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A Study on the Parametric Design Parameters That Influence Environmental Ergonomics and Sustainability

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Abstract: The parametric design applied to the built environment is critical to creating sustainable and resilient spaces. However, this research field involves a vast and complex amount of disconnected information. Therefore, this paper aims to analyse research trends in applying parametric design to optimise sustainability and environmental ergonomics parameters in built environments. The following specific objectives are identified to meet this objective: (i) a quantitative analysis based on a systematic literature review; (ii) a qualitative review based on a performance analysis and scientific mapping; and (iii) a comparative analysis of case studies applying parametric language for the optimisation of sustainability and environmental ergonomics parameters. The 1045 research records covering 1974 to 2021 illustrate a field in development that evolves from early digital advances to climate change adaptations, the circular economy and resilience. It highlights the importance of applying bioclimatic techniques in the built environment, identifying the most optimised measures and encouraging the creation of guidelines to serve as a protocol for future studies, contributing to the existing body of knowledge by highlighting trends, establishing research themes, outlining research networks and suggesting areas for further studies.

Keywords: parametric design; built environment; sustainability; environmental ergonomics; climate change; resilience; circular economy

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1. Introduction

Buildings and their environments make up a complex environment favouring any territory's environmental and socioeconomic development [1], facilitating social relations and economic development on an urban scale. At the same time, they cause an acceleration in climate change, consume many natural resources and generate waste and social inequalities [2,3]. In 2050, more than 60% of the world's population is predicted to live in cities [4]. Urbanisation enhances the potential for sustainable development (SD) in access to public and private services, public education and job opportunities under the 17 Sustainable Development Goals (SDGs) umbrella. Compounded city transformations resulting in population, manufacturing and land development patterns risk raising aggregate greenhouse gas (GHG) emissions, which translate into an environmentally costly and potentially dangerous increase in the health of citizens.

Built environments are the spatial response to urban development, spaces that depend on the environment in which they are inserted, influenced by the surroundings, climatic conditions, surrounding urban planning and qualities of the materials used [5]. Built environments offer new possibilities for sustainable development, broadening the field of research and allowing for the discovery of new ways of tackling problems. For example, the built environments of higher education institutions symbolise an influential space for innovation and education in sustainability. Student success is enhanced by access to outdoor environments and by creating a holistic learning environment [6]. In addition, with their high scientific value, these institutions offer new possibilities and advantages for this type of project. They represent an opportunity to add value to these spaces, facilitating the introduction of new concepts towards a more sustainable approach to society [7].

Research has focused on the analysis of conditions, the mitigation of environmental impacts and the design of a healthy and liveable outdoor environment. Additionally, the effect of design parameters on the energy demand of buildings has been analysed [8]. In addition, it has been shown that green infrastructures and spaces play a crucial role in encouraging outdoor activities and social encounters among pupils, demonstrating the social value of public gathering spaces [9]. In this regard, numerous centres have proposed ways to optimise and encourage the use of the built environment by enhancing comfort, study, relaxation, contemplation, socialisation and entertainment. These strategies have emphasised the importance of outdoor space design, location, circulation, slope, furniture, shading and vegetation [10].

In this context, policymakers, architects and engineers increasingly promote applying sustainability and circular economy criteria [11], which provide efficient spaces not only in terms of environmental performance, but also capable of optimising the environmental ergonomics of the users for whom they have been designed [3]. Environmental ergonomics is defined by the synergy between thermal comfort, acoustic comfort, lightweight comfort, visual comfort, indoor air quality (IAQ) and outdoor air quality (OAQ) that users experience [12–19]. These parameters are mainly influenced by the climatic context where they are located.

Parametric architecture uses an algorithmic scheme to design versatile, modern and creative structures. In architectural design, form emerges from under environmental conditions, which must be flexible and resilient [20]. In this sense, the parametric approach can generate numerous design variants based on different aspects during the initial project stage [21], such as the configuration and optimisation of cladding, fabrication and integration with renewable energy systems and construction processes, especially climatic parameters [22]. Thus, in the late 1980s, various digital tools began facilitating parametric design. Although it was not until 2010 that these systems reached their peak with the launch of the new AutoCAD features, opening a new range of opportunities.

These tools range from the most simplified ones that aim to estimate the environmental impact in the early stages of design. However, they do not consider other life cycle stages to the most complex programmes that allow for modelling buildings and its built environment, providing vast information on materiality, constructive solutions, and environmental parameters [23]. For example, Bombyx [24], a Grasshopper add-on that allows for the geometry modification and real-time calculation of the environmental impact according to the materials and shape generated, creates and modifies the parameters of a base model to obtain parametric results using mechanical elements [25] that, by applying a series of algorithms, modify 3D design parameters to obtain complex shapes.

With a comprehensive overview of the area of research and the development of issues in this field, obtaining unbiased and valuable information for further research is easy. In this field of study, starting from a single point became impossible due to the variety of topics. For this reason, there is a need for new publications that allow for the incorporation of studies and that provide a critical view of the subject. In this sense, a critical bibliometric analysis provides yardsticks and objectives to evaluate research papers as well as a snapshot of the vast academic literature [26].

Introduced by Alan Pritchard in 1969, the bibliographic analysis is a twofold integrated analysis, performance assessment and scientific mapping. A performance analysis sets out to assess the citation impact on the output of different scientific actors. Scientific mapping demonstrates the conceptual, social and intellectual structure, evolution and dynamic aspects of scientific research. Such methods, which examine bibliographic material objectively and quantitatively, allow for the visualisation of specialities and branches of knowledge that articles and authors are related to [27]. Many research fields use bibliometrics to expose the structural and dynamic aspects of research [10,28–31]. Therefore, this paper aims to analyse research trends in applying parametric design to optimise sustainability and environmental ergonomics parameters in built environments. The following specific objectives are identified to meet this objective: (i) a quantitative analysis based on a systematic literature review (SLR) of the research field; (ii) a qualitative review based on a performance analysis and scientific mapping; and (iii) a comparative analysis of case studies applying parametric language for the optimisation of sustainability and environmental ergonomics parameters.

This paper provides a valuable contribution towards the research body of knowledge by outlining existing trends and patterns in the field of research, setting out its research themes, mapping out researcher networks and suggesting potential areas for future studies.

Evolution of Parametric Design

With its origins in mathematics, parametric design represents optimising the shape and distribution of materials in each area according to conditions. Input parameters range from environmental, energetic, structural and economic to other aspects. Regarding the field's evolution, there is conflict about the first-time architects to have used the word. In his doctoral thesis, *Parametric Practice* [32], David Gerber credits Maurice Ruiter with first using the term in 1988. However, it achieved popularity within civil engineering and architecture in the early 21st century due to the development of computers and their potential to generate rational and aesthetic–artistic morphology [33].

At the beginning of the 20th century, parametric equations could already be observed in the architecture of Antoni Gaudí, where he developed the hanging chain model. This method consists of creating a funicular model fixed to the ceiling of a wooden board on which the building plan is drawn. At the same time, from points of support (columns and intersections of walls), some cords are hung from which, in turn, small, weighted bags are suspended to give the resulting catenary curve, both in arches and vaults. This system was used in the Crypt of the Colonia Güell and the Sagrada Familia, ending the classical conception of the perfect circumference and breaking up the arches with straight sections. Gaudí's work uniquely describes five curves: catenaries, spirals, sinusoidal, conical and rounded [34]. The lines traced by these catenaries helped Gaudí design the building because the result could be photographed once the model was finished. By inverting the resulting photograph, a good model of what the construction should look like would appear. Due to Hooke's principle, the chords would permanently settle in a form that, when inverted, would remain in pure compression.

In the 1950s, a long period of experimentation began. The architect, Félix Candela's representative, characterised his work not only by the rationality and optimal use of reinforced concrete, but also by the sculptural beauty of his projects. Félix Candela has succeeded with great skill and ability in simplifying and optimising complex calculations for the construction of various projects. These included the Bacardi bottling plant in Cuautitlán, Mexico; the Los Manantiales restaurant in Mexico City; and the Jacaranda nightclub.

In 1956, the Club Táchira project was presented, developed by the Venezuelan architect Fruto Vivas and the Spanish engineer Eduardo Toraja (Figure 1). This project has a very peculiar shape, with pronounced catenary curves with a bending behaviour that requires a "shell" that is a solid, inseparable and homogeneous unit. This design, advanced for its time, was based on complex mathematical calculations. Capone and Nigro [35] analysed this work and showed the advantages of using digital design tools to simplify the parametric design phases by introducing each parameter as required.

In the 1960s, Luigi Moretti, at the Twelfth Triennale exhibition in Milan presented different versions of the design of a stadium, explaining how the shape of the building can be derived from nineteen parameters, such as the viewing angles and the economic cost of the materials, among others. Moretti designed the Watergate Complex, believed to be the first significant construction project to effectively use computers in the five years following the exhibition.

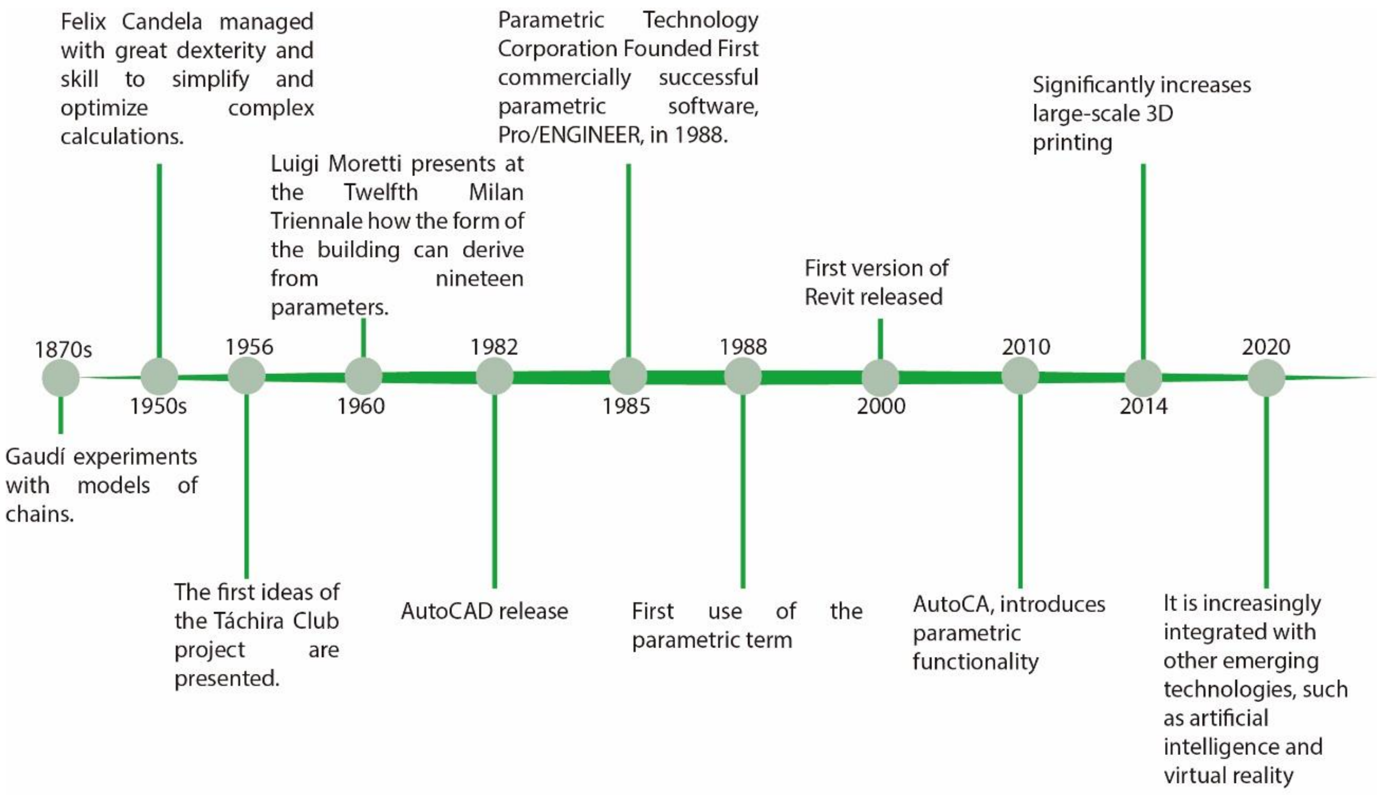

Figure 1. Identifying relevant milestones in the evolution of the research field.

In the 1980s, in the same way that Gaudi and Frei Otto used the laws of physics to accelerate the calculation of parametric equations, Sutherland used computers to accelerate the computation of any parametric equation. Thus, in 1982, AutoCAD was launched at a high cost, quickly dominating the fledgling computer-aided design industry and becoming more common and accessible in the following years. In 1985, professor of mathematics, Samuel Geisberg, established the Parametric Technology Corporation and, in 1988, the first commercially viable parametric software, Pro/ENGINEER, was born. The early 2000s saw the birth of Revit, where *parametric design* is defined simply as an object based on parametric equations that the designer can adjust according to circumstances.

The development of computers and design software led to the evolution of parametric design. The new possibilities were aimed at systems that develop more complex calculations and projects [36]. Thus, parametric design has resulted in impressive works such as Frank Gehry's Guggenheim Museum in Bilbao in 1997, with its titanium skin, the complex geometry of the National Stadium in Beijing by Herzog and de Meuron or the precarious cantilever of the MAXXI National Museum in Rome by Zaha Hadid [37].

2. Literature Review

In the academic literature, several works have applied parametric language to optimise sustainability or environmental ergonomics parameters. Turrin et al. [38] analysed the morphology of a dome as a function of structural performance and described the benefits of combining parametric modelling and genetic algorithms through the ParaGen program, together with a database that stores and retrieves solutions for further exploration. In addition, they evaluated solar energy transmission on a large roof. Stanković et al. [39] assessed the application of parametric design in a group of floating dwellings in Kiribati. They defined the architectural programme based on the general and specific needs of the users and set the parameters for the minimum perimeter and maximum area, achieving optimal and sustainable geometric forms. Zargar and Alaghmandan [40] analysed the application of parametric language in a stadium design through the Rhinoceros program to optimise the design, structure, evacuation, energy parameters and spectator viewing angles. Chronis et al. [41] applied parametric language to the bioclimatic design of a student housing complex. Al-Masoodi et al. [42] described a unique design technique based on a parametric approach using computational tooling components. Zhang [43] presented three methods in which parametric design connected buildings' technical requirements and aesthetics.

Generally, the most researched parameters are the building envelope, materiality, orientation, window-to-wall ratio, form and internal space. However, studies must consider the recent demands of climate change resilience and optimising environmental ergonomics parameters that make a building truly sustainable.

3. Materials and Methods

A comprehensive triple analysis was carried out to achieve the objectives of this work (Figure 2): (1) a quantitative analysis based on a systematic literature review (SLR) of the research field; (2) a qualitative review based on a performance analysis and scientific mapping; and (3) a comparative analysis of case studies applying parametric language for the optimisation of sustainability and environmental ergonomics parameters. Each of these procedures is described below.

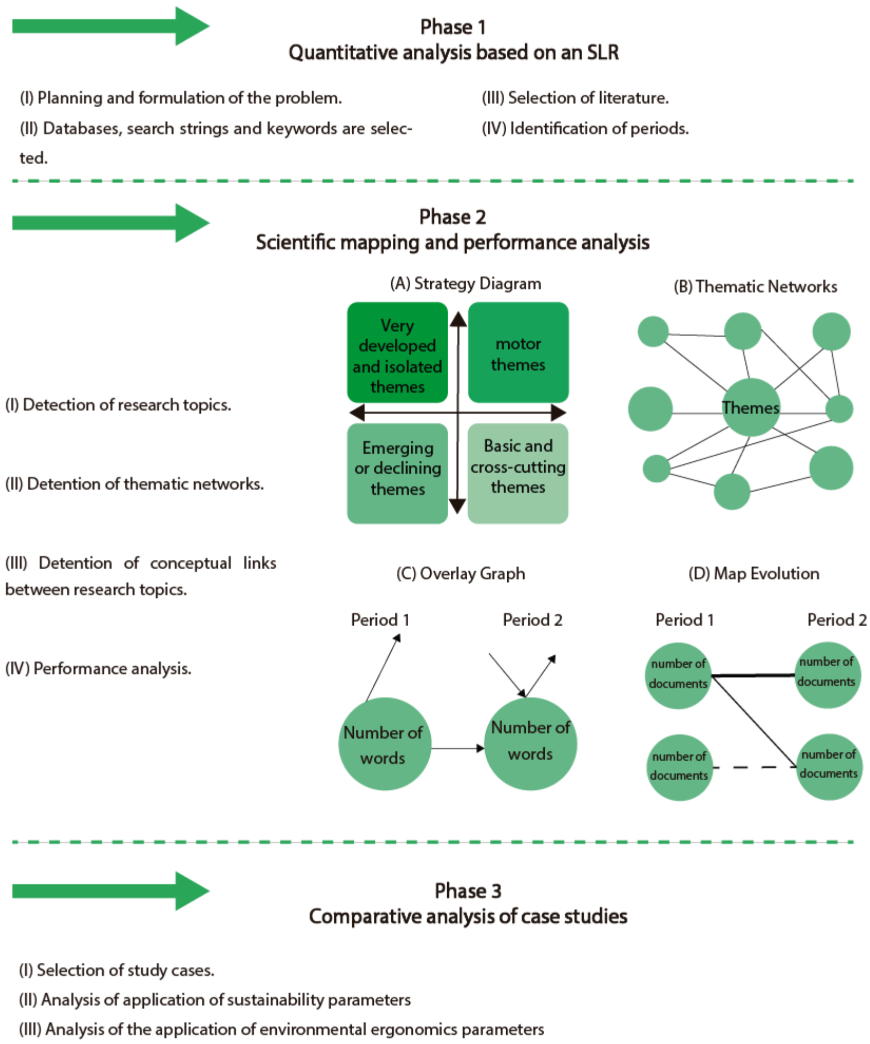

Figure 2. Materials and methods.

3.1. Quantitative Analysis Based on the SLR

The SLR proposes a systematic evidence-based methodological approach that analyses all information based on predetermined eligibility criteria [44]. This protocol employs strategies that define the research chain, establish exception mechanisms and data collection techniques and synthesise the results [45]. It highlights gaps, reduces errors in the information obtained and provides reliable results from which conclusions can be drawn to allow for better decision making. Some authors have applied this method to clear and transparent analysis procedures [46–53]. In this paper, the SLR is based on the guidelines of Kitchenham et al. [54], developing the following steps (Figure 2):

(I) **Planning and formulation of the problem.** Based on the formulated objectives, the research questions, the exclusion criteria for academic articles and possible outcomes are defined.

(II) **Selection of databases, search strings and keywords**. During this step, search databases, target keywords and strings are identified. It is essential to define the appropriate keywords and search string. The terms need to be broad and sufficient, not limit the range of documents and sufficiently focus on including only articles relating to the topic.

(III) **Literature selection.** The PRISMA flowchart guidelines select the relevant documents containing the data needed to address the research objectives.

(IV) **Identification of periods**. It identifies the periods according to the number of relevant documents defined, principal main elements and focal points of interest in the study area.

3.2. Scientific Mapping and Performance Analysis

In this phase, a dual integrated analysis, science mapping and performance analysis were carried out. A performance analysis identifies the impact of the research results. At the same time, scientific mapping reveals the intellectual, social or conceptual structure in the research field and its evolution and issues. This paper used the free software Science Mapping Analysis Software Tool v1.1.04 (SciMAT) based on the analysis of common words [55] and the h-index [56]. A researcher's h-index measures the overall quality of a scientist's research as a function of the number of papers and quotations received. SciMAT has been successfully applied in many areas, such as informatics, business, psychology, finance, marketing and government. It incorporates methods, algorithms and parameters for all scientific mapping processes, from preprocessing to reproducing results [57–65]. SciMAT builds on the approach defined by Cobo et al. [66] and creates the resulting four stages (Figure 2):

1. Detection of research topics and creation of strategic diagrams. SciMAT uses a unique centre algorithm to identify relevant themes. It produces the equivalence index to identify aspects of scientific production [67]. It produces a strategy diagram for each of the set periods. These diagrams are centrality and density based [68]. Centrality is the proportion in which an object of study relates to others. Density provides a measure of the unity of all the internal links between keywords that define the topic, giving an insight into the degree of the maturity of the topic [69,70]. The diagrams were organised into four quadrants that captured the following types of research topics (Figure 2A):

a. Motor themes: Found in the upper right quadrant. Motor themes are widespread and essential in the field of the analysed science. They have a strong centrality and high density. They are central themes for the construction of the research area.
b. Highly developed and isolated themes. Well-developed and vital themes in the field studied. They are essential themes for the construction of the investigated area. They have a marked centrality and high density. Found in the upper left quadrant.
c. Emerging or declining themes. Found in the lower left quadrant. These are issues that need more relevant development. Emerging themes may evolve, gain relevance or disappear. The next period reflects this.

d. Essential and cross-cutting themes. Subjects are fundamental to the studied academic environment but have yet to develop fully. Found in the lower right quadrant.

2. Detention of thematic networks. It shows the interrelationship of individual themes and keywords and their interlinkages. The name of an essential theme keyword identifies thematic networks. Figure 2B is an example of a thematic network related to some keywords. The size of the circle is proportional to the number of documents associated with each keyword; the thickness of the thread between two circles is proportional to the equivalence index.

3. Detection of conceptual links between research themes. The inclusion index [57] identifies the thematic connections between research works of different moments and the strength of the relationship between them based on various graphs presented below (Figure 2C,D).

The overlap graph. The upper input arrow shows the number of new words in the following period, while the upper output arrow shows the words that disappear in the next period. The horizontal arrow indicates the number of words that share both periods.

Thematic evolution map. The thickness of the borders is correlated to the number of inclusions and the size of the spheres by the number of publications. The dotted line indicates the elements that share the thematic axes and are not the central axis. Continuous lines represent the linked theme sharing the central part.

4. Performance analysis. The relative contribution of topics to the research field was measured in qualitative and quantitative terms. The most important, fruitful and high-impact subfields were established, such as the number of published articles, most prolific journals and most cited authors and papers using bibliometric indicators.

3.3. Comparative Analysis of Case Studies Applying Parametric Language for the Optimisation of Sustainability Parameters and Environmental Ergonomics

Finally, those defining representative projects of parametric design applications for optimising built environments were identified among the relevant documents. These documents were analysed and compared based on (i) the application of sustainability parameters and (ii) the application of parameters related to environmental ergonomics. In Table 1, 13 sustainability and 4 environmental ergonomics parameters were identified and defined.

Table 1. Identification and definition of parameters.

Parameters		Definition
Sustainability	Efficient water uses and management	Reduction in water consumption by using nonpotable water for various functions such as sanitary appliances and irrigation.
	Low environmental impact materials	Use materials whose origin and production are of quality standards, low CO_2 emissions and low environmental impact.
	Preliminary study of the environment	Information on urban, design, functional, technical, economic, energetic and ecological processes and conditions.
	Use of materials with sustainability certification	Use of materials whose origin and production meet recognised social and environmental standards.
	Use of renewable energies	Environmental standards.
	Calculation of CO_2 emissions	Use of clean and endless energy solutions. They differ from fossil fuels mainly in their variety, quantity and potential for global use.
	Calculation of the carbon footprint during the building's lifetime	Calculating greenhouse gases emitted by direct or indirect effects during the project, execution and useful life of the building.
	Durability, adaptation and deconstruction	Analysis of the impacts.

Table 1. *Cont.*

	Parameters	Definition
Sustainability	Revegetation of spaces	Generated by a building during all stages of its life cycle, from extracting the raw materials necessary for its manufacture to dismantling or demolition.
	Integration of existing vegetation	They are dismantled or demolished.
	Low CO_2 emission transport systems	Extending the useful life of the materials used and adapting to the changing conditions of the environment, as well as recovering a part or most of the building's components, thus, allowing the elements to be reused in another place where they can be placed to extend their existence.
	Air quality analysis	Recovery of areas with vegetation cover.
	Ground floor morphology and density	Respecting existing vegetation in the realisation of a new project.
	Urban heat island effect mitigation	Strategies implemented to reduce pollution, including using bicycles, vehicles with electric motors or promoting public transport.
Environmental ergonomics	Wind control	Monitoring and controlling the ventilation system to ensure adequate indoor air quality.
	Hygrothermal comfort	To reduce the effects of the urban heat island, the interior partitioning in buildings, especially on the ground floor.
	Acoustic comfort	Reduction in the heat island effect using vegetated spaces, green roofs or facades and installing shading and solar protection elements on accumulation surfaces.
	Lighting and visual comfort	Ensure an adequate level of lighting in the buildings and all workspaces.

4. Results and Discussion

After applying the steps of the previous section, the results were analysed in Tables 2–6 and Figures 3–12.

4.1. Quantitative Analysis Based on an SLR

(I) Planning and problem formulation. The primary purpose of this study was to examine the current results of applying the parametric design for optimising sustainability parameters and environmental ergonomics in built environments. Thus, the following research questions (RQ) were determined: RQ1. What is the objective of this review? RQ2: What is the status of this research field, and what have been the most critical turning points? RQ3: In which direction is this field of research evolving? RQ4: Who are the most prominent authors in this field of study? RQ5: What are the most influential works in this field? RQ6: What are the main research topics in this field? RQ7: What are the limitations of this field of research?

(II) Selection of databases, keywords and search strings. The databases SCOPUS and Web of Science (WOS), with numerous high-impact international scientific and technical publications in all disciplines, were selected. Regarding keywords, the review addressed the evolution of two main themes, parametric design and the built environment. The keywords had to cover both topics from the outset. Thus, an advanced search was conducted in ISI WOS and SCOPUS using the keywords in Table 2, including two search strings, one for each database.

Table 2. Keyword identification.

Concepts	Keywords
Parametric design	Generative design
	Parametric architecture
Built environment	Building
	Building
	Urban
	City
	Public space

(III) Literature selection. Following the identification of the selected keywords and search strings, the steps defined in the PRISMA flowchart were applied (Figure 3). As a result, 2715 bibliographic records were obtained from the two chosen databases. After removing 561 duplicates, 896 of the remaining 2154 records were excluded using the elimination factors (only leaving article-type documents, full articles related to the field of research and documents in English). In turn, the resulting 1258 records were reviewed for the title, abstract and keywords, and a further 145 records were removed for not covering the topics of this research. Ultimately, 1015 documents relevant to the study were selected and included in SCIMAT.

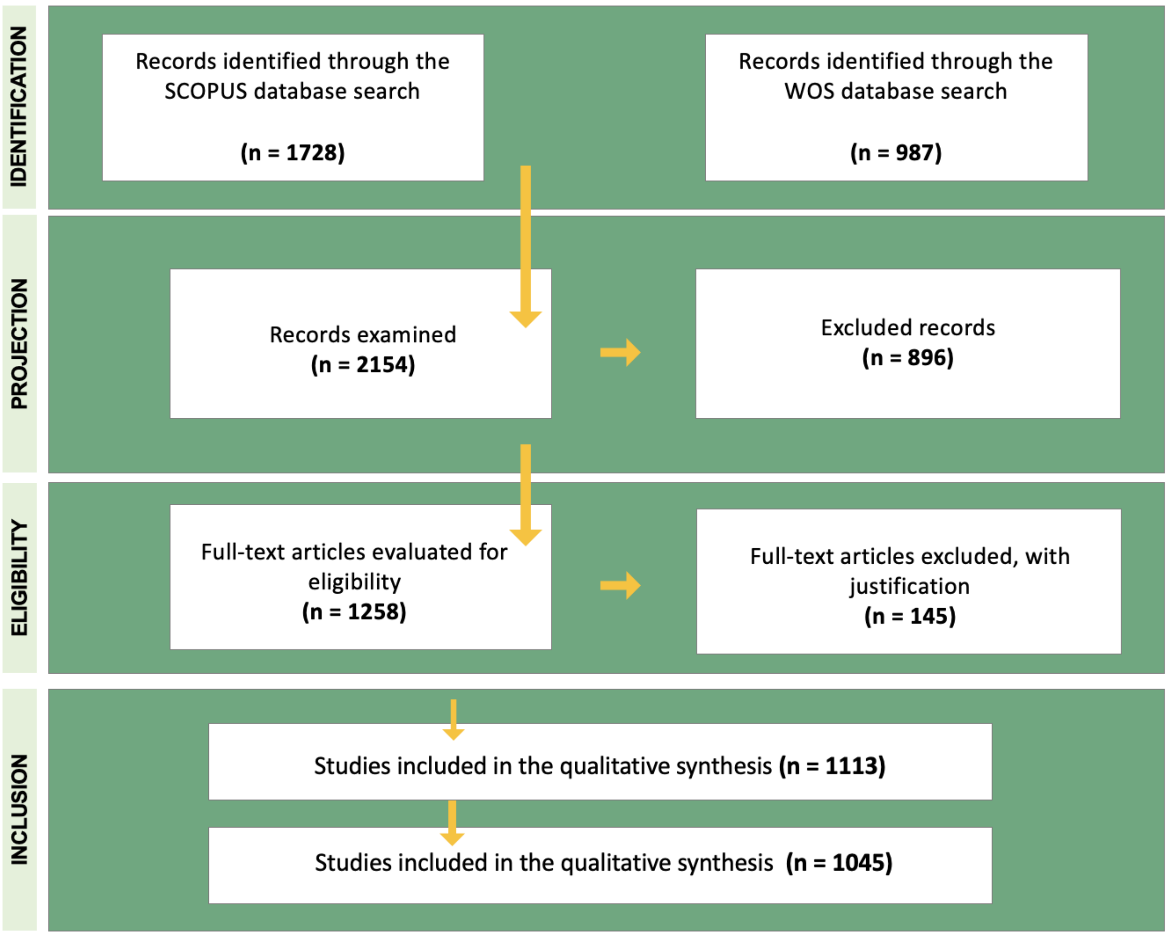

Figure 3. PRISMA flowchart.

(IV) Identification of periods. The period analysed was from 1974, where the parametric design term started incipiently, to 2021. The following three periods were determined based on the research field's main milestones and turning points:

- First period (1974–2009), with 124 documents. Although several associated terms were used then, parametric terms were not mentioned until 1988. The first steps were taken, and the first programmes associated with sectors outside architecture were created. One of the critical milestones marking this period was the launch of new tools in CAD programmes, with AutoCAD 2010 standing out.
- Second period (2010–2016), with 444 documents. Notable due to the launch of the SDG, this milestone marked a before and after, directing research and projects towards environmentally and user-friendly actions. Awareness began to be raised among the main actors involved.
- Third period (2017–2020), with 477 documents. The consolidation of Rhino marked this period as the most widely accepted software with the Grasshopper tool.

Finally, Figure 4 shows the distribution over time of the 1045 documents. As can be seen, until 2010, there were few studies. However, from 2011 onwards, there was a significant increase in scientific production, with the launch of the new functions of AutoCAD in 2010 and the ODS in 2015 being key milestones. This exponential increase demonstrated the interest in this research field and a growing trend, especially in the construction sector. However, this topic tended to be volatile, with inevitable dips and rises, such as in 2019.

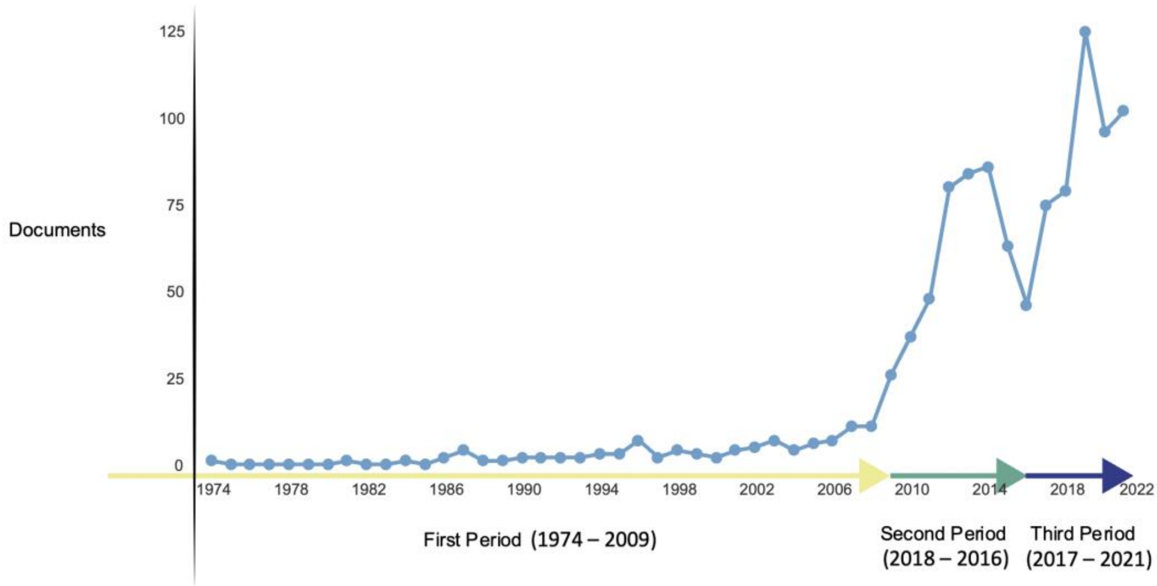

Figure 4. Distribution of documents studied by year.

In addition, there was a significant decrease in scientific production in 2014, which would have reduced the number of scientific publications in this specific field. In 2014, the topic of large-scale 3D printing increased significantly as a result of the decline in parametric design. In any case, it is important to bear in mind that scientific production can fluctuate depending on several factors, and that a decrease in the number of scientific publications in a specific year does not necessarily indicate a decrease in the importance or relevance of the research field in question.

4.2. Scientific Mapping and Performance Analysis

In this section, strategic diagrams, thematic networks of critical topics, the overlap graph, thematic evolution map and performance measures of the most prolific papers, journals and authors were analysed and discussed.

4.2.1. Strategic Diagrams

This section shows the strategy diagrams and measures of subject performance for each of the three periods.

First period (1974–2009). The strategy diagram presented in Figure 5 shows five relevant research themes in the 124 selected papers. Of these, two were motor themes, building and architectural design; one was emerging or declining, neural networks; one was highly developed and isolated, computer-aided design (CAD); and one was considered a core and cross-cutting theme, parametric design. According to the performance measures in Table 3, the topics with the highest number of citations were architectural design (16) and parametric design (14). This field of study was present in the most significant number of articles, and had a high h-index.

Table 3. Performance measures of the main themes.

Name	No. of Documents	No. of Citations	h-Index	Centrality	Density
Period 1 (1974–2009)					
Architectural Design	16	184	6	52.56	16.46
Parametric Design	14	123	4	57.03	13.77
CAD	8	42	4	43.25	27.48
Building	5	499	3	48.39	21.39
Neural Network	3	14	1	17.04	3.15
Period 2 (2010–2016)					
Decision Support System	20	149	6	36.09	4.92
Parametric Design	18	117	5	31.84	0.28
Environment	13	201	5	27.1	16.35
BIM	13	161	6	33.68	3.22
Buildings	12	90	5	11.66	13.81
Climatic Conditions	12	138	5	44.54	9.01
Structure	11	32	3	17.34	2.77
Architectural Design	10	22	3	14.49	17.29
Algorithmic Methods	10	91	4	43.45	31.16
Sustainable Development	9	139	3	40.51	12.56
CAD	9	20	2	6.45	26.27
FPGA	2	20	2	1.71	22.22
Period 3 (2017–2021)					
CAD	30	162	7	23.04	5
Climate Conditions	27	143	5	33.99	11.97
Sustainable Development	16	89	5	26.03	5.14
Parametric Design	13	81	4	28.66	0.28
Life Cycle Analysis	11	147	6	25.84	17.29
Architectural Design	11	25	4	14.63	9.06
Algorithmic Methods	11	176	7	23.73	9.94
Shame Optimisation	10	74	4	26.81	18.73
Comfort Conditions	8	107	5	26.81	8.08
Finite Element	8	27	3	7.56	19.76
Office Buildings	3	35	2	23.14	1.88
FPGA	1	0	0	0	100

Second period (2010–2016). The strategic diagram presented in Figure 6 shows 12 relevant research themes in the 444 papers selected for this period. In this period, we found three driving themes, algorithmic methods, the environment and sustainable development; one emerging or declining theme, structure; four highly developed and isolated themes, FPGA, architectural design, CAD and building; and four essential and cross-cutting themes, climatic conditions, system-assisted decisions, BIM and parametric design. According to the performance measures in Table 3, the topics with the highest number of citations were system-aided decision making (20), parametric design (18), the environment (13) and

BIM (13). This field of study was present in the most significant number of articles, and had a high h-index.

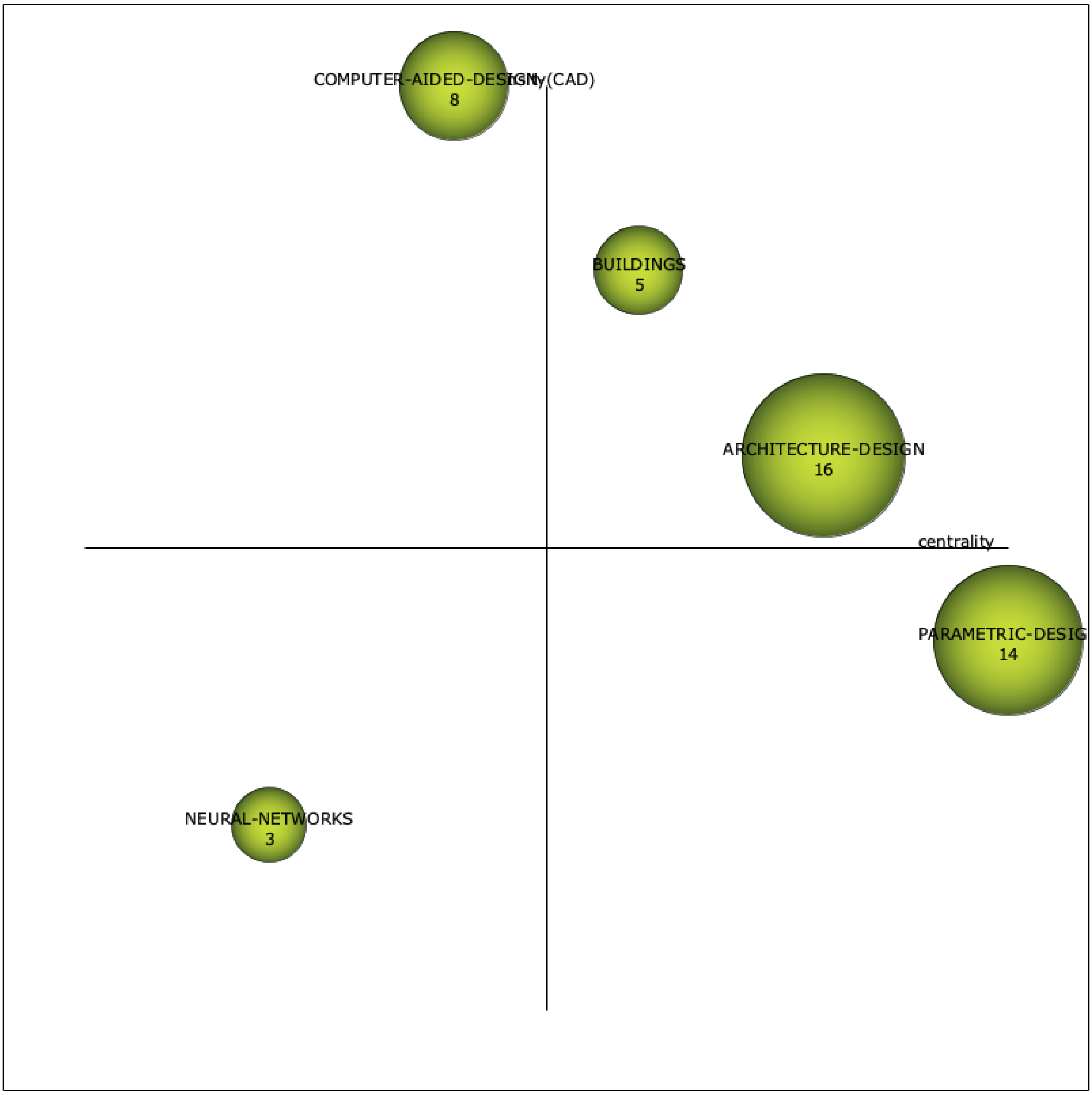

Figure 5. Strategy diagram for period 1.

