal comfort (ATC) model for naturally ventilated buildings, developed by de Dear and Brager, as an alternative to the conventional model of thermal comfort [64], with all the limits of its application, the energy saving potential and the problems of its development [55], was adopted as an amendment to the ASHRAE 55 Standard and then went through different stages of evolution from its conceptual formation to its application in buildings to minimise energy consumption.

First, it was found that the ATC model has a clear dependence on local climatic conditions and the thermal preferences of the population in different regions of the world. Generally, the ATC model is more applicable to regions of the world with a warm climate [118–120]. These studies showed that the effect of indoor air speeds on thermal comfort in buildings with natural ventilation requires detailed research for different climate zones [119,120].

The application of the ATC model in colder climate conditions was also considered with estimates of potential energy savings [121]. It has been shown that the ATC model can only be used in the summer period to natural ventilated office space under Dutch climatic conditions, with a cooling energy saving potential of up to 10%. [122]. For conference and exhibition building in Beijing, a hybrid HVAC system operated with natural ventilation cooling and with the application of a high standard level of the ATC model can be used between 63% and 66% of the hours in July and August, and that can help to reduce energy consumption [121].

This cluster presents studies not only on the ATC model, but also on the conventional model of thermal comfort. Thus, in 2008, although the author accepts the best applicability of the ATC model for naturally ventilated buildings, van Hoof conducted a review on the predicted mean vote (PMV) model of thermal comfort created by Fangér, demonstrating its strengths and weaknesses. Possible methods of optimisation and improvement of the PMV model were also analysed [60]. Later, the authors of a study carried out in Hong Kong concluded on the importance of taking into account air velocity for thermal comfort in an air-conditioned office building and recommended the use of air-conditioning systems with individual control for this type of building [123].

The existence of two models of thermal comfort, of course, leads to the development of research in terms of comparing them with each other. For example, in India, for residential buildings, it was concluded that the ATC model is more suitable for reflecting the thermal preferences of the population than the PMV model [124]. A good comparative study of the two models was published in 2013 on field studies in thermal comfort research, presenting all research according to the four Köppen climate zones. The authors concluded that the conditioned spaces have narrower comfort zones compared to free-running buildings. In all climate zones, the most popular adaptation methods are related to the modification of air movement and clothing of the building occupants [125]. Additionally, there were still attempts to develop a single ATC model for air-conditioned and natural ventilated office buildings [126].

Most of the above studies focus on office and residential buildings. However, on the other hand, school buildings also receive significant attention from thermal comfort researchers. The interest in studying thermal comfort in schools is because children spend most of their time there, and their academic performance and emotional health depend on thermal comfort. In one of these works, the acceptable temperature range for Australian school children was analysed. This research was carried out in nine schools, in three climate zones, with different HVAC systems. It was identified that the comfortable thermal sensation of the children was between 1 and 2 °C lower than the thermal sensation of the adults. Within this research, a review of work on thermal comfort in schools and in different geographical areas is presented [127]. Furthermore, in different countries of the world, there are policies to optimise energy costs in educational institutions, which depend on indoor thermal comfort [128]. Generally, in previous investigations, it was concluded that thermal comfort depends on the type of building and the age and gender structure of the building users.

Following, after the stages of development and evolution of the models, other studies on the practical application of the thermal comfort models can be found, in which the adjustment of the thermostat configuration based on the thermal comfort models is discussed, to minimise the energy consumption of the buildings in different climatic zones [69,129]. Finally, in one study, the use of an earth–air–tunnel heat exchanger is analysed for the minimisation of the energy consumption maintaining thermal comfort, according to the ATC model of the ASHRAE standard [130]. It can be said that the choice of using an ATC model, a conventional model or a combination of both for the operation of an HVAC system to minimise energy consumption, depends on the climate zone in which the building is located.

3.2.6. Cluster 6—Energy Optimisation of School Buildings

The sixth cluster consists of five articles dealing with the energy optimisation of school buildings, mainly based on the objective of maintaining indoor comfort conditions and focusing on a holistic approach (energy efficiency, thermal comfort and indoor air quality).

This cluster addresses energy-efficient strategies in school buildings and different climate zones, based on aspects such as maximising energy conservation, improving indoor air quality and visual comfort [131]. The studies have shown that this requires optimising the design parameters of the building, its shape, orientation, thermal insulation and HVAC systems for different climate zones [132], light control, infiltration, glazing, night ventilation and size of windows [133], in addition to the use of renewable energy (usually solar), to minimise energy consumption in buildings [134,135].

3.2.7. Cluster 7—Infiltration and Air Leakage

The low number of works in this cluster, with only three publications, presents studies on the infiltration of residential buildings in general, as well as infiltration specifically of windows and exfiltration of dwellings. In this cluster, there are general conclusions on the need to develop studies on infiltration and exfiltration in different regions of the world for different types of housing and their effect on energy efficiency.

In Finland, the relationship between infiltration and the energy consumption of the heating and ventilation system of a single-family house was analysed. It was determined that infiltration causes 15–30% of the heating and ventilation energy use of the dwelling. In addition, the authors proposed a climate zoning methodology for infiltration [136]. In Spain, the effect of window infiltration on the process of energy certification of windows was analysed. Two energy balance equations through the window were presented for two climate zones in Spain, depending on window leakage at a pressure difference of 75 Pa and outdoor temperature difference of 20 °C. Based on the energy balance equation, it was possible to carry out an energy qualification of the windows [137]. The last work carried out in the USA analysed air leakage in 134,000 houses. It was established that the built year and climate zone are the two most influential parameters on air leakage. This is a good methodological work to understand the air leakage concept in relation to buildings [138].

3.2.8. Cluster 8—Windows and Façade Optimisation

The eighth cluster is the smallest of those analysed and is made up of two studies about the energy saving potential of semi-transparent photovoltaic panels for windows and façades. One of these presents a possible energy conservation evaluation methodology with semi-transparent PV windows in offices in two cities in Brazil and one in Germany [139]. The second one presents a methodology for finding the optimal design of a ventilated photovoltaic double-skin façade to minimise energy consumption in housing. [140]. In both cases, the energy saving efficiency of these systems was directly related to the climate zones.

3.2.9. Cluster 9—Energy Simulation, Conservation and Meteorological Data

This cluster, with 39 publications, is the largest, has a central location among the other clusters (Figure 4), and deals with energy conservation. All studies in this cluster are presented in Table S4 and include studies on the simplification of methodologies for estimating energy consumption in buildings [141,142]; the relationship between thermal comfort [61] and visual comfort [143] with energy conservation in buildings; and comparisons of the energy efficiency of simulated dwellings according to the use of national building standards, both in Italy and Spain, for different building climate zones, showing the most favourable energy regulations [144]. Due to its size, and to facilitate the analysis of the results, this cluster has been manually divided into five sub-themes, which will be analysed below: (i) Multiparametric and multi-objective optimisations; (ii) Heat and energy recovery ventilators; (iii) Schedule occupancy and occupant behaviour; (iv) Renewable energy systems; (v) Meteorological data and climate change.

Sub-Theme 1—Multiparametric and Multi-Objective Optimisations

This first sub-theme presents 13 studies on the optimisation of buildings for energy conservation through four different approaches in the use of energy-efficient measures (Table 4): (i) building envelopes, (ii) architectural parameters (building orientation and geometry), (iii) building service systems and equipment, and (iv) internal conditions (thermal/lighting comfort, building occupation, occupant behaviour and indoor environmental conditions).

Table 4. Principal studies of the multiparameter optimisations.

Parameters for Optimisation	Tools	Year	Ref.
Insulation and thermal mass; aspect ratio; the colour of ext. walls; glazing system; windows size; shading devices	Energy Plus and validation with measured data	2008	[145]
Shape coefficient; building envelops (wall, roof)	Num. model—Overall thermal transfer value (OTTV) method	2008	[68]
Passive solar design; internal loads (lightning and equipment); operations of fans and pumps; wall insulation	Simulation tool DOE-2.1 E	2008	[74]
Window design; 4 types of glazing	TRNSYS software Economic model life cycle cost (LCC) criterion	2011	[146]
Transparent composite façade system (TCFS) vs. glass curtain wall system (GCWS)	DOE-2 (eQuest) Economic model LCA	2011	[147]
Orientation; wall and roof ins.; win. size; WWR; glazing; lighting; infiltration; cooling Temp.; refrigerator energy effic. lev.; boiler type; cooling sist. type	DOE-2 LCC	2012	[148]
Win. orientation; WWR; width to depth ratio (W/D)	Energy Plus	2013	[149]
Building occupation; ATC model; CO_2 emission	Energy Plus	2014	[150]
6 principal parameters: climate; envelope; equipment; operation and maintenance; occupation behaviour; indoor environmental conditions	Energy use audit	2014	[151]
Energy conservation tool for optimising existing buildings and to design new buildings. 100 configurable energy conservation measures; IEQ	CBES toolkit Energy Plus	2015	[71]
Multicriteria optimisation; orientation; win. size; overhang specification	Multi-objective non-dominated sorting generic algorithm (NSGA-II) and Energy Plus	2016	[152]
Tool for multicriteria optimisation; passive environmental design strategies; building geometry; orientation; fenestration configuration y others.	Passive Performance Optimisation Framework (PPOF) Energy Plus	2016	[153]

It can be seen that the older publications considered a limited number of parameters for optimising buildings and only with an energy purpose. With the progress of research, the number of parameters and measures analysed has increased significantly, and secondary objectives of optimisation have also been developed, be they economic, ecological or health-oriented. These objectives were later integrated with the energy aspect of the optimisation. Recently, there has been a trend towards a decrease in the number of parameters and optimisation techniques, through the search for more efficient methods and parameters for different types of buildings, in different climate zones [65].

Sub-Theme 2—Heat and Energy Recovery Ventilators

This sub-theme presents three papers related to heat and energy recovery ventilators. In the case of heat recovery ventilators, in countries such as France and China, it has been shown that the energy efficiency of an optimal ventilator depends on the climate zone and the type of building [154,155]. Besides that, for an energy recovery ventilator, the seasonal dependence of weighted coefficients (latent and sensible heat efficient) of enthalpy efficiency in different cities was demonstrated [156]. These conclusions are derived from the direct dependence of the energy efficiency of these ventilators on the outside temperature, the moisture content of the air, and the latent and sensible heat content.

Sub-Theme 3—Schedule Occupancy and Occupant Behaviour

The third sub-topic includes three papers and focuses on assessing the impact of building occupancy on energy consumption and finding models of schedule occupancy closer to the real occupancy in residential [157] and office buildings [158]. In the case of offices, it was shown that the improvement of the schedule occupancy model led to a decrease in the energy consumption of the HVAC system during simulations in hot climate types and an increase in cold climate types. It also highlights the importance of selecting daily optimal setpoint temperatures for HVAC and demonstrates the potential for energy saving in different climates. For small, medium and large office buildings, setpoint temperatures for an HVAC system in the range of 22.5 ± 3 °C would lead to 10.09–37.03%, 11.43–21.01% and 6.78–11.34% energy saving, respectively, depending on the climate zones [159].

