Responsive architecture: a bibliometric analysis of scientific production

Arquitetura responsiva: uma análise bibliométrica da produção científica

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Abstract

Responsive architecture deals with the integration of data and physical adaptations between building and environment. The importance of the building envelope as a responsive construction system is one of the mostly investigated issues in the research field of architecture. This literature review and bibliometric analysis took into account type, quantity and year of publication, co-occurrence of terms, authors and affiliations. Output regarding conferences and journals, authors and higher-education institutions, and knowledge fields related to responsive architecture were highlighted. The participation of conference papers is more evident from a quantitative point of view; its percentage of the sample was around 55%. Automation in Construction is the most significant journal reaching 17% from the total journal output. The Netherlands and United Kingdom are the most cited countries on the subject matter. The study confirmed that responsive architecture has relevant interactions between different areas of knowledge, from computational science, robotics, civil engineering, urban design, product design to sustainable architecture, hence exhibiting a pronounced collaborative and multidisciplinary approach. Results from the systematic review and bibliometric analysis allow us to stress the need for a continued assessment of scientific production in the area and also for further research initiatives aimed at database analyses.

Keywords: Responsive architecture. Bibliometric analysis. Systematic review.

Resumo

Arquitetura responsiva está associada à integração entre interpretação de dados do ambiente e uma resposta adaptativa da edificação. A importância do envelope de edificações como elemento responsivo é um dos temas mais investigados na área da arquitetura. Esta revisão de literatura e análise bibliométrca considerou tipo, quantidade, ano de publicação, co-ocorrência de termos, autores e instituições acadêmicas. Foi dado destaque às contribuições no que diz respeito à produção acadêmica e áreas de conhecimento. Os resultados mostraram que a contribuição das publicações em congresso é a mais evidente, com aproximadamente 55% da produção científica. Dentre os periódicos, destaca-se Automation in Construction por deter 17% do total dos artigos. Dentre os países, Holanda e Reino Unido sobressaem em número de publicações. Este estudo mostra que a área da arquitetura responsiva contempla um intercâmbio de conhecimento entre ciências da computação, robótica, engenharia civil, urbanismo, design e arquitetura sustentável, resultando em uma abordagem colaborativa e multidisciplinar. Os resultados no método empregado contribuem tanto para o levantamento da informação na referida área quanto para futuras pesquisas dedicadas à análise da informação registrada.

***Palavras-chave**: Arquitetura responsiva. Análise bibliométrica. Revisão sistemática.*

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Introduction

Recent advancements in architecture have taken the importance of responsive architecture to a completely new level (DESAI, 1992). Within this context, the building envelope assumes relevance, while performing different roles in building, on one hand creating the visual impact of a building (aesthetics) and, at the same time, working as a membrane that separates the indoor environment from the outdoor space (the so called "third skin"). Another relevant function is to maintain adequate indoor comfort conditions relative to outdoor climatic fluctuations, contributing this way to the building energy performance (SRISUWAN, 2017). Building façades capable of changing shape in order to improve Indoor Environmental Quality (IEQ) aspects in response to prevailing climatic conditions tend to perform an important role with respect to building sustainability (RICCI *et al*., 2020). Depending on the façade design, interactions with the urban environment may change significantly. In terms of categories of interactive façades, it is possible to identify contextual design, responsive skins, and sustainable elements (SANCHEZ, 2010).

According to Meagher (2015, p. 160), responsive components can be defined as "[...] elements of the building that adapt to the needs of people as well as to changes in environment [...]". In the same way, "[…] responsive architecture can be understood as any building or building component designed for adaptation to changes in its surroundings [...]" (MEAGHER, 2015, p. 161).

Buildings are usually designed irrespective of future modifications during their life cycle. The flexibility of occupant needs (due to changes in occupancy and activities schedules) as well as of building functions (residential, commercial, industrial etc.) is seldom considered at the design stage. In addition, IEQ aspects are subject to constant variations such as seasonal changes, daily schedules and, in the long term, to climate change scenarios. Under such conditions, static solutions for maintaining thermal comfort conditions indoors are forcefully complex. Consequently, conventional building design processes are often insufficient (ACHTEN, 2019; THUN; VELIKOV, 2013).

The beginnings of the responsive architecture concept have their roots with the work of Cedric Price and Joan Littlewood and their Fun Place project (1961), a building capable to change according to visitors' desires. Those principles were followed by Renzo Piano and Richard Rogers (1977) and concretized with the Centre Georges Pompidou in Paris, France (MEAGHER, 2015; ACHTEN, 2019).

The most common examples of responsive façades are building components (structural or architectural) that adapt to environmental conditions (CHANG; HUANG; DATTA, 2019). Such elements can be advanced technological apparatuses equipped with sensors and active components that gather outdoor data and turn building elements into self-controlled systems (MEAGHER, 2015). Additionally, human requirements and feedback data can also be used to regulate occupant interactions (SCHNÄDELBACH; IRUNE, 2012). This way, responsive façades go beyond environmental concerns as they also take into account occupants' needs. This kind of interaction was analyzed in the study published by Schnädelbach and Irune (2012), which resulted from a laboratory scale model of responsive architecture that "breathes" with its occupants and tranquilizes their heartbeat.

The purpose of the present study is to present a systematic review on the subject matter responsive architecture and to characterize the most relevant research output in terms of conference and journal papers, main authors, and institutional affiliations by means of bibliometric analysis. To our knowledge, a comprehensive bibliometric analysis on responsive architecture has not yet been performed. As responsive architecture is an emerging field with various ongoing research developments, a systematic review within this field has an important role in gathering and disseminating relevant information.

This paper was structured as follows. Materials and methods report the research strategy based on a systematic review approach. In Results and discussion, the bibliometric analysis is presented as well as results and discussion. Finally, the Conclusion closes the paper.

The main outcome of this study highlights major trends in responsive architecture and ranks scientific production based on higher-education institution and country of origin. By approaching the building conceptualization from the viewpoint of responsive architecture, new opportunities become visible for a variety of further research fields.

Materials and methods

Systematic reviews can keep scientists aware of the field literature by summarizing a huge amount of publications and helping others to understand differences within studies of the same area. This kind of

review requires the use of scientific strategies in order to limit biases, allowing gathering, critical evaluation, and synthesis of relevant publications that concern a specific content (COOK; MULROW; HAYNES, 1997). In turn, bibliometric analysis can be interpreted as the generation of metrics on previously published information (BEM; REINISCH, 2014).

One technique that allows a comprehensive review of responsive architecture based on IEQ improvements was introduced by Loonen *et al*. (2013). This analysis included magazines, weblogs, and video portals, as well as commercial websites. However, bibliometric analysis and the systematic review process were not presented.

The development of the present study was conducted as follows:

(a) preliminary bibliographic search;

(b) research-string definition;

(c) main database identification; and

(d) bibliometric analysis.

This systematic review followed the protocols described by Bem and Coelho (2013).

Preliminary bibliographic search

The main terms associated with Responsive Architecture were identified by a preliminary search in the Google Scholar website using the expression "responsive architecture". According to a classification by relevance order, the first 25 available publications had their abstract analyzed. Using the word cloud occurrence software WordArt[1] the most representative terms were highlighted (Figure 1). Those expressions were then used in the search-string creation.

Search-string definition

Considering the use of related expressions, "responsive" synonyms and correlated terms were added to the string. The word "building" attached with the Boolean character "AND" was also included due to the fact that the words "responsive" and "architecture" have also been used in connection to software development and computational areas. Table 1 summarizes our search-string construction.

Figure 1 – **word cloud occurrence**

[1]Word Art is an online tool for generating "word clouds" from a provided text. The cloud emphasizes the more frequent words that appear in the source text (WORD ART, 2021).

Table 1 - **Search-string structures**

Level	Word decomposition	Synonym and Correlated terms
Field	Architecture	Building
Subject	Responsive	Adaptive Morphing Reactive Dynamic Intelligent Sensitive Kinetic
Search-string	((“responsive architecture” OR adaptive architecture” OR “morphing architecture” OR “reactive architecture” OR “intelligent architecture” OR “sensitive architecture” OR “kinetic architecture”) AND building*) AND NOT hygro* AND NOT vernacular	

Note: *“vernacular” term was excluded for its association to diverse architectural characteristics understood as responsive; and
**“hygro* term was also excluded due to commonly refers to responsive materials as hygromorphic or hygroscopic materials.

Main database identification

In order to be able to identify databases that publish about responsive architecture, the CAPES website was selected in the present study. The “responsive architecture” term was introduced in the “subject” search tool. CAPES Portal – sponsored and made available by the Coordination for the Improvement of Higher Education Personnel (CAPES/MEC) – is one of the biggest virtual libraries of scientific information worldwide (MINISTÉRIO..., 2018). Table 2 lists the extent of the dataset for our search with a preliminary number of publications found as per relevant database in the Portal.

Results have shown that Scopus, Web of Science and Pro Quest databases contain the majority of publications on responsive architecture. A new search was then conducted on June 9th, 2020, employing the “advanced search” tool. This strategy allowed the use of Boolean characters and other arrangements in order to refine the search in each database. We adopted “title, abstract and keywords” or “any place, excepting full text” as search parameters. To avoid results that were not correlated with previously selected fields, all papers categorized in the areas of health, neuroscience, physics, chemistry, biology, mathematics, agriculture, economy and other areas were excluded from the search.

This systematic review was based on peer-reviewed articles with no restrictions of language and year of publication and that were published in conferences and journals. To support data analysis and to better manage derived classifications, the MyEndNoteWeb[2] software was used. This reference manager also allows the identification and exclusion of duplicates. Some databases were not included for search restrictions, as exemplified below:

(a) Elsevier (CrossRef): world editor association gathering metadata from many editors and related to the Elsevier collection incorporated into CrossRef database;

(b) Directory of Open Access Journals (DOAJ): this database does not contain search mechanisms that allow the use of Boolean characters, nor allows search parameters associations. Examples include search for document titles, abstracts and keywords.

(c) Emerald Insight: this database does not provide a tool to export data, which means that its results cannot be associated to a reference manager software;

(d) Gale Academic OneFile: this database was excluded because it does not allow the user to order, select or exclude areas of knowledge. It is also not possible to export results to a reference manager software; and

(e) MEDLINE/PubMeb: this database was excluded as it mainly publishes papers on health sciences.

In addition, the Taylor & Francis database has only four search parameters: title, authors, keywords and anywhere in the full text. Since it is not possible to combine these options and a search in the whole

[2]MyEndNoteWeb – designed by a British company (Clarivate ™) – is a free tool available for managing, storing and sharing scientific references (CLARIVATE, 2021).

document was not intended, results based only on the keywords were taken into account. Table 3 provides results and the corresponding amount of publications after the removal of duplicates.

Table 2 - **Database list**

Database	Preliminary results
Scopus (Elsevier)	132
Materials Science & Engineering Database (ProQuest)	108
Technology Research Database (ProQuest)	84
Engineering Research Database (ProQuest)	73
OneFile (GALE)	70
Civil Engineering Abstracts (ProQuest)	61
Science Citation Index Expanded (Web of Science)	53
Arts & Humanities Citation Index (Web of Science)	37
Advanced Technologies & Aerospace Database (ProQuest)	36
Directory of Open Access Journals (DOAJ)	33
Taylor & Francis Online – Journals	32
Abstracts in New Technology & Engineering - ANTE (ProQuest)	24
Materials Research Database (ProQuest)	23
Computer and Information Systems Abstracts (ProQuest)	21
ScienceDirect (Elsevier)	19
MEDLINE/PubMeb (NLM)	19
Elsevier (CrossRef)	18
Mechanical & Transportation Engineering Abstracts (ProQuest)	17
Emerald Insight	12
Materials Business File (ProQuest)	9

Table 3 - **Publication list**

Database	Search Date	Quantity		
		Initial	Duplicated	Final
Scopus (Elsevier)	06/09/20	203	03	200
Science Citation Index Expanded (Web of Science)	06/09/20	177	08	169
Arts & Humanities Citation Index (Web of Science)				
Materials Science & Engineering Collection – ProQuest (Materials Science & Engineering Database)	06/09/20	76	27	49
Technology Collection - ProQuest (Technology Research Database				
Engineering Collection – ProQuest (Engineering Research Database)				
Engineering Index – ProQuest (Civil Engineering Abstracts)				
Advanced Technologies & Aerospace Collection – ProQuest (Advanced Technologies & Aerospace Database)				
Abstracts in New Technology & Engineering – ANTE - ProQuest				
Materials Research Database - ProQuest				
Computer and Information Systems Abstracts - ProQuest				
Mechanical & Transportation Engineering Abstracts - ProQuest				
Materials Business File - ProQuest				
ScienceDirect (Elsevier)	06/09/20	48	23	25
Taylor & Francis Online – Journals	06/09/20	10	02	08
Elsevier (CrossRef)	-	-	-	-
Directory of Open Access Journals (DOAJ)	-	-	-	-
Emerald Insight	-	-	-	-
Gale Academic OneFile (OneFile GALE)	-	-	-	-
MEDLINE/PubMeb (NLM)	-	-	-	-
TOTAL		**514**	**63**	**451**

The most representative database, Scopus (Elsevier) was chosen as the reference database for the bibliometric analysis. Scopus is the biggest peer-reviewed abstract and citation database worldwide. With daily updates, Scopus database makes available more than 75 million records, 24,600 active titles and 194,000 books. An independent and international Content Selection and Advisory Board is responsible for title reviews (ELSEVIER, 2021).

Regarding journals, the SCImago Journal Rank (SJR) was used. This indicator is a bibliometric index that measures a given journal's impact based on the average number of received citations during the last three years before the current year analysis (BIBLIOTECA..., 2020). The SJR – developed by SCImago from Google PageRank™ – was also used to access and analyze scientific domains, as well as to recognize journal relevance embodied in the Scopus database (BIBLIOTECA..., 2020; SCIMAGO, 2020).

The VOSviewer software was used to support the analysis of co-occurrence keywords, an arrangement that is related to the number of occurrences of keywords as provided by the authors. VOSviewer version 1.6.16 is a tool for bibliometric analysis through the creation of maps based on bibliographic data (available for free at http://www.VOSviewer.com/) (VAN ECK; WALTMAN, 2010) and generates therefore desirable results for construction and visualization of bibliometric networks (VOSVIEWER, 2020). The bibliographic network nodes are displayed in such a way that the distance among them indicates their relationship according to a selected parameter (VAN ECK; WALTMAN, 2010).

Results and discussion

Despite the fact that the present study was limited to the analysis of just one database, the systematic review allowed us to assess most indexed databases related to the subject matter responsive architecture: Web of Science, Pro Quest, Science Direct and Taylor & Francis. This section describes the bibliometric analysis of the available and relevant information according to four main aspects:

(a) field category;

(b) paper characterization;

(c) co-occurrence of keywords; and

(d) authors' production and affiliations.

Field category

Responsive architecture can be understood as a construction or building component designed for the adaptation of the indoor environment to changing conditions (CHANG; HUANG; DATTA, 2019). As this expression is commonly used in different fields, it is necessary to split them into categories based on the applications of such concept. The selected categories for paper classification are shown as follows:

(a) *Climate Responsive and Sustainable Architecture (CRSA)*: this category encompasses inherent characteristics of architecture design concepts that lead to environmental interactions (without kinetic components) and to sustainable architecture;

(b) *Computer, software, robotic and sensor (CSRS)*: this category mainly includes architectural software development, computational improvement, robotics and sensors that do not necessarily match the desired applications;

(c) *Diverse (D)*: this category includes developments on engineering and design processes, media façades, illumination control and kinetic structures, among other issues;

(d) *Responsive architecture (RA)*: this category corresponds to the purpose of our study and comprehends its concept and definitions; design, fabrication and evaluation of responsive components; reviews on dynamic façades; human-building interactions and correlated studies;

(e) *Smart materials (SM)*: this category takes into account developments in responsive architecture but is focused on intelligent materials' responsiveness, and thus does not comprise the purpose of this study; and

(f) *Virtual Reality and Render Simulations (VRRS):* this category refers to software technology development and its application in virtual reality simulation and 3D rendering, and is not necessarily related to responsive architecture.

The first analysis is related to the number of papers gathered from the applied search-string. Results are demonstrated in Figure 2, which also indicates the proportion of each category.

The number of articles related to software and computer science, climate-responsive and sustainable architecture that appeared in journals and conference papers is significant. The result for CSRS represents 28.50% percent of the total academic output and 17.50% of the total amount of publications refers to CRSA. These most prominent fields are closely followed by a 15% output on the "D – diverse" category, that includes many uncorrelated areas.

Search results indicated that the responsive architecture expression and its variations do not necessarily correspond to the area of architecture. With respect to climate-responsive buildings (where the environmental interaction is often purposed), the contribution is less significant as a dynamic response is not often taken into account.

Conference series and journals

Another classification criterion is given by year of publication and paper type, since this study comprises conference papers and journal articles. Figure 3 demonstrates the amount of publication type per year. Results show that studies found in the Scopus Database and dated from the end of the 20th century and from 1997 onward, becoming more expressive after 2010.

Figure 2 - **Quantity of papers per category**

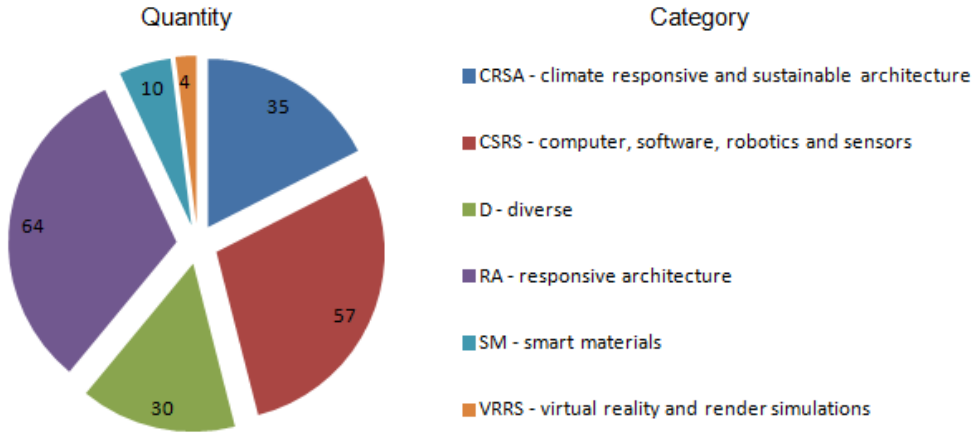
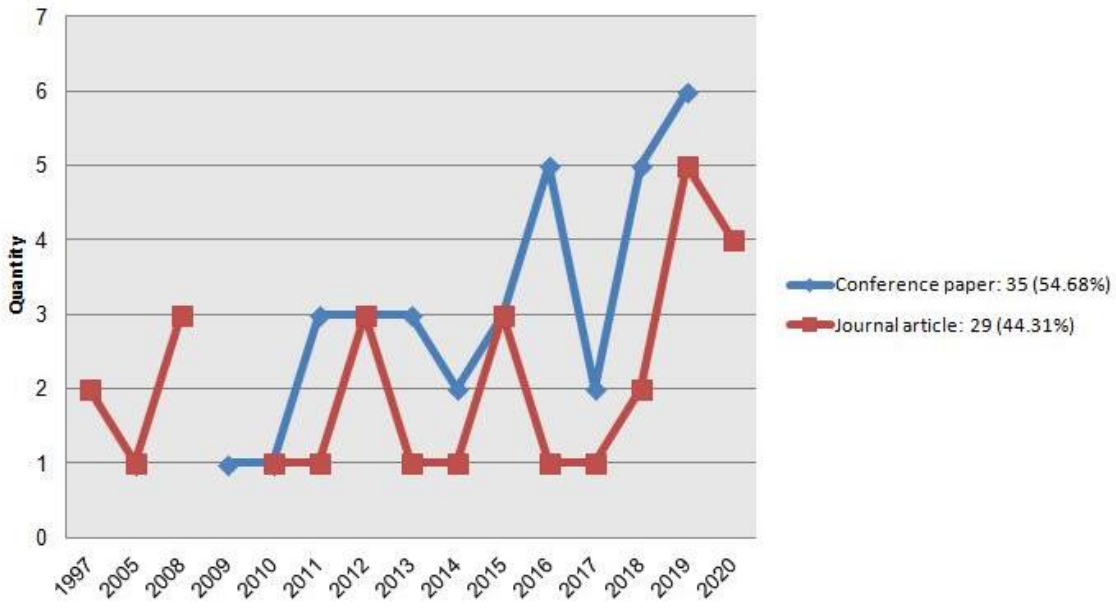


