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OPTIMIZATION APPLIED TO ENERGY EFFICIENCY AND THERMAL COMFORT OF BUILDINGS: BIBLIOMETRIC ANALYSIS ON TECHNIQUES AND APPLICATIONS

Cassiana Fagundes da Silva [1,2]
Roberto Zanetti Freire [1,2]
1 – Pontifical Catholic University of Parana – PUCPR
Polytechnic School – EP
Rua Imaculada Conceição, 1155, CEP 80215-901, