# Fire performance in buildings: academic insights and perspective analysis

## Desempenho do fogo em edificações: insights acadêmicos e análise de perspectivas

## *Comportamiento frente al fuego en edificios: conocimientos académicos y análisis de perspectiva*

Rejane Martins Viegas[1]
João Paulo Lima[1]
Michele Tereza Carvalho[1]
Caio Frederico e Silva[1]

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**Abstract:** Accelerated growth of urbanization and the consequent rise in the number of buildings results on an increase in rapid constructions without minimum criteria that enable the safe building performance and how it behaves during episodes of fire. In this scenario, this paper aims to analyze research trends and the *status quo* of building fire performance in the last five years, evaluating perspectives for research, and proposals for future directions through a Systematic Literature Review (SLR) approach associated with bibliometric analysis. The analysis was carried out based on the Web of Science database under parameters such as authors, countries and regions, journals, research areas, and keywords. For each rule, among all the results retrieved, those that stood out the most in the stipulated period were evaluated. It was found that research on fire performance in projects is increasing, with a total of 402 published works. In the analysis by Systematic Literature Review, there was a trend of research concerning materials and structural systems, evaluating the performance, behavior, resistance, and safety of buildings under fire conditions. Ultimately, the results pointed out a possible evolution of the trend in research on methodologies and intelligent control systems applied to the management of fire emergencies.

**Keywords:** fire performance; building performance; fire safety; systematic literature review; bibliometric analysis.

**Resumo:** Com o acelerado crescimento da urbanização e consequente aumento do número de edificações, houve acréscimo de projetos e construções céleres, sem critérios mínimos que possibilitem o bom desempenho do edifício e como se comporta durante episódios de incêndios. Nesse cenário, este trabalho tem como objetivo analisar tendências em pesquisa e o *status quo* de desempenho do fogo de edificações nos últimos cinco anos, avaliando perspectivas para pesquisa na área e propostas de direcionamento futuro, por meio de uma abordagem de Revisão Sistemática da Literatura (RSL) associada a uma análise bibliométrica. A análise foi realizada com base no banco de dados *Web of Science*, sob parâmetros como: autores, países e regiões, periódicos, áreas de pesquisa e palavras-chave. Para cada critério, dentre todos os resultados recuperados, avaliaram-se aqueles que mais se destacaram no período estipulado. Verificou-se que pesquisas voltadas ao desempenho no fogo em projetos são crescentes, apresentando um total de 402 trabalhos publicados. Na análise por Revisão Sistemática da Literatura, verificou-se uma tendência de pesquisa em relação aos materiais e sistemas estruturais, avaliando desempenho, comportamento, resistência e segurança das edificações em condição de incêndio. Além disso, os resultados apontaram uma possibilidade de evolução da tendência em pesquisa de metodologias e sistemas inteligentes de controle aplicados ao gerenciamento de emergências de incêndio.

**Palavras-chave:** desempenho do fogo; desempenho de edificações; segurança contra incêndio; revisão sistemática da literatura; análise bibliométrica.

**Resumen:** Con el acelerado crecimiento de la urbanización y el consecuente incremento en el número de edificaciones, hubo un incremento de proyectos y construcciones rápidas, sin criterios mínimos que permitan el buen desempeño del edificio y cómo se comporta durante los episodios de incendio. En este escenario, este trabajo tiene como objetivo analizar las tendencias en la investigación y el *status quo* del comportamiento frente al fuego en los edificios en los últimos cinco años, evaluando perspectivas de investigación en el área y propuestas para el rumbo futuro, a través de un enfoque de Revisión Sistemática de la Literatura (RSL)

[1] Universidade de Brasília (UnB), Brasília, Distrito Federal, Brasil.

asociado con un análisis bibliométrico. El análisis se realizó utilizando la base de datos *Web of Science* bajo parámetros como: autores, países y regiones, revistas, áreas de investigación y palabras clave. Para cada criterio, entre todos los resultados recuperados, se evaluaron los que más destacaron en el período estipulado. Se constató que la investigación sobre el comportamiento frente al fuego en proyectos está creciendo, con un total de 402 trabajos publicados. En el análisis de Revisión Sistemática de la Literatura, hubo una tendencia de investigación en relación a los materiales y sistemas estructurales, evaluando el desempeño, comportamiento, resistencia y seguridad de los edificios en condiciones de incendio. Además, los resultados apuntan a una posibilidad de evolución de la tendencia en la investigación sobre metodologías y sistemas de control inteligente aplicados a la gestión de emergencias contra incendios.

**Palabras clave:** comportamiento frente al fuego; comportamiento frente al edificio; seguridad contra incendios; revisión sistemática de la literatura; análisis bibliométrico.

## 1 INTRODUCTION

The construction industry is one of the main contributors to the global economy (KIFOKERIS; XENIDIS, 2017). Given the large participation in this sector, the management of a construction project involves the use of various resources to achieve project objectives related to attributes such as quality, duration, cost, function, and durability (ZHANG *et al*., 2019).

In building construction, the parties involved work in a flexible and dynamic environment that supports interactive processes based on knowledge and responsibility. However, those responsible for the fire safety design of buildings are insufficiently involved in this interactive process (MA; WU, 2020; MALUK, 2017). In the buildings' management phase, fire has always been a significant threat to their safe operation (MA; WU, 2020). Every year, building fires cause numerous deaths, along with a serious economic and social impact worldwide (LUCHERINI; MALUK, 2019). As an example, 38% of the causes of fires in the United States are residential (NATIONAL FIRE DATA CENTER, 2019). In the year 2018 alone, there were a total of 379,600 residential fires, which resulted in 2790 deaths, 11,525 injuries, and a material loss of $8.2 billion.

Thus, one must consider appropriate fire safety strategies, fire prevention regulations in particular. Each country has proper regulations, with parameters and requirements, for the analysis of structural systems under fire and smoke conditions, such as the International Building Code (ICC, 2018) adopted in the USA, the EN 13501-1 adopted in the European Union (EUROPEAN COMMITTEE FOR STANDARDIZATION [CEN], 2018), and the Performance Standard (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS [ABNT], 2013) adopted in Brazil.

Since the development of building codes, fire safety design and regulation in the building structural systems design have been based on the concept of compliance. In this way, the design looks at individual building elements, evaluating what is needed to meet the acceptability criteria presented in building codes to ensure that buildings provide an assumed, though typically unquantified, level of fire safety (LAW; BEEVER, 1995; MALUK, 2017). More specifically, current fire codes are prescriptive for passive building construction and active fire protection systems in many places (CHOW, 2015). As such, a building, when ensuring fire performance, must: (i) enable the safe exit of occupants; (ii) ensure conditions for the employment of public rescue with timely (iii) prevent or minimize damage to the building itself, to adjacent buildings, to public infrastructure and the environment (ABNT, 2013).

Fire performance research was first addressed at the end of the twentieth and the beginning of the twenty-first century, and since then, it has been presenting a growing number of proposed works in the area. Even so, fire performance in buildings is a recent concern and a gap in research. Moreover, according to (MALUK; WOODROW; TORERO, 2017), there are still adversities in allying

the fire safety community – both in research and practice – with other areas of building design. In addition, the authors highlight the greatness and potential benefits of this relationship.

About the trend allied to technologies, the literature has been recurrent in pointing out that performance assurance leads to a consideration of normative requirements or other performance parameters demanded by users since the feasibility analysis and initial studies (COTTA; ANDERY, 2018). This requires the integrated and simultaneous development of architectural design and engineering (KAMARA; ANUMBA; CUTTING-DECELLE, 2007). In addition, (BRÍGITTE; RUSCHEL, 2016) indicate the need for a systemic view between the various variables that make up the performance requirements.

Too often, fire design professionals participate only in the non-essential part of a building's design process, sometimes to obtain regulatory approval–restricting the design to align with prescribed fire safety measures that are supposed to provide adequate fire safety. The result is a suboptimal relationship between the overall design and the fire safety design in many buildings (MA; WU, 2020; MALUK, 2017). Thus, according to (MALUK; WOODROW; TORERO, 2017), the fire safety community (both in research and practice) recognizes the need for integration to the other design fronts and has reacted to the continuous evolution of buildings. In recent decades, global efforts have been made to develop and implement performance-based approaches to fire safety design.

Therefore, it is important to evaluate the current conditions regarding research on building fire performance, as well as the applications that are contributing to the promotion and development of the proposed analysis.

This paper aims to analyze the trends in research and the status quo of building fire performance in the last five years, evaluating perspectives for research in the area, in the construction sector, by Systematic Mapping of the Literature associated with bibliometric analysis.

## 2 METHOD

The research trends and the status quo of fire performance in buildings will be evaluated in this research from aspects such as global contributions, leading countries and regions, most productive institutions, journals, authors, leading research areas, collaboration patterns between countries/regions and institutions, most cited articles and historical maps of keywords of authors, international standards, and important topics. To understand the current status quo, an analysis of papers published in the last 5 years will be considered.

Systematic Literature Review (SLR) is used to identify the issues and explore new research approaches regarding building fire performance. In addition, Bibliometric Analysis is adopted for data collection and analysis.

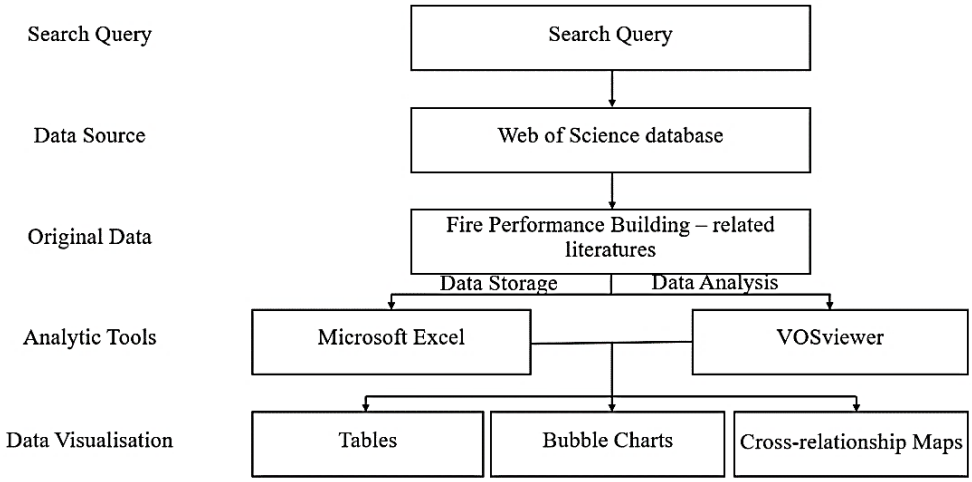
### 2.1 Method of analysis and data collection

The flowchart of the data collection method used is shown in figure 1. The data collection and analysis were carried out in the following parts, with their respective steps: determination of the research question adopted in the research, data collection, data analysis, and data visualization.