Figure 3 - **Number of publications per year**



Many papers were published in international conferences, which represent almost 55% of the total amount of papers. On the other hand, there has been a considerable increase in the number of journal articles since 2018.

Papers presented at conferences are sometimes strategic and can be understood as the beginnings of new threads in scientific research (WORRALL, 2016). However, the academic value of peer-reviewed articles in conferences is usually less important than published peer-reviewed papers in scientific journals. On the other hand, as the peer-review process in conferences is faster than in journals, it tends to comprehend more recent development in the desired field. According to Worrall (2016, p. 4), "[...] presenting a paper at a conference often gives the researcher their first chance to expose their ideas […]". In this sense, the importance of accounting for conference papers in a systematic review can be stressed, as it may be present the most recent innovations in a given research area.

Results shown in Table 4 are classified by conference name and academic output. Out of 23 international conferences, Computer-Aided Architectural Design Research in Asia published 14.28% of all papers, which makes it the most relevant conference in the sample.

The previous discussion may guide researchers to identify further conferences more correlated with responsive architecture, hence contributing both to publishing and networking.

The subsequent analysis is focused on peer-reviewed journal articles. To better characterize journal impact, effective contribution to responsive architecture and international relevance and representation, three topics were listed here as detailed in Table 5:

(a) publication quantity;

(b) SJR indicator; and

(c) the ISSN.

Journals were classified in a decreasing order to emphasize their overall impact in terms of the SJR index.

Table 4 - **Conference series**

Conference series	Published papers
International Conference on Computer-Aided Architectural Design Research in Asia	5
International Symposium on Automation and Robotics in Construction	3
World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium	3
Annual Conference of the Association for Computer Aided Design in Architecture	2
International Conference on Construction, Architecture and Technosphere Safety	2
Symposium on Simulation for Architecture and Urban Design	2
World Forum on Internet of Things	2
International Workshop of the European Group for Intelligent Computing in Engineering	1
ACADIA 2005 Conference	1
ACM Conference on Ubiquitous Computing	1
Conference SOLINA Sustainable Development: Architecture - Building Construction	1
Healthy Buildings America Conference: Innovation in a Time of Energy Uncertainty and Climate Adaptation	1
International Association for Bridge and Structural Engineering	1
International Conference on Artificial Intelligence and Pattern Recognition	1
International Conference on Civil Engineering and Urban Planning	1
International Conference on Cybernetics and Intelligent Systems	1
International Conference on High Performance Structures and Materials	1
International Conference on Structural Engineering, Mechanics and Computation	1
International Conference on Structures and Architecture	1
International Congress on Construction History	1
International Joint Conference on Pervasive and Ubiquitous Computing	1
International PLEA Conference on Sustainable Architecture + Urban Design	1
TensiNet - COST TU1303 International Symposium	1

Table 5 - **Journal on responsive architecture**

Journal	Quantity	SJR	ISSN
Renewable and Sustainable Energy Reviews	1	3.63	13640321
Automation in Construction	5	1.69	09265805
Engineering Structures	1	1.60	01410296
Sustainable Cities and Society	1	1.36	22106707
Advanced Engineering Informatics	1	0.95	14740346
ACM Transactions on Computer-Human Interaction	2	0.83	10730515
Alexandria Engineering Journal	2	0.58	11100168
Frontiers of Architectural Research	2	0.56	20952635
Buildings	2	0.48	20755309
Architectural Science Review	2	0.39	00038628
Archnet-IJAR	1	0.37	19387806
International Review of Law, Computers & Technology	1	0.36	13600869
Structural Engineering International (IABSE)	1	0.35	10168664
International Journal of Architectural Computing	2	0.28	14780771
International Journal of Design Sciences and Technology	1	0.27	16307267
Light and Engineering	1	0.22	02362945
Journal of Green Engineering	1	0.19	22454586
Journal of the Institution of Engineers	1	0*	0257344X
Journal of Building Appraisal	1	0.16**	17428262

Note: *not yet assigned a quartile; and
**this journal is no longer covered by Scopus Database. SJR 2013.