Third period (2017–2021). The strategic diagram presented in Figure 7 shows 12 relevant research themes in the 477 papers selected for this period. The four motor themes were shape optimisation, climatic conditions, life cycle analysis and algorithmic methods, which, despite being above the line, was a driving theme due to its number of citations. There were three emerging or declining themes, computer-aided design, office buildings and architectural design; two highly developed and isolated themes, finite element and FPGA; and three essential and cross-cutting themes, comfort conditions, sustainable development and parametric design. According to the performance measures in Table 3, the topics with the highest number of citations were computer-aided design (162), climate conditions (143) and sustainable development (89). This field of study was present in the most significant number of articles and had a high h-index.

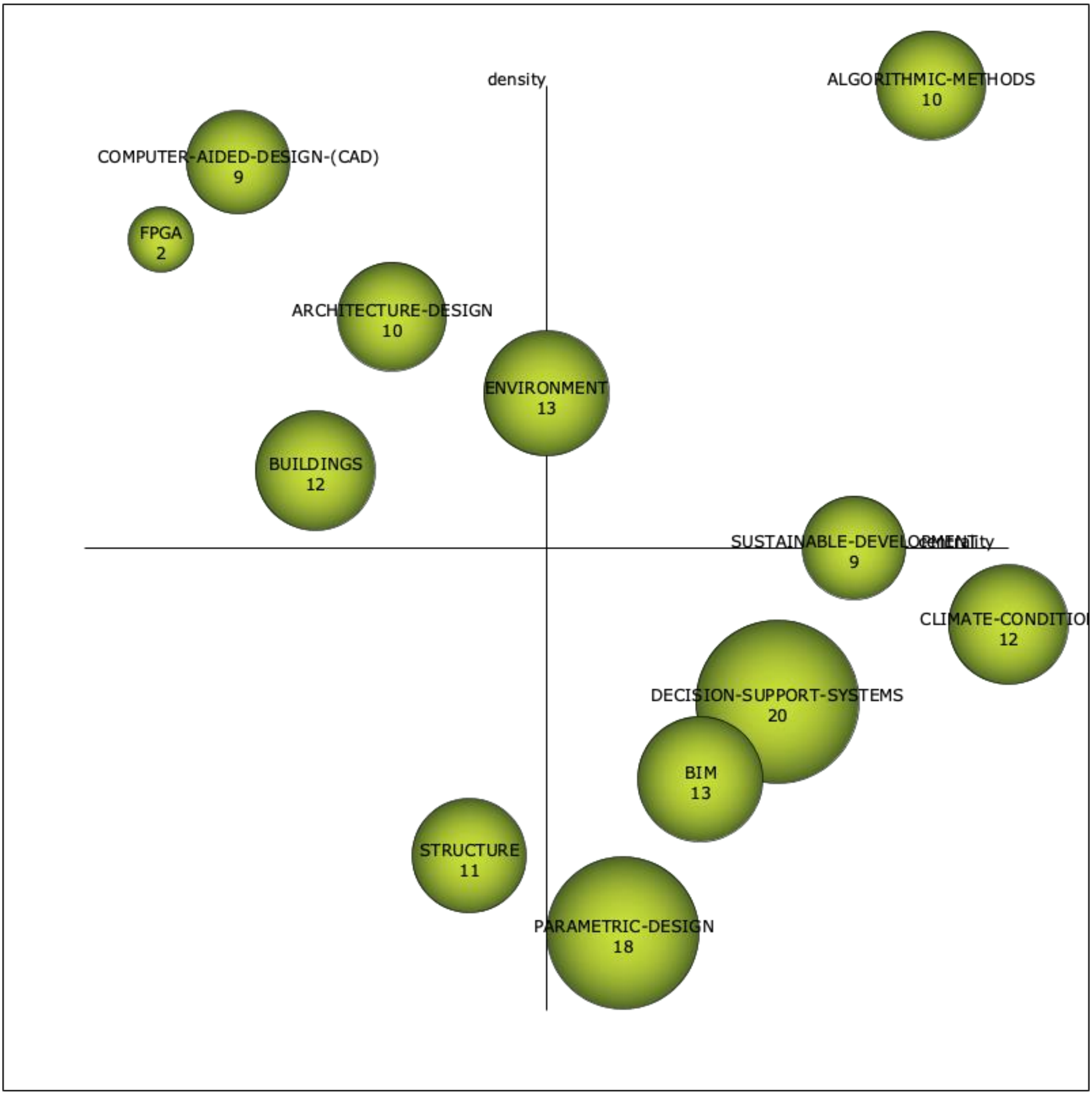

Figure 6. Strategy diagram for period 2.

The evolution and relevance of topics, such as parametric design, architectural design and CAD, can be seen above, becoming critical concepts for the field. It can also be seen how parametric design evolved in parallel with technological development towards the optimisation of comfort conditions and respect for the environment, leaving aside its mere conception as a computer tool.

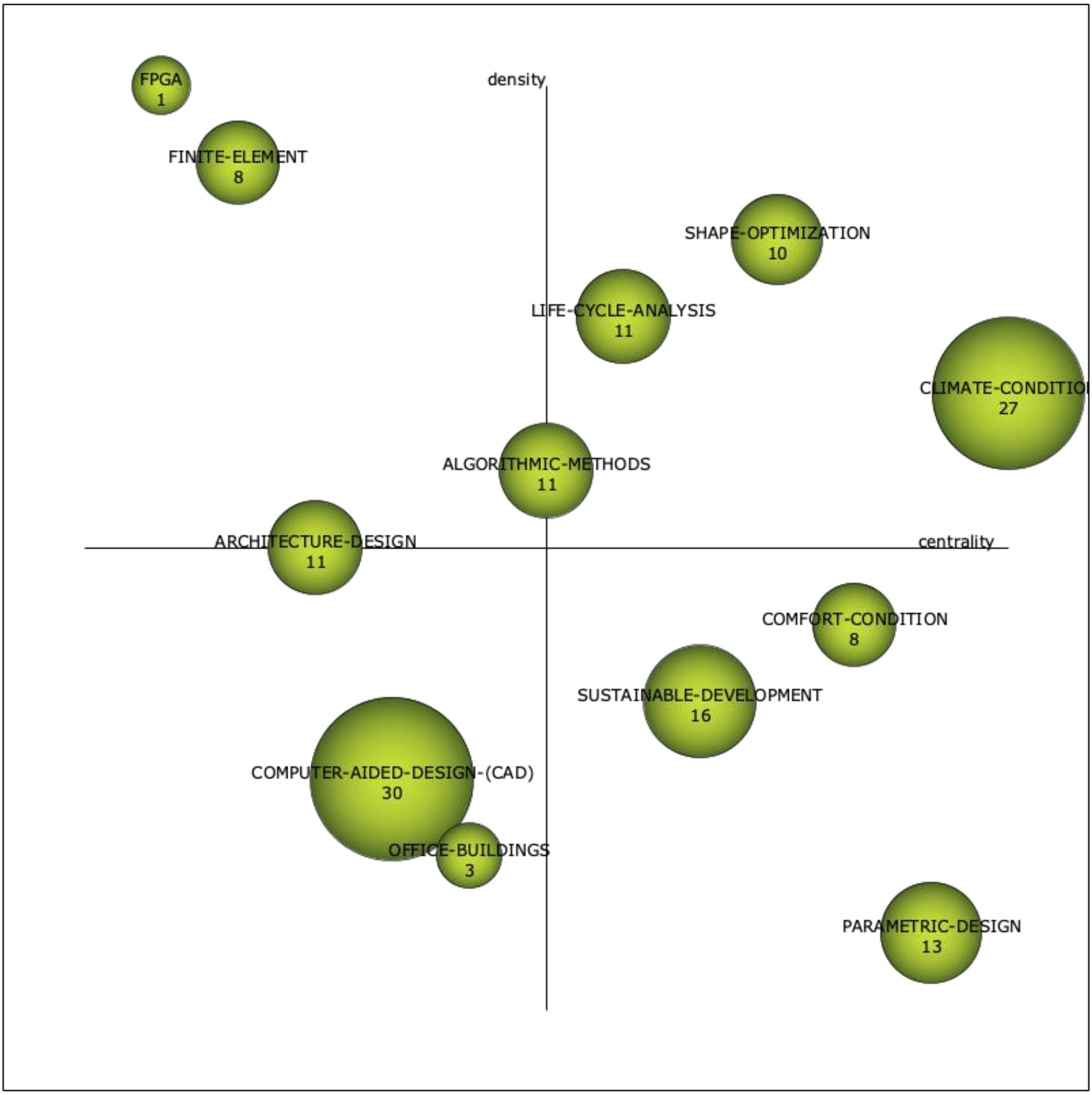

Figure 7. Strategy diagram for period 3.

In the first period, computers began to develop and became standard for creating architectural projects, offering a new range of opportunities. The parameters were geared towards formalism in this first stage, leaving social and environmental aspects aside. The second period was marked by the development of computers, where algorithmic methods were perfected and facilitated calculations. The optimisation of form was conditioned by environmental, climatic, structural and functional criteria, among others. In addition, there was a new awareness of respect for the environment and the user. It gave rise to issues related to resilience to climate change and environmental ergonomics, thus, aligning with the new considerations set out through the SDGs. In recent years, optimising environmental ergonomics became a vital issue, starting to be introduced in regulations. Growing concern for access to databases and tools for analysing the socioeconomic and climatic contexts began. In addition, passive architecture started to gain relevance.

4.2.2. Thematic Networks

This section shows the relationships of each theme to other themes and their interconnections. In Figure 8, the first-period CAD theme was linked to satellite themes such as zero-emission buildings, environmental impact and robust design. In Figure 9, the second period building theme related to other satellite themes such as renewable energy, green buildings and shape tessellation. In Figure 10, the last period's comfort conditions were linked to themes such as energy, parametric environmental design, building function and residential buildings.