According to (KITCHENHAM, B.; CHARTERS, 2007), the systematic mapping study is complementary to the systematic review, which in turn is characterized as a review of a broad

character and results in the primary studies in a specific area, thus seeking to identify possible evidence available in that area (CHEN *et al.*, 2019). Also, according to the authors, systematic mapping is a method whose goal is to build a classification scheme and structure in a field of interest. Systematic mapping studies are used to structure a research area, typically providing visual summaries (outcome maps), while systematic reviews are focused on collecting and synthesizing evidence (PETERSEN; VAKKALANKA; KUZNIARZ, 2015).

Figure 1 – Method flowchart: column of process steps, and step discretization scheme

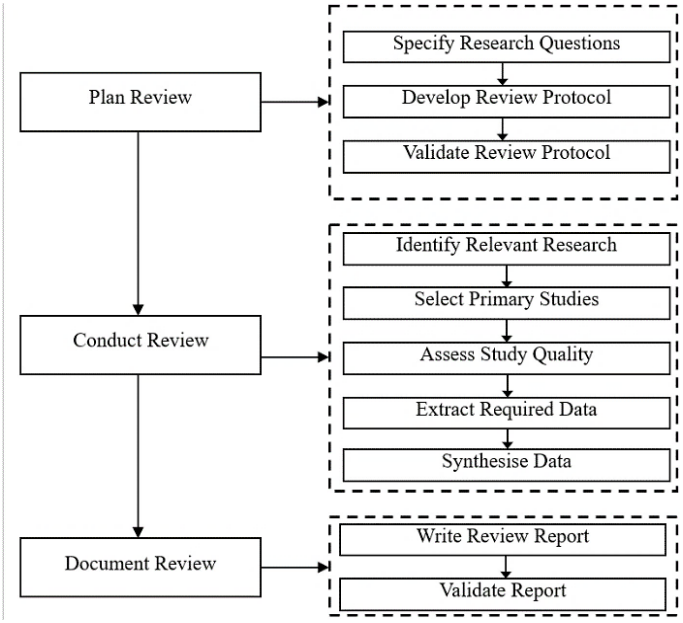



Source: Self-Elaboration

## 2.2 Research protocol

The execution of the systematic mapping or RSL is presented in figure 2 (KITCHENHAM, B.; CHARTERS, 2007), as the definition of research protocol with its respective guidelines, prior to the execution of the literature review. It will be followed in these guidelines, which include activities grouped into three main phases: (i) planning, (ii) conducting, and (iii) reporting.

Figure 2 – Steps in the Systematic Literature Review process




Source: Kitchenham e Charters (2007).

### 2.3 Research Process

The goal of a systematic review is to find as many primary studies as possible related to the research question, using an unbiased search strategy.

The rigor of the search process is a factor that differentiates systematic reviews from the usual ones (KITCHENHAM, B.; CHARTERS, 2007). In this study, the strategy for identifying published research was the use of WoS.

WoS is widely regarded as a standard tool for generating citation data for scientific research and other evaluation purposes. Its flagship collection includes more than 12,000 authoritative, high-impact academic journals worldwide, including the natural sciences, engineering, biomedicine, social sciences, arts, and humanities (LI *et al*., 2020).

In the present study, the main concepts, i.e., title (TS), abstract, and keywords, were addressed in topics as well. To elaborate the search string, the terms building, fire, performance, and standard were highlighted. In addition, synonyms and relevant variants were added to the search, resulting in TS = ((building OR house* OR residential) AND (fire) AND (performance) AND (code OR regulation OR standard* OR certification)).

Exclusion and inclusion criteria were adopted to obtain consistent results: (i) inclusion: papers that are journal articles in English, Spanish and Portuguese languages; (ii) exclusion: duplicate studies; studies older than five years. It is worth mentioning that the search string adopted may not cover all the existing synonyms for the term fire performance standards in buildings and, thus, may be insufficient to reach all the studies in the area. In addition, it should be noted that the WoS database may not publish all studies, and consequently, not be shown in this research.

To manage the data extracted from the documents, we used the VOSviewer software - a data mining and visualization platform that creates maps based on the network data and can be visualized, explored and indicate useful information that lies behind the data.

### 2.4 RESEARCH QUESTIONS

The research questions specified at the beginning of the systematic mapping (KITCHENHAM, B.; CHARTERS, 2007) are as follows:

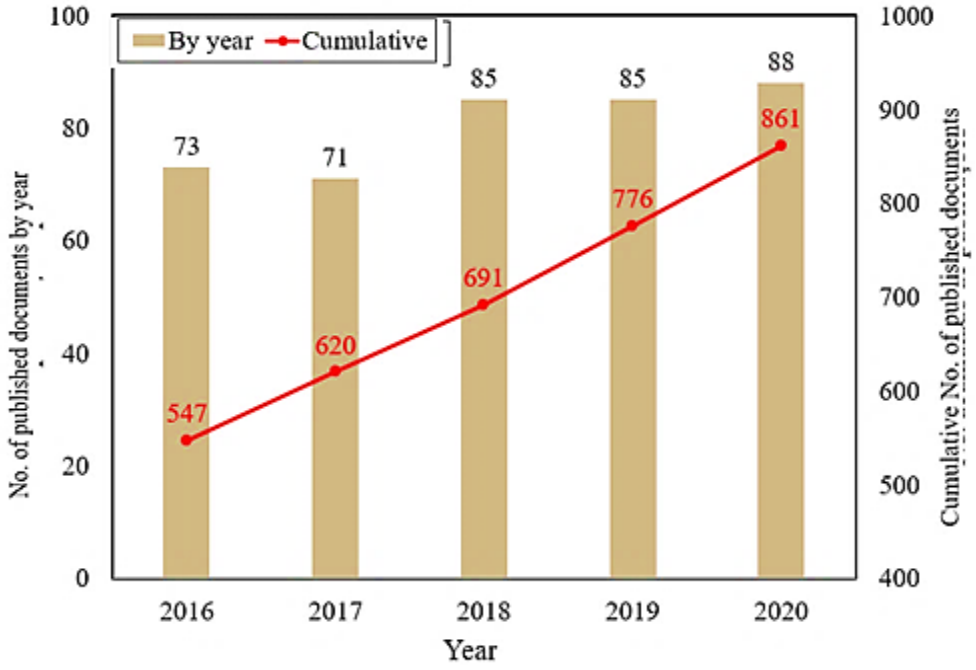
- Q (i): What is the frequency of publications in Web of Science (WoS) journals regarding building fire performance in the last five years?
- Q (ii): What is the category of the publications?
- Q (iii): Which are the most cited journals related to the specific theme?
- Q (iv): What are the most common keywords for the proposed theme?
- Q (v): Which countries stand out in the research of fire performance in buildings?
- Q (vi): Which authors have worked with the proposed theme?

## 3 RESULTS

When analyzing Q (i), we obtained 402 papers published from January 2015 to April 2020. Of these, 402 documents, 381 articles, and 21 reviews. Regarding the analysis of the results obtained, 64 countries contributed to the research field of fire performance in buildings.

It can be seen that the trend in the growth of published research over time, for the specific research field, is an average of 81 published papers per year (in the last 5 years), which can be seen in figure 3.

Figure 3 – Number of published documents on building fire performance




Source: Self-Elaboration

The cumulative publication rate shows a first stage growth for 2016 and 2017, and a second stage growth for 2018, 2019, and 2020, with a 19.8% increase in the number of articles for 2018 compared to the previous year. It is estimated that 46.7 % of the building fire performance literature was published from 2016 to 2020.

To answer question Q (ii), 76 different WoS classification categories resulted from the 402 papers on building fire performance, where the same paper can be classified in more than one category. Thus, the WoS categories labeled in the same papers are connected. Table 1 shows the top ten WoS categories by a record count for the topic covered.

The Civil Engineering area represents the vast majority of the category list, with a total of 40.30 % of the papers published in the last five years, followed by Building Construction Technology, Multidisciplinary Materials Sciences, and Multidisciplinary Engineering. The remaining categories contributed to less than 10 percent of papers published on the specified topic. The categories Energy and Fuels, Thermodynamics and Sustainable Technologies lead the average number of citations per paper, with 7.05; 5.30 and 4.95 citations per publication, respectively. It is also possible to evaluate the h-index of each category, highlighting Civil Engineering with an h-index of 15 (15 publications with at least 15 citations each), followed by Building Construction Technology with h-index = 12 and Multidisciplinary Materials Sciences with h-index = 11. The other categories have h-indexes less than 10. When analyzing all papers, there is a total of 1542 citations, an average of 3.7 citations per paper, in an h-index = 18.

The results in Table 1 also point to a concern for research within Engineering on the term

fire performance in buildings. Many papers (62.40% of the total) fall within the fields of Civil Engineering, Building Construction Technology, and Multidisciplinary Materials Science. Thus, one can associate the recurrence of research in the last five years to the search for fire performance in buildings through the minimum strength of the materials used in structural systems, as required by national and international standards.

Table 1 – Contribution from the main Web of Science research areas

| | **Category Web of Science** | **TTTT** | **FT** | **TC** | **MC** | **h-index** |
|---|---|---|---|---|---|---|
| 1 | Civil engineering | 162 | 40.30% | 700 | 4.32 | 15 |
| 2 | Building construction technology | 143 | 35.57% | 564 | 3.94 | 12 |
| 3 | Multidisciplinary Materials Science | 126 | 31.34% | 419 | 3.33 | 11 |
| 4 | Multidisciplinary Engineering | 46 | 11.44% | 114 | 2.48 | 6 |
| 5 | Energy and Fuels | 39 | 9.70% | 275 | 7.05 | 9 |
| 6 | Mechanical engineering | 25 | 6.22% | 117 | 4.68 | 5 |
| 7 | Sustainable Technologies | 20 | 4.98% | 99 | 4.95 | 4 |
| 8 | Thermodynamics | 20 | 4.98% | 106 | 5.30 | 5 |
| 9 | Environmental engineering | 18 | 4.48% | 63 | 3.50 | 5 |
| 10 | Environmental sciences | 18 | 4.48% | 66 | 3.67 | 3 |

*Note: TT: Total number of jobs; FT: frequency of work; TC: Total citations; MC: Average number of citations.
Source: Self-Elaboration

In question Q (iii), academics and those interested in building fire performance must know in which journals the search scare presents recent publications relevant to the topic. In the proposed search field, 233 journals contributed to the scientific literature. Table 2 presents the list of the 10 most recurrent journals in the analyzed topic.