Sub-Theme 4—Renewable Energy Systems

The fourth sub-theme, with four papers, deals with energy saving techniques in buildings from the use of renewable energy-based systems such as solar thermal systems, photovoltaic systems [160], solar-assisted liquid desiccant air-conditioning systems [161], ground-source heat pumps [162] and hybrid ground-source heat pumps with an auxiliary heat source [163]. In this work, a clear dependence was shown on the possibilities and limits of the application of the above systems in the different climate zones.

Sub-Theme 5—Meteorological Data and Climate Change

This fifth sub-theme shows nine papers linking energy conservation and meteorological data. To simulate energy consumption, meteorological data is needed, so the quality and selection of the data are important.

Results of the use of typical meteorological year (TMY) data for energy simulation were compared with the use of real measurement data over a period of 30 years [164], with the use of typical principal component year (TPCY) data [165], and with the use of actual meteorological year (AMY) data [166]. It was concluded that, in the era of availability of meteorological data and the increasing power of computer technology, it is necessary to use real meteorological data from different years to simulate the energy consumption of households in order to obtain more realistic results or, as in Finland, to develop individual methodologies to create energy reference year data for energy simulations in different climate zones [167].

The simulation of energy consumption for the present, meanwhile, has generated scientific interest in the study of future energy consumption. This interest has a basis in the development of climate models and forecasts, as well as the unification of climate change projections. Thus, in 2011, researchers presented construction methods for adapting designed residential buildings to climate change [168]. In 2012, other authors pointed out the importance of the ability to analyse how buildings will respond to future climate changes and assessed possible quantitative changes in energy use and carbon footprints. In addition, they discussed possible climate change mitigation and adaptation strategies [85].

In the USA, changes in energy consumption in different types of buildings and climate zones were assessed according to IPCC climate change projections. It was found, by the 2080s, residential energy consumption will increase in climate zones 1–4 of ASHRAE and decrease in climate zones 6–7 of ASHRAE [25]. Similarly, in Greece, the effect of climate change on the energy consumption of buildings will be more noticeable in warmer climate zones [169].

3.3. Studies without Clusters

As noted above (Figure 2), 14 papers were left out of the clustering, which are presented in Table S5. In general, these studies are related to the topics that have been identified in the previous analysis of the clusters, such as thermal comfort and energy saving, CHCP and renewable energy systems, multicriterial optimisation for energy saving, climate change and change of energy consumption, etc.

Nevertheless, there are interesting researches, for example, on energy efficiency, where, with a group of analytical hierarchical processes, it was possible to identify 17 basic parameters out of 83 parameters that should be used to assess the energy efficiency of residential buildings in the hot summer and cold winter zones in China [170]. Likewise, studies are also presented on climatic building zones in Spain [171] and on the development of bioclimatic zones in India, with potential for the development of passive solar design strategies for residential buildings [172].

3.4. General Analysis of the Typology of Climate-Oriented Research

After a detailed description of the content of each cluster and a complete in-depth analysis of the papers in these clusters, it was concluded that there are seven main types of climate-oriented studies in building (I–VII). One-hundred-and-twenty of the 128 studies analysed could be classified into a particular type (Tables S1–S5). To facilitate an understanding of these seven types of studies, a schematic diagram is shown in Figure 5.

In the first macro-group, comparative works were classified. These were carried out to demonstrate differences between various climatic zones or geographical locations, as well as to develop general conclusions and patterns:

I. In 41.6% of the analysed studies, the research involves studies in a single geographical location for each climate zone studied. The results and conclusions obtained for each geographical point are extrapolated to the whole climate zone, and this logic applies to all climate zones of the study. The results for the climate zones are then compared with each other or are used for developing general conclusions.
II. In 26.7% of the studies analysed, the research involves studies in more than one geographic location for each climate zone studied. The results and conclusions obtained for different geographical locations are extrapolated to the whole climate zone, and this logic applies to all climate zones of the study. The results for climate zones are then compared with each other or are used to develop general conclusions.
III. A small proportion (6.7%) of the studies analysed compares results in different geographical locations to obtain general conclusions, without focusing on climatic zones. In the second macro-group are investigations on the development of recommendations, standards, and conclusions for a specific area or geographical location:
IV. In 10% of the studies analysed, conclusions were drawn for a climatic zone, extrapolating results and conclusions from a representative geographical location.
V. In 5.8% of the analysed studies, conclusions were drawn for one climate zone, extrapolating results and conclusions from several representative geographical locations.
VI. A small proportion (4.2%) of the studies analysed were designed to obtain conclusions and results for a specific geographical location, without focusing on climatic zones. Finally, the last group of studies:
VII. A small proportion (5%) of the studies analysed focused on the development of climate zones, including the analysis and identification of urban climate zones.

Figure 6a shows the time distribution graph of the main types of climate-oriented research. It can be observed that, in general, up to 2006, comparative works of Types I, II and III prevailed. After 2006, studies of Types IV, V, VI and VII started to appear. The maximum variability of climate-oriented research type in building was in 2010. This may be connected to the logical feasibility of doing comparative work first, looking for common patterns and differences in results in order to develop conclusions. This type of work leads to the need to generate studies to develop and establish standards and techniques, to find optimal systems and their correct functioning for certain geographical points and/or climate zones. For this reason, the studies corresponding to Types IV, V and VI appeared later. Similarly, there is a need for works on the development of climate zones; as these are more specific investigations, they require more involvement from specialists in different areas of science and the use of multiple climatological and meteorological data. Finally, these studies require more time and computing resources. Actual examples of Type VII are studies on the definition of new climatic zones for building construction [173,174] and urban local climate zones [175].