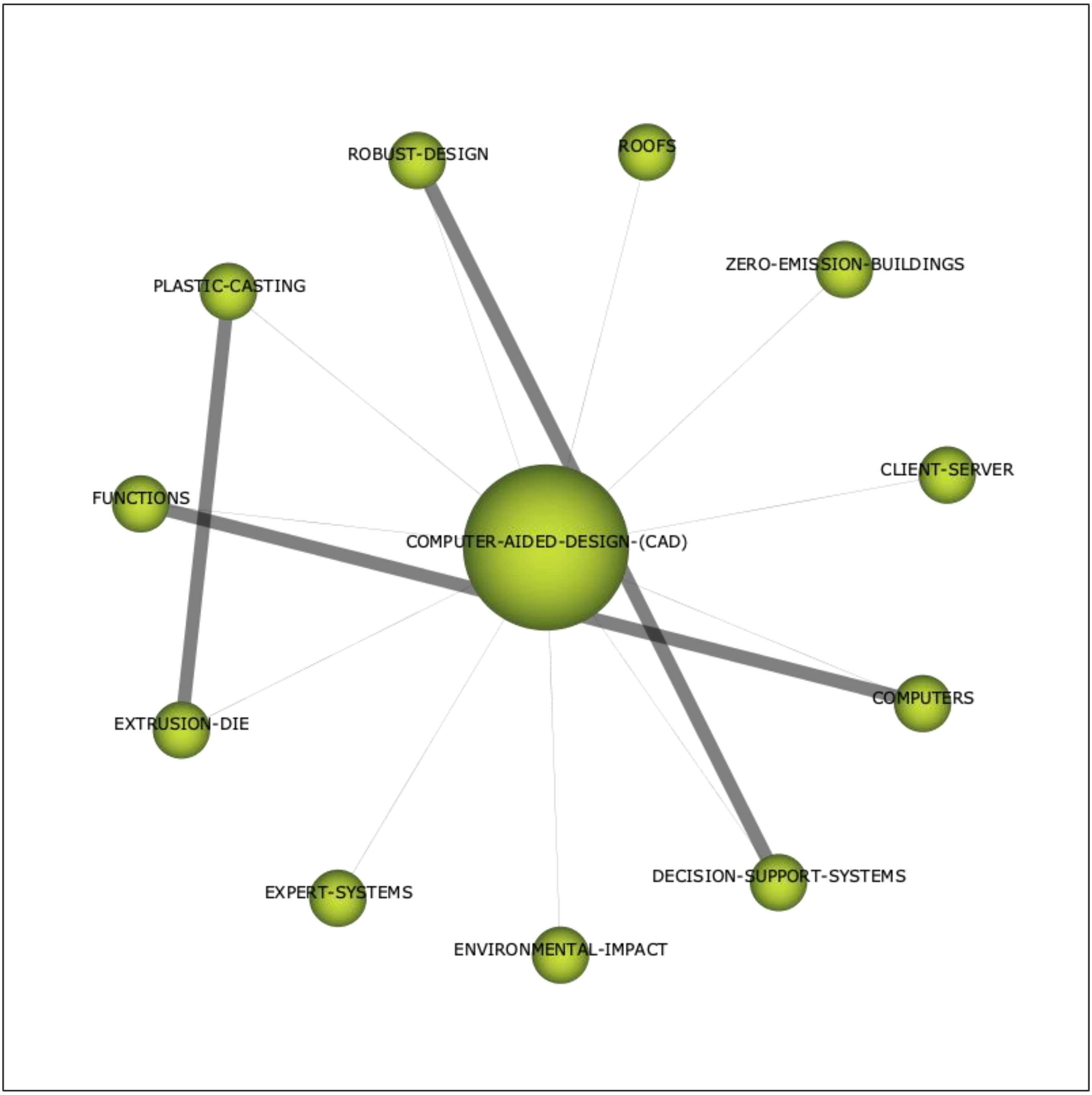

Figure 8. Thematic network for period 1.

Figure 9. Thematic network for period 2.

In the early years, parametric design supported with CAD tools provided the possibility to determine assessments and decisions at an early stage. In addition, the environmental impact started to be considered, especially in the early design stages. Over the years, renewable energies have become a vital issue. Thus, Lin et al. [71] researched the development of methods applicable to the parameterisation of nearly zero-energy buildings, promoting green buildings based on the simplified calculation of algorithmic methods offered by parametric design. In addition, the research highlighted the advantages of integrating vegetation into the design of built environments as a key to optimising user comfort, especially on roofs and façades. On the other hand, the visualisation of buildings was facilitated thanks to design modelling and 3D printing. In addition, more complex forms, mimetic to nature, were being achieved.

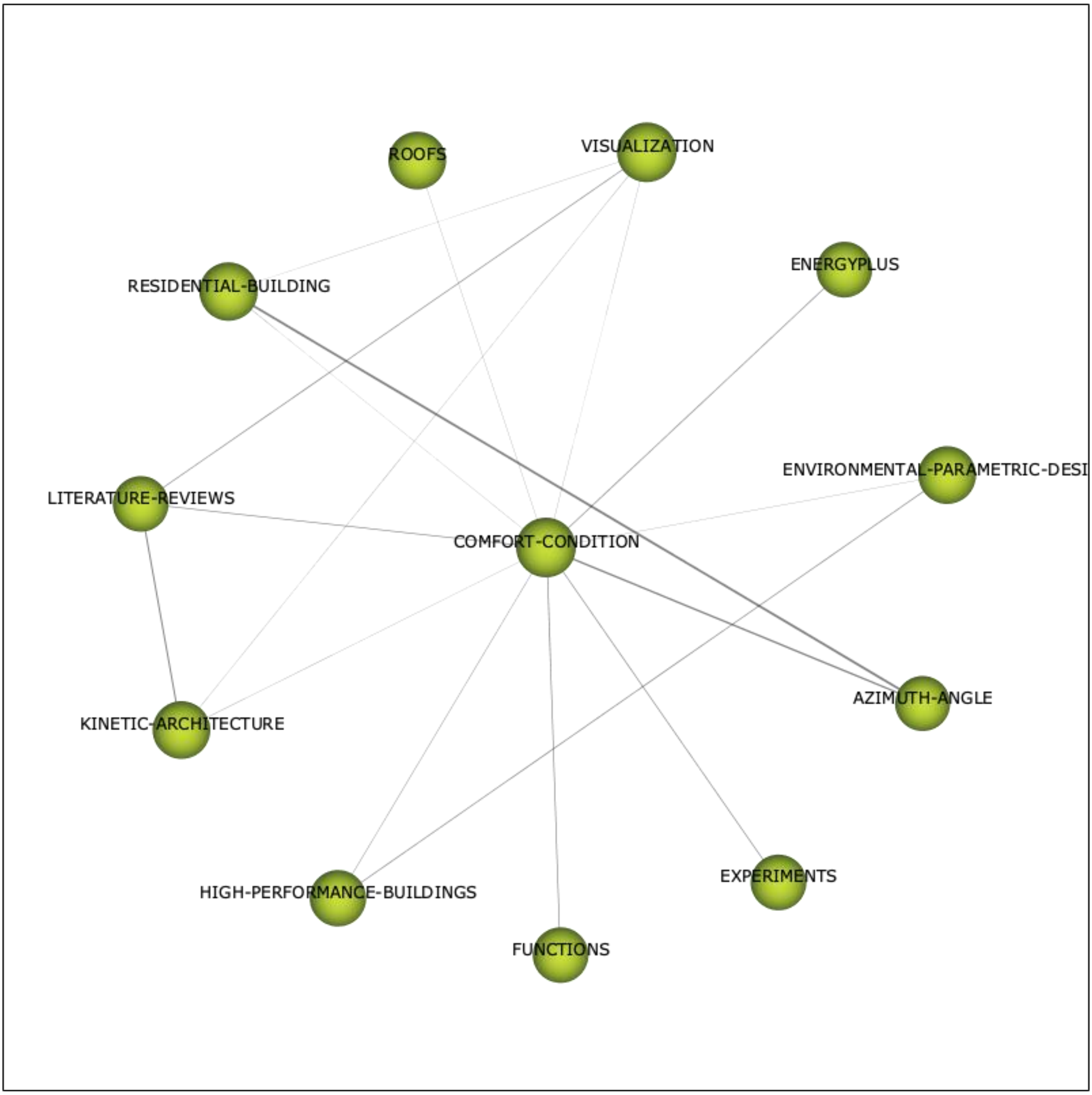

Figure 10. Thematic network for period 3.

4.2.3. Overlay Chart and Map of Thematic Evolution

Figure 11 shows keyword numbers per period, their development, the incoming and outgoing keyword numbers and the number and share of keywords that remained the same between periods.

Over time, the volume of keywords increased, along with the importance of documents. The horizontal arrow in Figure 11A indicates the number of words that coincided in both periods. The incoming top indicator shows the number of new words in period two, and the outgoing top arrow indicates the disappearing terms in period two.