Table 2 – Ten most recurrent magazines

| **N** | ***Journal*** | **TT** | **FT** | **TC** | **MC** | **FI** |
|---|---|---|---|---|---|---|
| 1 | *Fire Technology* | 25 | 6.22% | 98 | 3.92 | 1.67 |
| 2 | *Fire and Materials* | 23 | 5.72% | 68 | 2.95 | 1.92 |
| 3 | *Fire Safety Journal* | 20 | 4.98% | 92 | 4.60 | 2.29 |
| 4 | *Journal of Building Engineering* | 14 | 3.48% | 43 | 3.07 | 3.38 |
| 5 | *Construction and Building Materials* | 14 | 3.48% | 189 | 13.5 | 4.42 |
| 6 | *Engineering Structures* | 9 | 2.24% | 85 | 9.44 | 3.55 |
| 7 | *Thin Walled Structures* | 9 | 2.24% | 57 | 6.33 | 4.03 |
| 8 | *Energy Procedia* | 6 | 1.49% | 20 | 3.33 | - |
| 9 | *Journal of Constructional Steel Research* | 6 | 1.49% | 56 | 9.33 | 2.94 |
| 10 | *Journal of Structural Engineering* | 6 | 1.49% | 18 | 3.00 | 2.45 |

*Note: TT: Total number of jobs; FT: frequency of work; TC: Total citations; MC: Average number of citations.
Source: Self-Elaboration

While Fire Technology and Fire and Materials are the most recurrent in a number of documents, with a total of 25 (6.22%) and 23 (5.72%) articles covering fire performance in buildings, the Construction and Building Materials has the highest number of citations (189 citations), correlated to the highest average number of citations per article (13.5). In addition, it has the highest impact factor (4.42) among all the journals presented, followed by Fire Technology

(with a total of 98 citations) and Fire Safety Journal (with a total of 92 citations). Engineering Structures and Journal of Constructional Steel Research have relevant average citations per paper, respectively 9.44 and 9.33. When selecting the top three most productive journals (Fire Technology, Fire and Materials, and Fire Safety Journal) it is possible to analyze the critical points of building fire performance research.

Occupant safety, building evacuation, and life safety risks are also important topics in the journal Fire Technology. (KULIGOWSKI *et al.*, 2015) describe the performance of exit systems through movement in stairwells during building evacuations; already (HAVEY *et al.*, 2018) and (DINABURG; GOTTUK, 2016) evaluate building occupant warning systems; finally, (SABAPATHY; DEPETRO; MOINUDDIN, 2019) evaluate the life safety risks of a building with an open stairwell interconnecting the floors. Works addressing the influence of assembly or material failures on building fire performance are highlighted as proposed by (MALUK, 2017) who evaluated the failures of building assemblies on the environment barriers in an arbitrary fire; (BEDON; FRAGIACOMO, 2019) evaluated the fire resistance of wooden walls of the type Log-House.

Research by Fire and Materials is presented in studies that characterize the fire behavior of materials applied to structural elements and systems. The publication conducted a study of the fire behavior of facade mock-ups equipped with aluminum composite material-based coatings using an intermediate scale test method (GUILLAUME *et al.*, 2018); in another, it performed a comparative energy analysis of fire resistance tests on combustible and noncombustible slabs (BARTLETT *et al.*, 2020).

In the articles published by Fire Safety Journal, a multidisciplinary among the subjects treated in fire safety engineering may be observed. However, all works have a bias to safety and housing performance. Solutions for the resistance of structural elements and systems in high-temperature exposure are a recurrent topic in this journal. Among various works, the one by (DIAS; KEERTHAN; MAHENDRAN, 2019) may be given as an example, as it presented a fire performance analysis of Light Steel Frame walls with steel cladding and gypsum board through experimental tests. (WANG *et al.*, 2018) performed a numerical procedure for the thermal analysis of flaming reinforced concrete slabs at elevated temperatures. (JATHEESHAN; MAHENDRAN, 2016) presented a numerical fire performance study of Light Steel Frame floors made of hollow flange channel section beams under fire conditions.

The application of studies on civil construction materials also can be highlighted, as proposed by (ABBAS *et al.*, 2019) who suggested predictive relationships based on Artificial Neural Networks for the fire performance of high-strength concrete and compared their results with codes, standards, and other research. Also, one can notice the presence of works that evaluate fire safety codes in buildings such as (GISSI; RONCHI; PURSER, 2017) and (GRIMWOOD; SANDERSON, 2015).

Finally, attention is brought to works focused on Fire Safety Design and Management, such as (ARIYANAYAGAM; MAHENDRAN, 2015) which evaluated the potential of integrating fire safety into modern building design; and (ABNT, 2013) which presented fire design rules for cold-formed steel frame walls exposed to realistic design fire curves. The keywords defined by the author reflect the main focus and trend of the research on Fire Performance in buildings. To discuss question Q (iv), 1956 author keywords were analyzed from the retrieved results. Keywords with the same meanings were unified into a single word. Publications that have no author keywords might not have been included in this analysis. A total of 1615 (82.56%) keywords were used

only once, which demonstrates a wide range of research interests in building fire performance. Table 3 shows the most frequently occurring keywords. Figure 4 presents a bubble graph used to evaluate the keyword development trend.