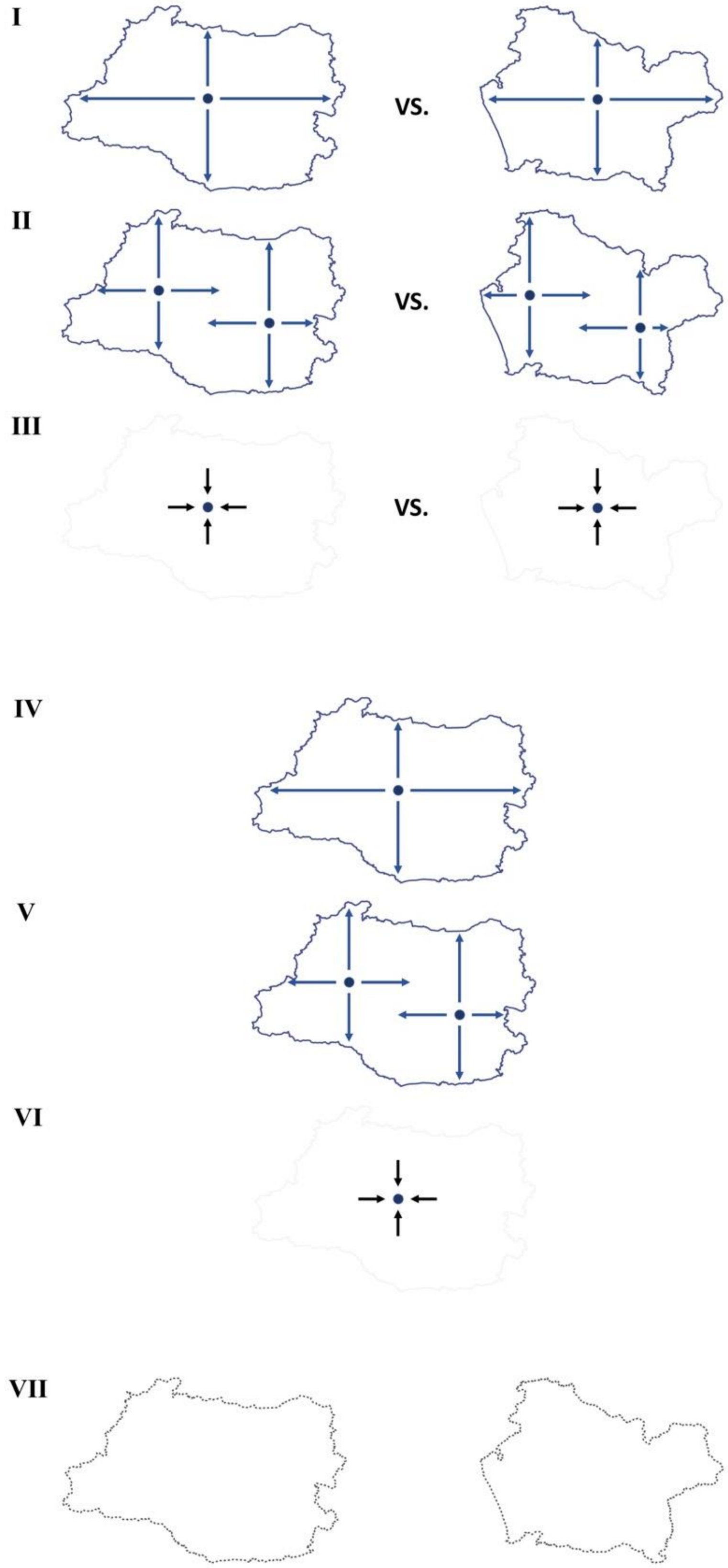

Figure 5. Seven main types of climate-oriented researches in building.

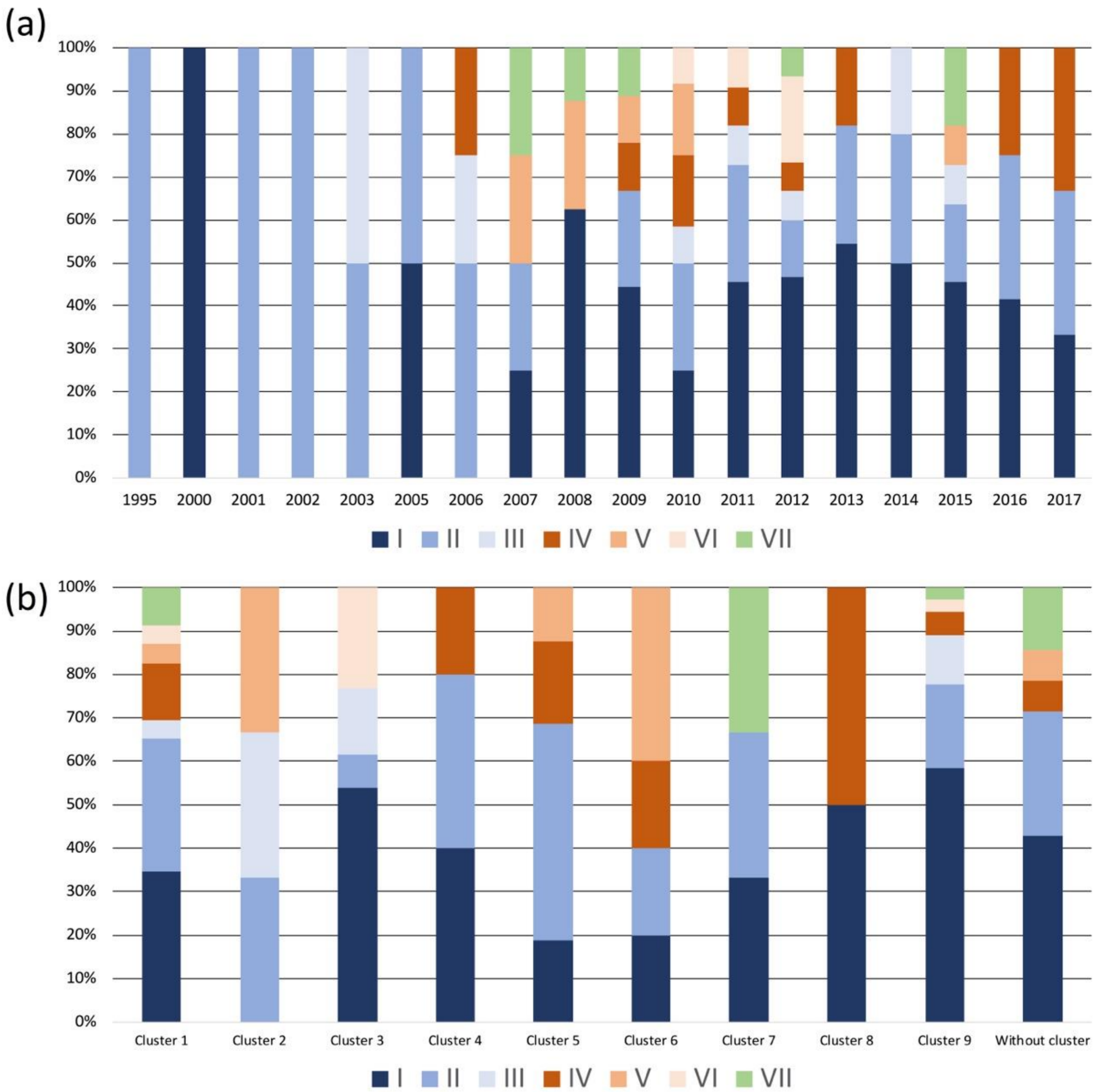

Figure 6. Temporal distribution of the seven main types (**a**) and content of each of them in the nine clusters analysed (**b**).

Figure 6b shows the remarkable difference in variability of the types of climate-oriented research in the clusters. Additionally, the types of analysed studies are presented in Tables S1–S5. Cluster 1 presents the largest variability in the types of climate-oriented research, from research on the establishment of urban climate zones, to the qualification of the application of UHI mitigation techniques for certain specific geographical locations. Among the other clusters with a large number of studies, Clusters 3 and 9 are mostly characterised as comparative studies (>75%) and Type I (>50%). This is due to the particularities of this works, which are based on the use of meteorological data for a single reference point, extrapolation of the results to a climatic zone and comparison with other zones. In addition, Cluster 3 has a higher number of Type VI studies, which corresponds to research carried out in a single geographical location without focusing on the climatic zone. In comparison, Cluster 5 has 32% of the Type IV and V studies, generally associated with the development of ATC models for different climate zones and specific regions based on a single or several geographical locations.

In general, it can be concluded that among all the investigations analysed, those corresponding to Type I are more representative, so concerns arise about the adequacy of the extrapolation of the results and the local conclusions for the whole climate zone.

Certainly, the practice of using one geographical point to cover a specific climate zone should no longer be used for climate-oriented research in building. Type II and V studies must be carried out in a more frequent manner. For example, recently, Type V research related to the assessment of the energy demand of buildings in various countries was published [176,177]. Additionally, recent work corresponding to Type II about the procedure for selecting glazing at different points of the same bioclimatic zone has been published [178].

Furthermore, the typology presented for climate-oriented researches in building can be applied and used in future research, not only in the scientific area of buildings.

3.5. General Analysis of Types of Climate Zoning and Climate Zones Used in Climate-Oriented Research

As climate-oriented research was analysed, the main types of climate zoning used in the reviewed studies are presented. In addition, the climate zones most commonly engaged in the research were analysed. Figure 7 shows an overview of the different types of climate zonings analysed in this study. It can be seen that most of the works included climate zonings from the National Building Codes (BCs). In 120 studies, where it was possible to identify the type of zoning, the National BC climate zonings were used 74 times. The total number of times zonings were used exceeds the number of studies, because some research has included more than one type of climate zoning. Additionally, the types of zoning and principal zones of the studied research are presented in Tables S1–S5.

Among the most popular National BC climate zonings were China (used 17 times in the studies reviewed); the USA, specifically ASHRAE zones (15); and Turkey (8). It can be noted that in the USA, some research has included the use of climate zones of the International Energy Conservation Code (IECC), the California Energy Commission (EC), the U.S. Energy Information Administration (EIA) and the Statewide Pricing Pilot (SPP) and climate zones of the California Public Utilities Commission. The IECC zones were generally used for studies related to energy analysis. The California EC zones were applied for state-oriented work in California.

Within the climate zones of National BC, China's "hot summer and cold winter" climate zone was the most popular in the works analysed. This zone includes the cities of Shanghai, Nanjing, Nanchang, Wuhan and Hefei, among others. Beijing, in contrast, is in the "cold" zone. Note that Chinese studies show a clear tendency to use representative geographical locations for each climate zone. China's research usually attempts to cover the whole country, using at least one representative location for each of its five climatic building zones.