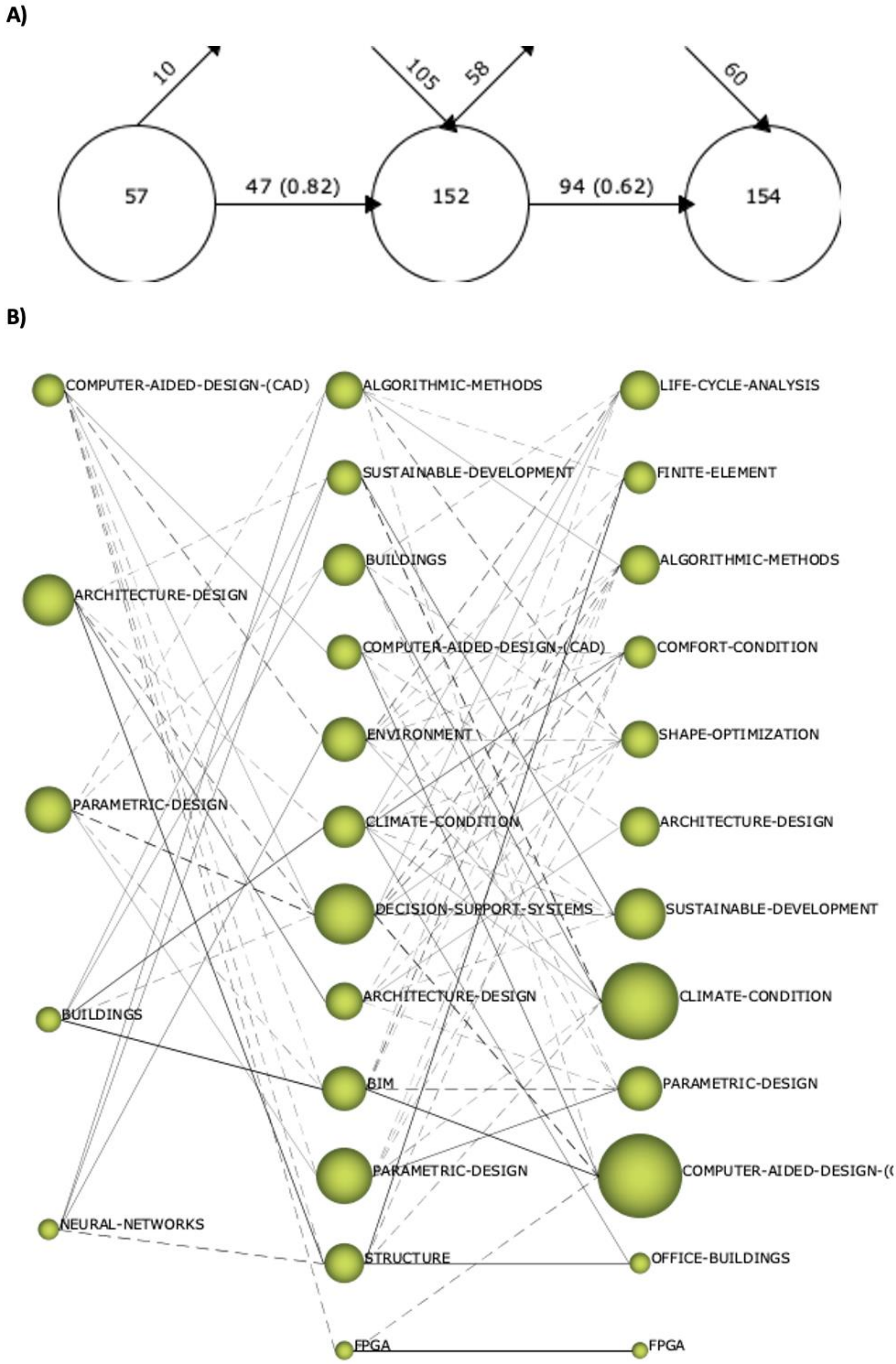

Figure 11. Overlay chart (**A**) and map of thematic evolution (**B**).

Based on the results, the number of new and transitional keywords was high, and the number of keywords sharing successive periods increased. Between the first and the last period, the number of keywords rose from 57 to 154, a growth rate of 270%. Specifically, of the 57 keywords that appeared in the first period, 82% (47) were maintained in the second period, and 105 new words were added, giving a total of 152 words. Thus, the progressive thematic variety of the research field and the maintenance of the keywords in the following time intervals indicated a gradual consolidation of the research field.

The trend of the research field realized through analysing the origins and relationships between the themes is shown in Figure 11B. The solid lines indicate that the related article was the main element. The dashed line indicates that the themes shared other elements than the main one. The border's thickness correlated to the inclusion rate, and the volume of the spheres was a consequence of the number of articles published.

If the graph was analysed from the point of view of the number of documents, in the first period, the architectural design theme appeared with the highest number of primary documents. It evolved towards structure, climatic conditions and system-assisted decisions for the second period. In the second period, the theme of system-assisted decisions had the highest number of primary documents and evolved towards relevant themes such as sustainable development, algorithmic methods and BIM. Awareness was raised about integrating buildings into the built environment. In addition, algorithmic strategies were becoming more efficient, able to provide a greater variety of answers to the parameters set.

In the third period, architectural design, CAD and parametric design were maintained from the first stage, while the building theme evolved towards climatic conditions, form optimisation and life cycle analysis. In contrast, BIM positioned itself at the centre of design due to the high level of information. New articles, such as comfort conditions and the life cycle analysis (LCA), appeared.

4.2.4. Performance Analysis

A total of 275 journals were identified in the study. These journals focused on building science and computer science applied to design, building automation, efficient energy use and involving alternative fuels for electricity generation. Table 4 shows the journals that accounted for 42% of the analysed papers, sorted in descending order according to the number of documents.

Table 4 also includes the total number of citations for papers in each journal. The number of papers and citations was only sometimes related; automation in construction stood out above the rest in terms of documents and citations. However, the number of citations varied in the rest of the cases. In other words, the most prolific sources did not necessarily have the most significant impact on the field of research.

Table 4. Leading journals contributing to the field of instigation.

Title	No. of Documents	No. of Citations.	No. of Citations	Most Cited Documents
Automation in Construction	28	1351	404	[72]
International Journal of Architectural Computing	14	115	19	[73]
Sustainability (Switzerland)	13	69	18	[74]
Nexus Network Journal	10	13	7	[75]
Architectural Science Review	10	78	19	[76]
Journal of Building Engineering	9	97	29	[77]
Journal of the International Association for Shell and Spatial Structures	9	16	4	[78]
Frontiers of Architectural Research	9	92	39	[79]
Building and Environment	8	116	39	[80]
Energies	7	72	41	[81]

Table 5 identified the ten papers with the most citations, totalling 1644, or 22%. These papers focused on various research topics, revealing their diversity. They analysed energy performance and its importance in decision making from the design stage. They discussed combining parametric modelling and genetic algorithms, studying shape optimisation that combines and preserves the advantages of previous techniques, evaluating the influence of shape on the energy performance of buildings, applying LCA from a parametric point of view and analysing the current use of parametric design software and the main advantages or difficulties in its development.

Table 5. Primary documents contributing to the field of research.

Document	Keywords	Contribution	Citations
[72]	building information modelling; building performance; design support; energy analysis; exergy analysis; parametric design	Energy performance of buildings and its importance in decision making from the design stage.	404
[82]	three-dimentional printing; additive construction; additive manufacturing; architectural design; construction design; construction materials; buildings; civil engineering; LCA; multiple-constraint design; parametric design; structural design	Benefits of large-scale additive manufacturing. Systematic mapping to obtain the most relevant publications on this research topic.	229
[83]	exploration; genetic algorithms; integrated design; enhancement; parametric modelling; performance-oriented design	Discussions on combining parametric modelling and genetic algorithms (ParaGen). Two case studies were analysed, 1. the morphology of a dome as a function of structural performance and 2. a calculation of solar energy transmissions in a roof.	192
[84]	computer-aided conceptual design; evolutionary design; generative design; parametric design	Proposal of a CAD-based generative design exploration method. It is based on constructing a genotype within a parametric CAD system and then varying its parameters to obtain several variants within defined limits.	156
[85]	Implicit representation; level set; parametric design; R functions; shape optimisation; shape sensitivity analysis; topology optimisation	A strategy for shape optimisation is proposed that combines and preserves the advantages of previous techniques.	125
[86]	anchoring structural; corrosion; covering	Experimental research on the effects of corrosion products, testing the strength of the joints. The results were obtained through simple parametric design expressions.	121
[87]	building energy simulation; building envelope shape; early design stages; generative design system; parametric design; shape grammars	Proposed methodology for determining design decisions concerning building the envelope form and energy performance from the design stage.	111
[88]	architectural design process; improvement; parametric design; simplified LCA; sustainable building; sustainable building	Present an analysis of the building life cycle from a parametric point of view—applying this system to two case studies with positive results.	109
[89]	architectural and construction modelling; geometric modelling; parametric design	Analysis of the current use of parametric design software and the main advantages or difficulties for its development.	102

Table 5. *Cont.*

Document	Keywords	Contribution	Citations
[37]	expected significance levels; K-function; pseudolikelihood function; replicated spatial point patterns; spatial analysis of variance	Analyses how to implement approaches in the specific context of an experiment and uses simulations to demonstrate how the parametric approach can be more efficient when certain aspects are met.	95

Table 6 shows those authors with the highest number of published studies in the field, ordered in descending order. The number of citations received and the h-index were identified as a measure of the authors' professional quality according to the number of times their scientific articles were cited. The authors had few publications and citations, corroborating the research field's complexity and incipient beginning. Undoubtedly, this research topic is in full development and is predicted to face new challenges in the coming years, as well as an increase in publications being foreseen.

Table 6. Primary authors contributing to the field of research.

Author	Affiliation	Document			
		h-Index	No.	Citations	Most Cited Document
Wang, Y.	The University of Liverpool, Liverpool, UK	2	12	150	Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings.
Yang, Y.	Wuhan University, Wuhan, China	1	9	9	A surrogate-assisted optimisation framework for microclimate-sensitive urban design practice.
Schnabel, M.A.	Victoria University of Wellington, Wellington, New Zealand	12	9	35	Parametric designing in architecture: A parametric design studio
Li, J.	The North China University of Technology, Beijing, China	4	8	32	Parametric design based on building information modelling for sustainable buildings
Holzer, D.	The University of Melbourne, Parkville, Australia	7	7	27	Design exploration supported by digital tool ecologies.
Gerber, D.J.	University of Southern California, Los Angeles, CA, USA	17	7	92	Designing in complexity: Simulation, integration, and multidisciplinary design optimisation for architecture
Burry, J.	The Swinburne University of Technology, Melbourne, Australia	10	7	45	Software openness: Evaluating parameters of parametric modelling tools to support creativity and multidisciplinary design integration
Alaghmandan, M.	Shahid Beheshti University, Tehran, Iran	5	6	24	Mutual effect of geometric modifications and diagrid structure on structural optimisation of tall buildings
Wang, Hui.	FAMU-FSU College of Engineering, Tallahassee, FL, USA	13	6	23	Design and modelling of bamboo biomorphic structure for in-plane energy absorption improvement
Wiltsche, A.	Technische Universitat Graz, Graz, Austria	6	6	4	The intelligence of ornaments: Exploring ornamental ways of affordable nonstandard building envelopes

4.3. Comparative Analysis of Case Studies

4.3.1. Description of Case Studies

Finally, this section identified three projects representative of parametric design applications for optimising built environments. These documents were analysed and compared based on the application of sustainability parameters and the application of parameters related to environmental ergonomics.

Figure 12 identifies images that graphically depicted the three identified projects: project one (hereafter P1) [90], Efficient Outdoor Educational Space (E4); project two (hereafter P2), Confluence Park [91]; and project three (hereafter P3), The Future of Us pavilion [92].

Figure 12. Case studies.

P1 was carried out by a multidisciplinary team of the University of Malaga and located in a plot of the Faculty of Health Education Sciences in the University Campus of Teatinos in Malaga, Spain. It consisted of a semioutdoor educational space, a classroom with a capacity of approximately 35 people, corresponding to an average small group according to the European Higher Education Area. Regarding the formal composition, the maximum total surface area referred to the total surface area the proposal would occupy according to a given capacity. This area may be subdivided but always maintained the same scale. The average occupation of the enclosure was foreseen as the necessary space (room + circulation) that a student would need in a didactic space, 2.9 m^2/person.