The SJR indicator was found not to be correlated to publication amount. Renewable and Sustainability Energy Reviews, whose index SJR is 3.63 (higher one), contributed with just one paper. Automation in Construction, SJR 1.69, has 5 papers. The number of published papers that appeared in the Automation in Construction journal is relatively more useful for those who are looking for a better understanding of the state-of-the-art in responsive architecture. The output in Automation in Construction represented 17.24% of the total academic production. Nonetheless, a paper published in a high quality journal – as per its SJR indicator or JCR Impact Factor[3] - can potentially foster authors' visibility (WORRALL, 2016).

Co-occurrence of keywords

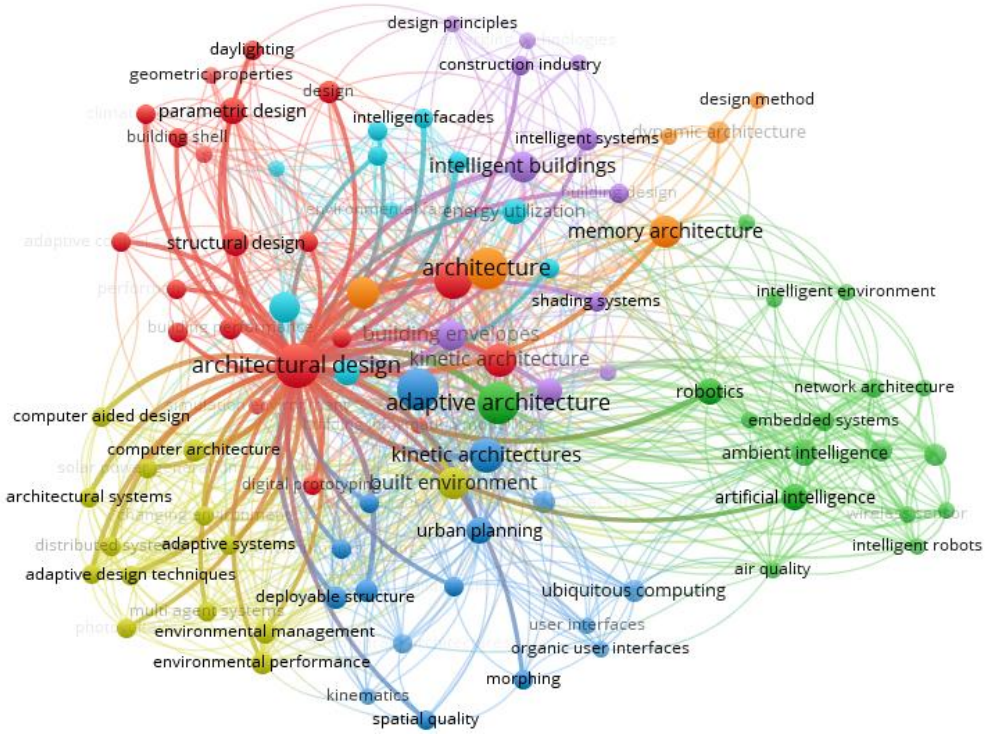
The co-occurrence of keywords gives researchers a notion on the predominance of given keywords in the sample. The proximity of the network nodes, obtained in VOSviewer, represents its correlation fields or identifiable clusters (Figure 4).
Results shown above also indicate a tendency of responsive architecture in four main correlated areas (clusters).

Design process: this clusters encompasses "structural design"; "architectural design"; "geometric properties"; "design"; "parametric design" and "digital prototyping" (in red)

The design and assembly of responsive structural elements demands an integration of spatial configurations, kinetic mechanisms and geometric properties. A parametric design approach allows the exploration of structural configurations due to its flexible and versatile characteristics (CHANG; HUANG; DATTA, 2019; PHOCAS; KONTOVOURKIS; MATHEOU, 2012). Regarding geometric properties, origami and deployable scissors structures are examples of the advantages behind folding, unfolding, contracting and expansion of rigid structures resulting in a flexible and adaptive (responsive) element (CHANG; HUANG; DATTA, 2019; ANDREOZZI *et al*., 2016; YI *et al*., 2020). On the other hand, despite being a useful tool for design studies, the parametric approach needs to be complemented by physical prototypes (JAYATHISSA *et al*., 2018). The introduction of digital prototyping by way of 3D printing allows the construction of key joint elements in order to connect different materials and parts (CHANG; HUANG; DATTA, 2019; YI *et al*., 2020).

[3]JCR annual Impact Factor of a journal is a parameter that includes citation of an article during a specific period correlating current year citations to the source items previously published (GARFIELD, 2020).