In the case of the USA and the ASHRAE zones, the climate zones most commonly used in the studies are 3B and 4A. Zone 3B represents the cities of Los Angeles, San Diego and Sacramento, among others. On the other hand, zone 4A represents the cities of New York, Washington and Philadelphia, among others. Zones 1A, 1B and 5C are less represented. Moreover, there are no works with climate zone 0. This is related to the climatic reality of the USA, as there are no such zones in the territory of this country. For this reason, for some studies, geographical points from other countries of the world are used to cover the areas that are missing. Additionally, note that due to the clear ASHRAE zoning methodology, it is possible to identify ASHRAE zones in other geographical locations around the world. Among all the studies analysed in this research with National BC zones, only ASHRAE zones have this characteristic. For example, recent work on the analysis of the applicability of ASHRAE climate zones in the territory of China [179].

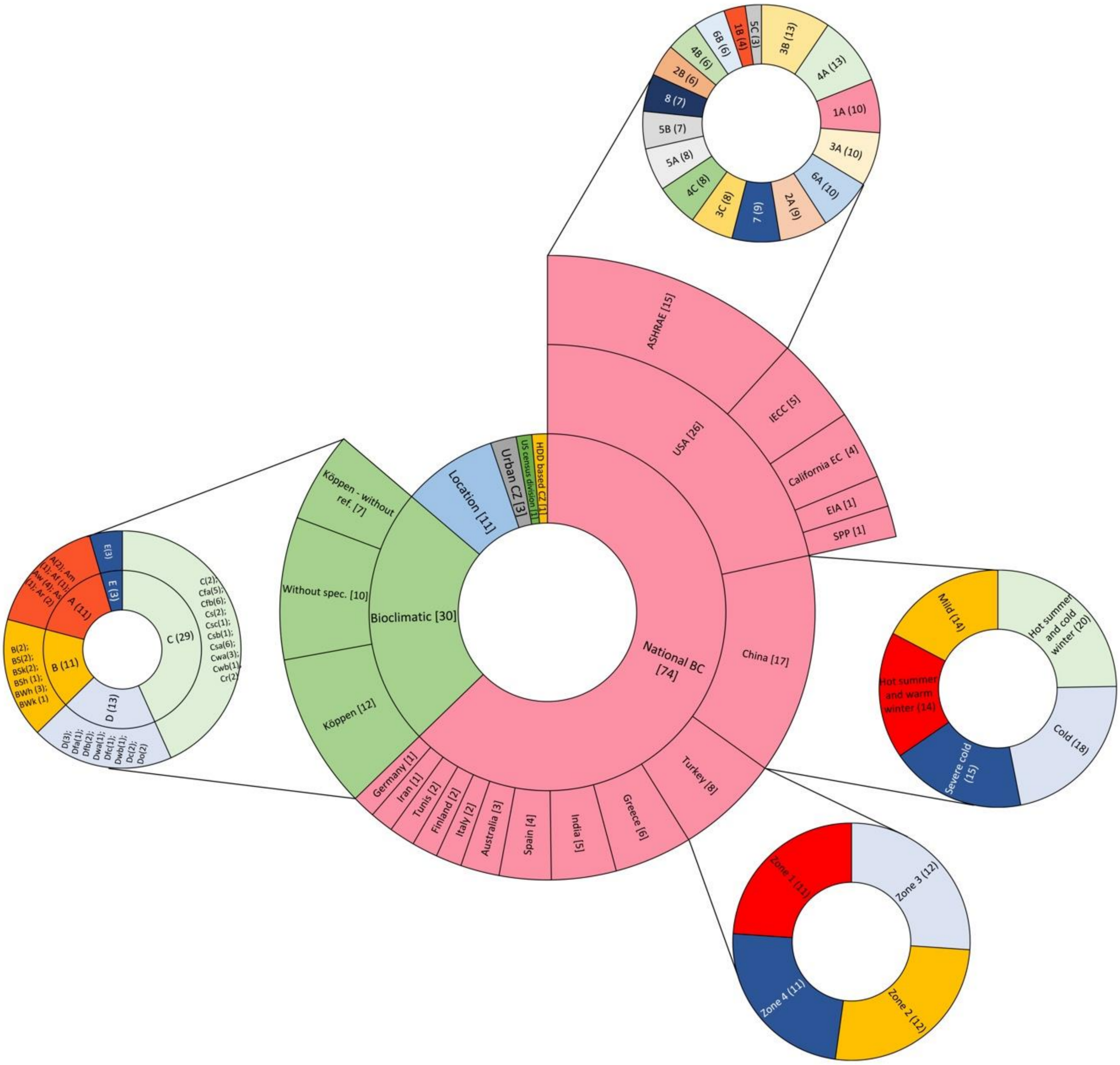

Figure 7. Main climate zonings [number of times of use] in analysed works and the most used climate zones (the number of geographical points corresponding to each zone).

In the case of Turkey, almost all the works generally involve the four climate zones of Turkish Thermal Insulation Standard TS 825. In this standard, zone 1 represents cities with warmer thermal conditions—Antalya and Izmir, among others. Zone 4 represents cities with colder thermal conditions—Erzurum and Kars, among others. Istanbul and Ankara are categorised in zones 2 and 3, respectively. The papers corresponding to Cluster 4 were totally realised under Turkish climate zones. At the same time, the methodology of this cluster has firmly entered the scientific field of building construction, which is reflected in its use for actual research [180,181].