P1 was based on parametric language, using the Rhino programme and the Grasshopper plugin to be a replicable prototype that could be relocated and scaled to adapt to the new environments in any other space on the campus.

Concerning the sustainability and environmental ergonomics criteria, the climatic parameters of the site were analysed using sensors. A 2D numerical model was created to simulate the conditions obtained from the monitoring. Additionally, a three-dimensional representation was created using the laser-scanned point cloud to analyse the shadow cast by the elements around the building and the vegetation. The wind speed and wind direction could be predicted from the model. This way, design errors could be identified and modified to improve comfort in the classroom.

Concerning constructive solutions and improving the comfort of the classroom, a modular enclosure system was used designed using a numerical method and built with marine plywood composed of wood suitable for outdoor use and finished with chromated copper arsenate salts, which would function as an adjustable or elastic lattice depending on the location. In addition, the shape and location of the educational space acted as solar protection elements.

On the other hand, two concrete sheets that left a space between them, filled with thermal insulation, prevented overheating during the day and favoured cooling at night. On the other hand, an active system consisting of a combination of radiant surfaces and installing embedded pipes through which water circulated improved the internal thermal sensation in winter by at least 5 °C. A radiant heating system would heat the horizontal surface of the stands. The room temperature was assumed on the outer side of the insulation; this was a conservative assumption for calculating the peak power, as the thermal inertia of the ground was neglected. Although the pavilion was partially open to the outside, it was not feasible to use a convective system, as the slightest breeze or natural air movement would make it impossible to control the air temperature. Photovoltaic energy was also used.

Regarding the application of circular economy criteria, P1 has yet to consider possible solutions regarding recycling or using local materials. However, rainwater channelling was foreseen. The perimeter of project one would have a wall waterproofing treatment consisting of a waterproofing sheet, a delta drains sheet and a perimeter drainage pipe connected to the rainwater drainage system. Thus, the entire area of the perimeter paving would have slopes for rainwater towards the exterior terracing. The water from the interior area would be collected using interior drains.

P2, realised by the multidisciplinary team, is located next to Mission Reach (Figure 11) in Texas on a 13 km stretch surrounded by a wooded landscape, through a set of pedestrian paths, with several surrounding communities. It is a nonprofit space for educational and artistic projects that aims to create an educational space that integrates architecture and outdoor space, educating the community about the fundamental role of water in ecosystems. It uses innovative technologies and construction methods to reduce costs through a form, fabrication and performance analysis. It consists of an iconic, unique and inspiring pavilion to catalyse a new identity for the city.

In terms of formal composition, the petals pavilion, known for its plant-like form, was structured like funnels of dew and rainwater, right down to the scale of the paving patterns, reminiscent of flowing watercourses. It was inspired by the vegetation of local plants that cantilever out to collect and redirect drainage water. The doubly curved funnels' construction using various construction strategies was highly complex. The prefabrication of specific parts was necessary to split up the more complex shapes. Instead of constructing an integral funnel, different parts were built as half-arches. The union of several of these formed the integral element. Thus, the petal concept and the initial strategy determined the exact shape and the number of elements to be constructed.

The centre of each pentagon was funnel-shaped for the channelling of rainwater, while the pentagon's edges represented each arch's apex. Concerning the sustainability and environmental ergonomics criteria, the pavilions provided shade and shelter and invited visitors to visualise the water cycle and its relationship with the San Antonio River. In addition, a rainwater storage area was designed as the primary source of the entire park.

A rainwater simulation script was developed that sampled points on the surface and then iteratively found the direction of the most significant slope to test how rainwater moved on the top surface of the concrete elements. If the paths of rainwater flowing on the surface ran into the spaces between the petals instead of into the valley of each petal, the petal parameters were modified until all rainwater flows ended up in the central drains.

Although this design did not apply circular economy criteria, the link with the surrounding environment was indisputable. In addition, it included several photovoltaic panels to offset 100% of the energy used.

Finally, P3 for The Future of Us exhibition was executed by the Advanced Architecture Laboratory of the Singapore University of Technology and Design. It is in the Singapore Gardens by the Bay at 30 Marina Boulevard, Singapore. It provides a space for users to perform all the daily functions of a city while experiencing the feeling of being in a forest. Rhinoceros was used for the design.

The design was inspired by biomimetic forms related to the shapes of nature, linked to advanced design and manufacturing technologies. It is an open space functioning as a passage area or a forest. The project was conducted with a lattice of a metallic lattice, and in its concept, it handled the idea of a walk through an imaginary forest.

The roof structure was approximately 40 m long and rose approximately 16 m with a structural depth of no more than 20 cm. The formal composition comprised some 11,000 triangular aluminium panels with different load distributions and perforations that produced varied patterns in their geometry. The design program was fed with density parameters, the entrance openings and curvature. In the case of the roof, sizing parameters of the structural grid and orientations of the structural components were used.

P3 comprised a pattern of 20 parametrically defined mosaics, which achieved a density gradient defined by the points at each corner of the triangles. These functions constructed a set of closed polylines from the corner points with three corner points and three corresponding density values. The pattern created a density module by addressing the requirements, creating entrances and a play of light and shadow in the interior. A point cloud of density values defining these requirements was created, with each point corresponding to a point on the mesh. For the creation of the point cloud, there were several variants; one was through generating random patterns, another through performance simulations and, finally, in the case of programmatic requirements, direct assignment. This repetition caused the regularity of the panels to be less visually apparent in the case of the grid structure. Additionally, these density patterns could be manually changed, which allowed for an immediate adjustment by the designers.

Regarding the sustainability and environmental ergonomics criteria, the designers used advanced tools to analyse environmental data, including prevailing wind speed, prevailing winds and daylighting. They aimed to recreate structures that generated shadows reminiscent of a tropical forest, where vegetation and indoor shade played a fundamental role in the user's hygrothermal comfort. The environmental data taken allowed the building form to adapt to the conditions, creating a project that was certainly sustainable and resilient to climate change, mitigating the effects of the urban heat island.

4.3.2. Comparative Analysis of Case Studies

Finally, Table 7 compares the application of the sustainability and environmental ergonomics criteria identified. As seen in Table 7, none of the three projects achieved all the identified parameters. However, the integration of pre-existing vegetation, ground floor morphology, density and urban heat island effect mitigation was present in all of them. On the other hand, low environmental impact materials, the use of materials with sustainability certification, durability, adaptation, deconstruction and acoustic comfort were absent in all of them, highlighting the urgency of introducing circular economy criteria in this type of environment.

Table 7. Sustainability and environmental ergonomics parameters identified.

Category	Parameter	Project		
		P1	P2	P3
Sustainability	Efficient water use and management	•	•	
	Low environmental impact materials			
	Preliminary study of the environment	•		•
	Use of materials with sustainability certification			
	Use of renewable energies	•	•	
	Life cycle analysis			
	Durability, adaptation and deconstruction			
	Revegetation of spaces			•
	Integration of pre-existing vegetation	•	•	•
	Low CO_2 emission transport systems			
	Air quality analysis	•		•
	Ground floor morphology and density	•	•	•
	Urban heat island effect mitigation	•	•	•
Environmental ergonomics	Wind control	•	•	
	Hygrothermal comfort	•		
	Acoustic comfort			
	Lighting and visual comfort	•	•	•

Specifically, P1 complid with seven sustainability parameters. In the case of environmental ergonomics, it applied three of the four aspects that were analysed: wind control, lighting and visual comfort and hygrothermal comfort. P2 made excellent use of efficient water management; its shape was designed for this. This project also used renewable energies, with which it managed to satisfy 100% of its demands. In addition, P2 fulfilled two of the four aspects. It simulated a forest, where comfort conditions, in this case, occur naturally. P2 and P3 focused on achieving comfort conditions through natural elements, while P1 optimised comfort conditions through mechanical systems that complemented natural features. P3 carried out a preliminary climatic study of the site, which helped the designer to determine more accurate decisions. In addition, the location of the existing vegetation was respected, and new vegetation was integrated.

5. Conclusions

This paper used SciMAT software for the bibliometric trend analysis of the research field between 1974 and 2021, based on research accessible in the ISI Web of Science (ISIWoS) and SCOPUS. The trends were examined, considering a general overview and a specific study of three different time intervals (1974–2009, 2010–2016 and 2017–2021).

The strategy diagrams, performance analysis, thematic networks and evolution map showed that the emerging studies included energy aspects, environmental impacts and constructive solutions. There were hardly any bibliographical records in the early years (from 1974 to 2009), and it was not until 1988 that parametric design was introduced. From the 1980s onwards, the first parametric language tools began to appear, although they were expensive and did not focus on the building sector. However, there was an apparent concern for the digitalisation of mathematical problems, but not for social, economic or environmental aspects. From the beginning of the century, the socialisation of this type of software increased its use in the sector, with an apparent reference to the BIM tool.

In the second period, coinciding with the SDGs, the authors began to worry about social and economic aspects. They investigated the functionality of spaces and the suitability of the built environment to the user and the climatic context in parallel to the development of sustainable building assessment tools, such as LEED and BREEAM. It was encouraged to design green buildings in line with the latest European renewable energy initiatives.

Finally, parametric environmental design emerged in recent years, no longer just concerning efficient buildings or climate change mitigation. However, research has focused on positive building consumption and climate change resilience within the principles of the circular economy. All this was within the new level(s) indicator language framework that promoted parametric language tools for optimising environmental ergonomics and sustainability parameters of built environments.

The analysed case studies symbolised an influential space for innovation and education in sustainability. The built environments of these buildings were the spatial response to urban development, highly complex spaces that depended on specific characteristics such as their dimensions were influenced by the climate, the urban planning in which they were inserted and the qualities of the materials used. Finally, the above results showed how research has been increasingly oriented toward climate change mitigation and adaptation activities, highlighting the importance of parametric design in the built environment, based on studies already carried out, identifying optimal measures and encouraging the creation of guidelines to serve as a model to be followed in subsequent studies. These guidelines could serve as a standard method for adapting ecoefficient equipment in built environments based on the techniques used in different climatic zones.

The above findings showed that this study is a valuable contribution to research on the application of parametric design for the optimisation of sustainability and environmental ergonomics parameters in built environments, because it provides researchers and practitioners in the field with a detailed understanding of the status and predicts the dynamic directions of this field.

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