Figure 4 – **Co-occurrence of keywords**



Building performance: this cluster corresponds to “computer aided design”; “adaptive design techniques”, “computer architecture” and “architectural systems” (in yellow)

Computer-aided design can considerably reduce time needed for the design and testing stages. Simulations allow the designer to predict design interferences and test its performance from different variables in terms of geometry, energy consumption and indoor conditions (WANG; HOU, 2018; RICCI *et al*., 2020). Building energy simulations increase the possibility of verifying design performance solutions for different climate zones (RICCI *et al*., 2020). Among a variety of applications of responsive architecture, simulations can entail structural analyses, solar radiation appraisal, thermal simulations, photovoltaic performance tests, daylighting and glare interferences, and automated kinetic responses (CHANG; HUANG; DATTA, 2019; JAYATHISSA *et al*., 2018).

User interactions: this cluster refers to “user interfaces”; “ubiquitous computing” and “organic user interfaces” (in blue)

Responsive components supported by computational tools changed the way occupants interact with the built environment. Equipped with sensors and controlled by predictive and reactive systems, the building can autonomously respond to users’ needs (KOTSOPOULOS; CASALEGNO, 2015). Regarding user interaction, it is possible to highlight three domains:

(a) the interface between indoor and outdoor environment associated to thermal performance without the need of user intervention in order to achieve higher IEQ and comfort levels in terms of heating or cooling requirements;

(b) the interface between private (indoor) and public (outdoor) domain; and

(c) individual user preferences (KOTSOPOULOS; CASALEGNO, 2015).

The adoption of context-responsive elements also facilitates managing the variability of environmental conditions in different parts of the building, thereby coping with user needs (CHENG; BIER, 2016). The ubiquitous computing in turn comprehends smart environments which are able to enhance the building adaptability to occupants’ actions, in a dynamic fashion (LEHMAN, 2021).

Intelligent building: this cluster highlights "artificial intelligence"; "intelligent robots"; "intelligent environment"; "embedded systems" and "robotics" (in green)

According to Kroner (1997, p. 382), "[...] scientific and technological developments in materials, electronics, computing, communication, artificial intelligence (AI), and robotics have led to the emergence of the intelligent building (IB) [...]". This complex field requires the comprehension of interactions between architecture, robotics, AI and structural engineering. The adoption of electronic components, actuators, sensors, kinetic mechanisms and micro-controllers enables a building to perform different roles in order to achieve programmed functions (STERK, 2005).

The main clusters identified point to an integrated way to achieve responsive architecture goals. Results also demonstrate a lack of correlation between responsive systems and other constructive systems due to the appearance of correlated terms as building shell, building envelopes and intelligent façades. Additionally, network nodes emphasize the importance of multi-disciplinary research, comprising civil engineering (structural design), software and computational engineering (ubiquitous computing, artificial intelligence, embedded systems), robotics (robots, morphing, kinematics), urban design, product design, sustainable architecture (environmental management and performance, spatial quality, built environment, architectural design and urban planning) and building thermal performance (daylighting, shading systems and air quality).

Authors' production and affiliations

Main authors' production (Figure 5) was assessed directly from the Scopus database. Z. Nagy appears as the most productive author. Assistant professor in the Department of Civil, Architectural and Environmental Engineering at the University of Texas at Austin, Nagy previously conducted research at the Swiss Institute of Technology (ETH) in Zurich, working with Schlueter, who appears as co-author (UNIVERSITY..., 2021). However, the four publications by this author discuss further developments of a same study: photovoltaic system embodied in an adaptive solar façade comprehending design process, mechanical design, simulations, prototype construction and interactions with environment and building occupants (ROSSI; SCHLUETER, 2012; ROSSI; NAGY; SCHLUETER, 2012; NAGY *et al*., 2016; JAYATHISSA *et al*., 2018).

Cheng and co-authors follow a different approach. Researcher at Delft University of Technology and member of the Royal Architectural Institute of Canada (RAIC) and Colegio de Arquitectos Del Ecuador – Pichincha (CAE-P), the corresponding author, Cheng, does research on the following areas: robotics, assisted living, wireless sensor networks, ecosystems, ambient intelligence, actuators, ventilation and gesture recognition (TU DELFT..., 2021). Resulting papers by this group in our systematic research focused on intelligent façades that rely on intuitive and responsive interface between building and environment and consider environmental, thermal acoustics and user-comfort aspects (CHENG; BIER, 2016). In a later study, such authors worked on the ability of the built environment to perform intelligent behavior regarding information with communication technologies as well as adaptive architecture (CHENG; BIER, 2018). In recent papers, the authors investigated human-gesture recognition associated to environment sensing to achieve an intelligent environment, building performance and user comfort (CHENG *et al*., 2019).