Other National BC climate zonings exist: for example, in studies in Greece, climate zones from buildings' Thermal Insulation Regulation (TIR) and the Hellenic Regulation on the Energy Performance of Buildings (REPB) were used. Mostly these zones have been used in the research grouped in Cluster 6. The climate zones of Energy Conservation BC of India were used in three investigations belonging to cluster 5, "Indoor thermal comfort".

Moreover, in the climate-oriented studies, bioclimatic zones were used 30 times, generally, from the Köppen or Köppen–Geiger classification. The papers reviewed did not necessarily include bibliographical references that would allow the type of classification to be identified. In certain cases, it was difficult to establish the type of classification, because a quantitative description of the climate was used, for example, “warm climate” or “temperate climate”. However, among the works where the zones could be identified, the most used Köppen zones in the climate-oriented works analysed were identified (Figure 7). It can be seen that climate type C (Temperate climates) is the most popular, analysed in 29 geographical locations, where Cfb (Oceanic climate or Marine west coast climate) and Csa (Mediterranean hot summer climates) are the Köppen subzones most commonly used. Zone Cfb represents cities located on the Atlantic coast of northwest Europe, southwest Australia and New Zealand. Zone Csa represents cities located in the Mediterranean Sea region, part of the Pacific coast of the USA and part of Australia. Additionally, it can be said that Köppen’s climate zone E (Polar and alpine climates) is less represented in the climate-oriented building studies analysed. On the other hand, 11 studies involved specific geographical locations, three of which dealt with urban climate zones (Figure 7).

The distribution of climate zoning types used in the different clusters is presented in Figure 8. It can be seen that among the clusters with a large number of investigations, i.e., Clusters 5 and 1, there is a higher percentage of work based on bioclimatic zones, compared to Clusters 3 and 9, plus the “without clusters” investigations, which are related to energy simulations based on National BC climate zones. This is because, in the case of simulation-related research, building regulations strictly related to climatic building zones must be applied, as, for example, in current research of the assessment of the profile of the use of the HVAC system based on the Spanish national BC in the aspect of energy efficiency of residential buildings [182]. In the case of thermal comfort studies, and urban areas studies, outdoor comfort works can be carried out using bioclimatic zones, such as, for example, in actual studies about adaptive comfort in temperate and tropical climates [183,184].

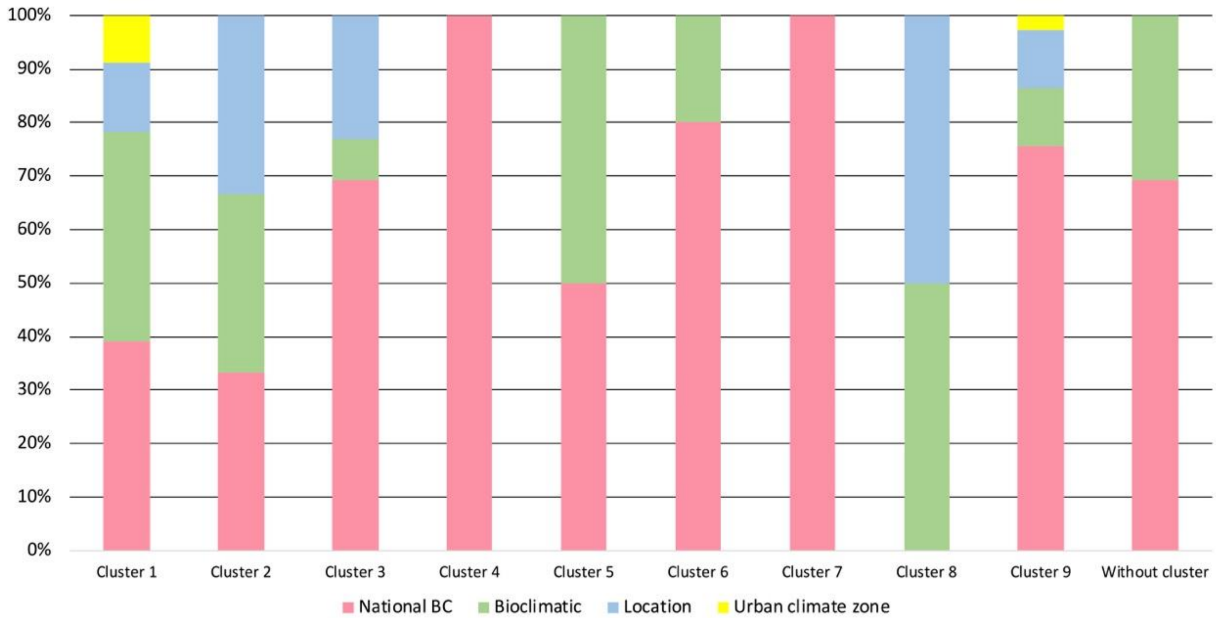

Figure 8. Main climate zonings for the clusters.

Note that most of the studies have a well-determined local view, these were carried out in climate zones established under the National BCs of different countries. In general, it can be said that differences were revealed both in the typologies of studies and in the types of climate zoning used in the works of various clusters and topics.