Figure 4 – Keyword Trends by Year


Source: Self-Elaboration

At the top of the graph are the years of publication. The number in each bubble is the annual number of publications for each keyword listed on the abscissa axis. The larger the bubble is, the more publications for each topic were found. Performing a vertical comparison of the sizes of the bubbles identifies the trending keywords for each year. The size of the bubbles horizontally shows the possibility of determining the growth trend of each keyword over time. It can be seen that performance is the most used keyword with 84 recurrences, which had a significant growth between 2016 and 2020. It should also be noted that, even joining similar words, performance is still widely associated in different compound keywords, such as performance-based design (12th in the recurrence ranking, defined in 16 papers) and fire performance (18ª in the recurrence ranking, which was used in 13 papers), as well as examples not shown in Table 3 like "performances analysis, structural performance, and building performance".

Table 3 – Authors' Keyword Recurrence

| N | *Keywords* | TT | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|
| 1 | *performance* | 101 | 11 | 15 | 21 | 25 | 29 |
| 2 | *behavior* | 67 | 6 | 5 | 13 | 21 | 22 |
| 3 | *fire resistance* | 62 | 8 | 6 | 13 | 17 | 18 |
| 4 | *fire* | 49 | 10 | 7 | 12 | 13 | 19 |
| 5 | *design* | 36 | 3 | 4 | 8 | 11 | 10 |
| 6 | *systems* | 32 | 3 | 5 | 7 | 8 | 9 |
| 7 | *resistance* | 32 | 4 | 4 | 7 | 7 | 10 |
| 8 | *steel* | 31 | 3 | 3 | 3 | 10 | 12 |
| 9 | *model* | 25 | 3 | 4 | 2 | 7 | 9 |
| 10 | *fire safety* | 24 | 2 | 7 | 8 | 1 | 6 |
| 11 | *mechanical-properties* | 27 | 3 | 3 | 4 | 7 | 10 |
| 12 | *performance-based design* | 14 | 4 | 2 | 4 | 2 | 2 |
| 12 | *simulation* | 16 | 2 | 3 | 2 | 4 | 5 |
| 14 | *beam* | 17 | 1 | 3 | 2 | 6 | 5 |
| 14 | *buildings* | 16 | 4 | 1 | 3 | 3 | 5 |
| 16 | *combustion* | 13 | 3 | 3 | 2 | 2 | 3 |
| 17 | *concrete* | 15 | 1 | 2 | 2 | 5 | 5 |
| 17 | *fire performance* | 25 | 1 | 1 | 3 | 8 | 12 |
| 17 | *wood* | 15 | 2 | 0 | 3 | 5 | 5 |
| 20 | *columns* | 11 | 2 | 1 | 2 | 3 | 3 |

*Note: TT: Total number of jobs
Source: Self-Elaboration

Finally, it is noticed that, throughout the positioning, terms related to materials such as *steel*, *concrete* and *wood* appear. In addition, the recurrence of structural elements such as *beams* and *columns* is also noted. For most of these keywords, there is a tendency to stabilize in recurrences over the years, highlighting the possible associations of terms that result in new keywords, as previously presented.

In Q(v), verifying the results obtained by countries or regions that stood out in relation to the subject, the co-participation among them is of paramount importance to researchers in order to establish a research network. Table 4 presents the ranking with the main countries that contributed to the fire performance theme in buildings in the past five years. The Republic of China is the most productive region, with a total of 72 publications (21.82%) in the last five years, followed by the United States, with 71 (21.52%) publications. In the third position is Australia, with 52 (15.76%) publications.

Brazil is in the 32nd position in the ranking, with 3 publications (0.91%). Analyzing the average of citations, Portugal stands out, with an average of 11.38 citations per article (91 citations), followed by Switzerland, with an average of 8.56 citations per article (77 citations), and by Italy with an average of 6, 90 citations per article (207 citations). Australia, China, and Italy stand out for total citations, with respectively 286, 256, and 237 citations in the past five years. Finally, comparing the h-index by country, Australia and Italy stand out, with an h-index = 9.

By analyzing Table 4, it can be concluded that Australia is the most active country that cooperated with other countries in 40 studies, with Scotland, China, England, and the United States, in particular. England, which comes in second place (34 works in partnership), also maintains close relations with Scotland, the Republic of China, Sweden, and Australia.

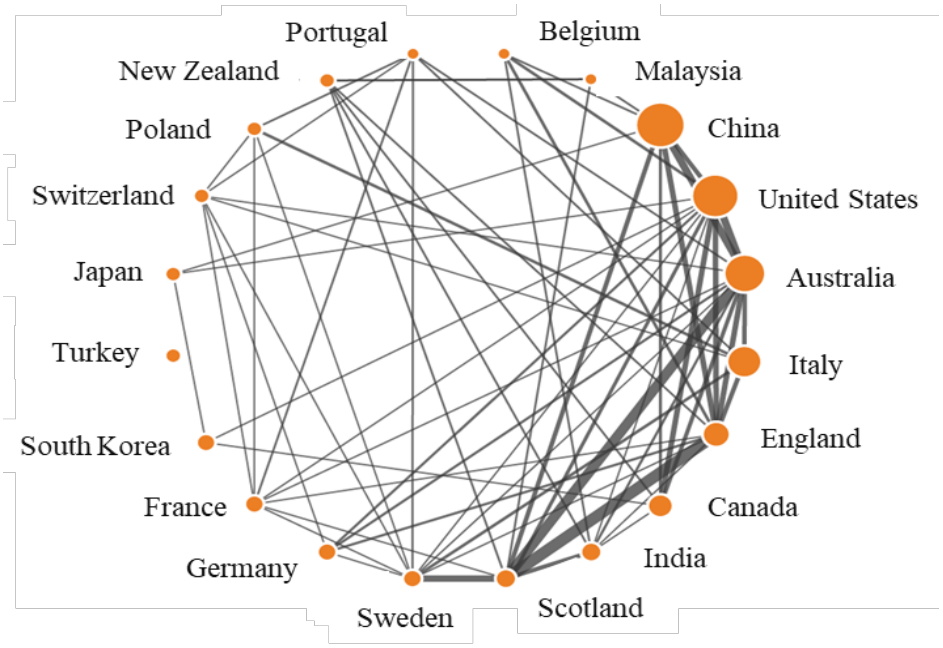
Table 4 – Contribution by countries and regions