Results reported above have demonstrated that the diversity of knowledge construction strongly depends on whether the author's production is focused on the same area of development or if he/she/they are involved in different projects. As database metrics are based on information gathered from authors' output, this quantitative analysis cannot be a reliable indicator of innovations. Regarding authors' affiliations, Figure 6 provides a summary of the 15 most representative higher-education institutions in terms of published papers on responsive architecture.

The main countries of origin of the publication output identified in this figure are The Netherlands and the United Kingdom. Delft University of Technology and Faculteit Bouwkunde van de TU Delft typically represent the Netherlands with nine publications and The University of Nottingham, Loughborough University and the University of Sheffield, with seven publications for each of them. Switzerland and the US follow those countries with four productions each.

Figure 5 – **Author's production**

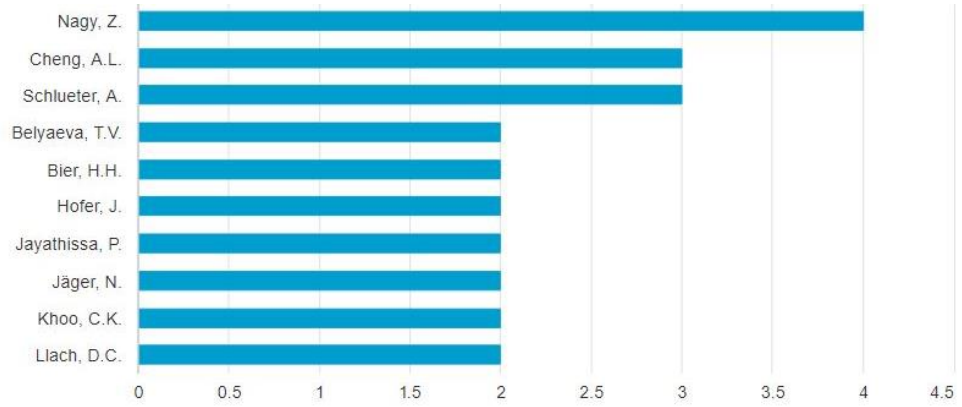
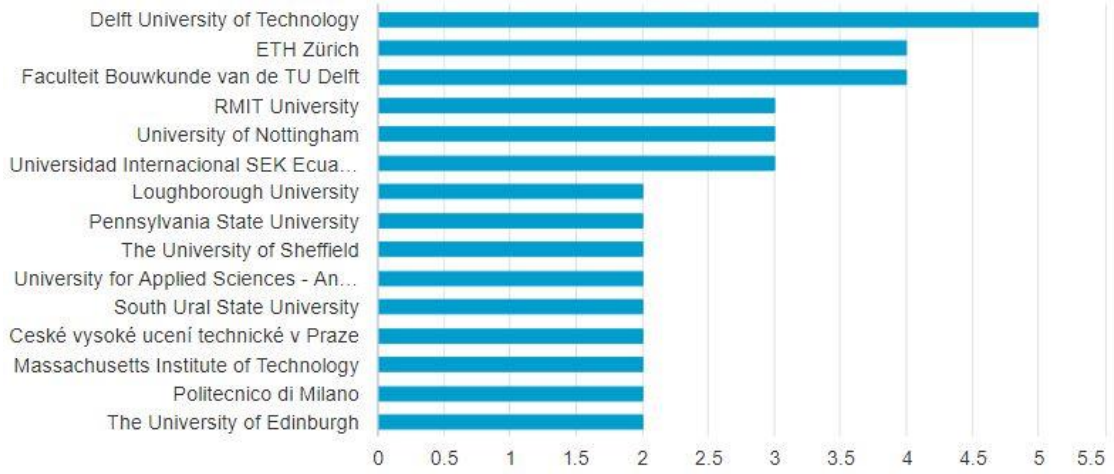


Figure 6 – **Authors' affiliations**



Conclusions

This study proposed a systematic review approach and a bibliometric analysis of responsive architecture publication output. The study focused on the Scopus database, hosted at one of the biggest virtual libraries of scientific information worldwide, the CAPES Portal. From obtained results, it was possible to characterize published papers in terms of research areas, quantity and type of publications. The relevance of conferences and journals was also assessed as well as the journals' overall impact and authors' productivity.

The primary outcome presented in our study is that The Netherlands and the United Kingdom are the most relevant countries in terms of amount of publications on the subject matter. By developing the protocol of analysis presented in this paper, we have underlined correlated research fields on responsive systems and verified that the area is multidisciplinary in nature. The integration of information technology, parametric design strategies, simulations, robotics, artificial intelligence and user demands as well as building thermal performance showcases the complexity of responsive architecture projects. In addition, it was possible to notice a lack of publications and research output on responsive systems associated with built elements other than building façades.

This combination of systematic review method and bibliometric analysis can be useful for future studies. Follow-up studies should aim to investigate the full contents of the papers in the sample in an analytical way so as to better characterize applications of responsive systems. The relatively high amount of keywords identified with the search-string reveals that, currently, responsive architecture cannot be restrained to a single expression. Rather, it should also include kinetic and dynamic, intelligent, morphing, sensitive and adaptive architecture.

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