3.6. Future Lines of Research and Recommendations

The following are the main recommendations for future climate-oriented studies, both in the scientific field and in decision-making in public administration in building, considering the trends and knowledge gaps observed:

- In issues connected with UHI, it was found that there is a need to develop research and analyse the effect of UHI on energy consumption for the heating and cooling of dwellings in regions with cold climatic conditions and on climatic zoning for building.
- The topic of Indoor air microorganisms should be integrated with that of thermal comfort, and IEQ control should be applied to different types of buildings.
- In the area of thermal comfort, it is important to carry out research on the development of adaptive thermal comfort models for different age groups, for different types of buildings and in different geographical areas, and to a greater extent applicate in the practice of the thermal comfort models for functioning HVAC systems.
- As far as visual comfort is concerned, it is important to carry out studies on different types of buildings and climate zones. The use of visual comfort is also an objective in the multi-objective energy optimisation of school buildings.
- In terms of different building systems, it is important to develop comparative work in search of optimal parameters and of operating modes for CHCP systems for different types of buildings in various climate zones, to analyse hybrid building HVAC systems and energy saving capabilities in different climate zones; study possibilities for the integration of renewable energy systems; and analyse and map renewable energy capacities, which can be used for air conditioning, domestic hot water, and electrical energy in buildings in different regions of the world.
- In climate zoning, the need for research on dynamic building standards, that consider the effects of future climate change is notable. On the other hand, it is important to carry out studies on the climatic zoning of infiltration and to analyse further the energy effects of infiltration in different regions of the world.

It is possible to implement all the recommendations presented above under actual climatic conditions and taking into account the effect of climate change in future periods. In general, a significant amount of research related to climate change, the dynamics of climatic zones and modifications in meteorological parameters can be implemented. At the same time, note that the Sixth Assessment Report (AR6) of the IPCC is expected to be published in the coming years. This document will present new climate change assumptions, which will be based on four geophysical RCP scenarios of the AR5 and five new Shared Socio-Pathways (SSP) scenarios [185]. The development of Phase 6 of the Coupled Model Intercomparison Project (CMIP6) is also expected [186]. Approximately 70 climate modelling centres are involved in this project. The quality of climate modelling is expected to improve significantly. So far, a small number of climate modelling centres have completed the calculations. The first studies in the field of energy using new climate change scenarios have already been published [187,188]. Therefore, it is recommended that the possibility of using new SSP scenarios and climate modelling data from CMIP6 in future research in building be noted, as most studies are now carried out considering the effect of climate change.

4. Conclusions

The main conclusions of a bibliographic and manual analysis carried out on the climate-oriented publications with the highest impact in building are presented below.

The bibliographic coupling clustering method demonstrated reliable results in the scientific map definition, which was validated with manual analysis. According to that, a broad spectrum of issues directly and indirectly related to climate and climatic zones in building was defined. The climatic factor was identified in many aspects of the building construction—not only in studies on building climate zones and on the analysis of the effects of climate change, which represent only 3.1% and 4.7% of all studies, respectively, but also in studies on the optimisation of various building systems in different climate zones.

Eighty-eight percent of all climate-oriented studies, to one degree or another, are within the scope of the overall topic of energy conservation. Understanding the fact that energy conservation is directly or indirectly related to climate and climatic zones in buildings will help specialists in architecture and civil engineering design climate-appropriate housing in various aspects, for different regions of the world. In other words, it will be helpful to consider, at the design stage, many parameters, techniques and methodologies of buildings influenced by the climate factor. Additionally, the possibilities for the adaptation and mitigation of buildings in the context of climate change can be maximised.

Furthermore, this work is a significant contribution, as it presents a methodology that facilitates the establishment of a typology of climate-oriented studies that can be used in future research and is not only related to buildings. Variations in the types of research were observed in different clusters and topics. At the same time, the predominant type of studies analysed (41.6%) was comparative studies, carried out for different climate zones, with one representative geographical location in each zone.

From the point of view of the specific climate zones in which the analysed investigations were carried out, the prevalence of National BC climate zones and bioclimatic zones was revealed. It was found that, in the studies directly related to the simulation of the energy consumption of dwellings, research on the National BC climate zones is prevalent. In the case of studies focusing on indoor and outdoor thermal comfort, a significant proportion of them were carried out in bioclimatic zones. One-third of the research analysed was carried out in the climatic building zones of three countries—China, the USA and Turkey. The prevailing types of climatic zones correspond to regions with a large population. In addition, it was found that the only National BC climate zoning that was used in other countries outside the USA was ASHRAE.

Finally, note that the results obtained from the present study will help researchers to find knowledge gaps and identify new opportunities for studies connected to climate and climatic zones in building. In addition, this work can be used in the public administration field for the development and updating of building codes in different countries.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app11073251/s1, Table S1: Studies of Cluster 1; Table S2: Studies of Cluster 3; Table S3: Studies of Cluster 4; Table S4: Studies of Cluster 9; Table S5: Studies without cluster.

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Nomenclature

AMY	Actual meteorological year
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATC	Adaptive thermal comfort
BC	Building code
CDD	Cooling degree-days
CHCP	Combined heating, cooling and power system
CHP	Combined heating and power system
CMIP6	Coupled Model Intercomparison Project (v 6)
CZ	Climate zone
EIM	Environmental impact minimisation
ES	Energy saving
FEL	Following the electricity load operation strategy
FTL	Following the thermal load operation strategy
GHG	Greenhouse gases
HDD	Heating degree-days
HRV	Heat recovery ventilator
HVAC	Heating, ventilation and air conditioning systems
IEQ	Indoor environmental quality
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCC	Life cycle cost
OCR	Operation cost reduction
PCM	Phase change materials
PMV	Predicted mean vote thermal comfort model
PV	Photovoltaics systems
RCP	Representative Concentration Pathway
SSP	Shared Socio-Economic Pathway
TMY	Typical meteorological year
TPCY	Typical principal component year
UHI	Urban heat island
WOS	Web of Science
WWR	Windows/wall ratio

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