| N | País | TT | FT | TC | MC | *h-index* | CP |
|---|---|---|---|---|---|---|---|
| 1 | China | 72 | 21,82% | 256 | 3.56 | 8 | 20 |
| 2 | U.S.A. | 71 | 21,52% | 181 | 2.55 | 7 | 27 |
| 3 | Australia | 52 | 15,76% | 286 | 5.50 | 9 | 40 |
| 4 | Italy | 30 | 9,09% | 237 | 7.90 | 9 | 21 |
| 5 | England | 24 | 7,27% | 106 | 4.42 | 7 | 34 |
| 6 | Canada | 24 | 7,27% | 62 | 2.58 | 3 | 12 |
| 7 | India | 17 | 5,15% | 82 | 4.82 | 2 | 31 |
| 8 | Scotland | 17 | 5,15% | 24 | 1.41 | 5 | 8 |
| 9 | Sweden | 16 | 4,85% | 71 | 4.44 | 4 | 14 |
| 10 | Germany | 15 | 4,55% | 28 | 1.87 | 2 | 8 |
| 11 | France | 14 | 4,24% | 91 | 6.50 | 6 | 21 |
| 12 | South Korea | 13 | 3,94% | 16 | 1.23 | 3 | 5 |
| 13 | Turkey | 11 | 3,33% | 70 | 6.36 | 3 | 0 |
| 14 | Japan | 11 | 3,33% | 13 | 1.18 | 2 | 3 |
| 15 | Switzerland | 9 | 2,73% | 77 | 8.56 | 5 | 15 |
| 16 | Poland | 9 | 2,73% | 52 | 5.78 | 3 | 13 |
| 17 | New Zealand | 9 | 2,73% | 9 | 1.00 | 2 | 8 |
| 18 | Portugal | 8 | 2,42% | 91 | 11.38 | 3 | 13 |
| 19 | Belgium | 7 | 2,12% | 28 | 4.00 | 3 | 5 |
| 20 | Malaysia | 6 | 1,82% | 35 | 5.83 | 3 | 4 |
| 32 | Brazil | 3 | 0,91% | 13 | 4.33 | 1 | 1 |

*Note: TT: Total number of jobs; FT: frequency of work; TC: Total citations; MC: Average number of citations.; CP: Coparticipations

Source: Self-Elaboration

Figure 5 – Co-participation between countries and regions




Source: Self-Elaboration

Finally, on Q (vi), the main authors who contribute to a certain area have a high reputation, and their works can inspire scholars to identify research directions. Thus, they are listed as the main most productive authors based on the number of publications on building fire performance (Table 5). Table 5 also presents the main scientific contributions of the authors with the highest number of papers.

Table 5 – Most productive authors based on number of publications on fire performance

| N | Autor | TT | Universidade | Contribuições |
|---|---|---|---|---|
| 1 | Mahen Mahendran | 17 | Queensland Univ. Technol., Australia | Residual capacity analysis of LSF systems under fire conditions; like wall (Magaraboosha nam et al. 2019) and floor-ceiling (Steal e Mahendran, 2020); Full-scale system test results Light steel frame (LSF) (Dias et al., 2019) Development of fire performance factors for boards (Dodangoda et. Al., 2019) |
| 2 | Thomas Gernay | 8 | Johns Hopkins Uni., United States | Reviews on current practice in structural probabilistic fire engineering (Jovanović et al., 2020); Development of fuel load survey methodologies in office buildings (Elhami-Khorasani et al. 2020); Recommendations for performance-based fire design of steel buildings using computer analysis (Gernay e Khorasani; 2020) |
| 3 | Wojciech Wegrzynski | 6 | Instytut Techniki Budowlanej, Poland | Intelligent Smoke Control Systems in Historic Buildings (Wegrzynski et al., 2020a), with glass facades (Wegrzynski et al., 2020b); Experimental and computational analysis of smoke dynamics in high-volume buildings (Vigne et. al, 2020) |
| 4 | Chiara Bendon | 5 | University of Trieste, Italy | Fire resistance of thermally insulated wooden walls (Bendon e Fragiacomo, 2019) and with partial insulation (Bendon e Fragiacomo, 2018); Survey on the development of research on glass facades (Bendon, 2017; Bendon et al., 2018) |
| 5 | Priyan Mendis | 5 | University of Melbourne, Australia | Fire resistance analysis of precast aerated concrete elements (Nguyen et al., 2018), in slab systems (Weerasinghe et al., 2020) and with fiberglass composites (Nguyen et al., 2016a); Literature review on the performance of facades of modern buildings on fire (Nguyen et al., 2016b) |
| 6 | Takafum Noguchi | 5 | University of Tokyo, Japan | Experimental studies of fire propagation in structural systems (Nishio et al., 2016; Zhou et al., 2019; Zhou et al., 2020) |
| 7 | Hideki Yoshioka | 5 | Chiba University, Japan | |
| 8 | Anthony Ariyanayagam | 5 | Queensland Univ. Technol., Australia | Analyzes of vertical sealing systems on various materials exposed to fire curves under realistic fire conditions (Ariyanayagam e Mahendran, 2018; Ariyanayagam e Mahendran, 2018b). |
| 9 | Juan P. Hidalgo | 5 | Univ. Edinburgh, Scotland | Development of fire safety and performance criteria in thermal insulation systems in buildings through tests (Crewe et al., 2018). |

*Note: TT: Total number of jobs
Source: Self-Elaboration

Among the main authors presented, Mahen Mahendran, Thomas Gernay, and Wojciech Wegrzynski, are from universities in Australia, the United States, and Poland: countries that rank 3rd, 2nd, and 16th in the production of publications in the world. Among the correlations between the main authors, Mahen Mahendran and Anthony Ariyanayagam have a total of 5 papers in common. In addition, Takafum Noguchi and Hideki Yoshioka also stand out with 5 papers in common, in the past 5 years.

## 4 DISCUSSIONS

By analyzing the results, it can be seen that more than 60% of the publications on fire performance in buildings were published in the last 5 years. Moreover, the increasing trend rates presented in most of the results in Figures 3 and 4 and Tables 1 to 5, show a high interest in research related to the theme. The emergence of collaborations between different research areas can be attributed to the development of methods for evaluating building fire performance and the diversity of practical problems to be applied. This growing relationship between the different areas is directly associated with the challenges of meeting the requirements of multi-objective optimization techniques in current building designs (HIDALGO; WELCH; TORERO, 2015). Similarly, this is the scope of the fire performance standards given as an example in Section 1 (ICC, 2018; CEN, 2018; MA; WU, 2020) that guarantees the different performance criteria and, in a multi-objective and conflicting manner, must be met, in isolation (MA; WU, 2020).

The characteristics and trends of research in fire performance in buildings vary slightly over the years, as can be easily seen in Table 3 and Fig. 4. However, associating the results, it can be seen that the concern with materials and structural systems will be the basis for studies that analyze the performance, behavior, resistance, and safety of buildings under fire conditions. As an example, we highlight one of the hot papers obtained through the retrieved data: *A review of the fire behaviour of pultruded GFRP structural profiles for civil engineering applications* (CORREIA; BAI; KELLER, 2015).

Furthermore, in a distributed trend, each country that researches fire performance addresses different techniques when analyzing materials or systems, or even a combination of them. This is associated with the fact that each region has specific climate conditions, availability of materials, and construction techniques. Thus, it shows the possibility that researchers from different countries or institutions can work together to further promote research on fire performance in buildings.

In general, there is a perceived lack of correlation between fire performance research and current methodologies applied to fire emergency management. Such methodologies also allow intelligent monitoring and continuous and accurate observation of fire conditions. Despite not being recurrent in the search parameters associated with data collection, one can highlight the papers *BIM-based building fire emergency management: Combining building users' behavioral decisions* (MA; WU, 2020), *The Evaluation of Building Fire Emergency Response Capability Based on the CMM* (MA; TAN; SHANG, 2019) and one of the retrieved hot papers, *BIM integrated smart monitoring technique for building fire prevention and disaster relief* (CHENG *et al*., 2017).

There is a lack of detailed guidance for conducting performance-based fire engineering analysis for the built environment, in particular, how to identify and specify performance criteria, fire scenarios, and fire design.

## 5 CONCLUSION

This research on fire performance in buildings was conducted for scientific literature published between the years 2015 to 2019. It was based on the Web of Science database. Applying the RSL study made it possible to survey of the research characteristics on the subject, identifying topics, journals, countries, and trending authors among 407 articles. The application of RSL associated with bibliometric analysis permitted the interpretation of the results and trends found.

The products of this research pointed out a tendency to analyze the elements, systems, and materials used in buildings by numerical and experimental tests proposed in standards, which guarantees a performance-based design for buildings.

It was identified that the analysis of fire performance in projects is growing, but when compared to the numerous publications that investigate the quality of projects based on performance, it presents a significantly low number. This is justified by the fact that many design professionals still do not recognize the topic of fire safety as an explicit design variable.

Finally, it is concluded that performance-based design should be seen and practiced as a multidisciplinary area to be developed and that for this, it is of utmost importance to evaluate the status and future applications of building fire performance analysis in different research areas, trends, and collaborations (technologies that enable multi-objective optimization analysis).

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**Sobre os autores:**

**Rejane Martins Viegas:** Doutoranda em Arquitetura e Urbanismo pela Universidade de Brasília (UnB). **E-mail:** rejanemviegas@gmail.com, **Orcid:** http://orcid.org/0000-0002-1444-0125

**João Paulo Lima:** Doutorando em Engenharia Civil pela Universidade de Brasília (UnB). **E-mail:** joaoplima@ufg.br, **Orcid:** https://orcid.org/0000-0002-6002-0076

**Michele Tereza Carvalho:** Professora Adjunta do Departamento de Engenharia Civil e Ambiental na Universidade de Brasília (UnB). **E-mail:** micheletereza@unb.br, **Orcid:** https://orcid.org/0000-0001-7969-9341

**Caio Frederico e Silva:** Professor Adjunto do Departamento de Arquitetura e Urbanismo da Universidade de Brasília (UnB). **E-mail:** caiosilva@unb.br, **Orcid:** https://orcid.org/0000-0001-8910-1841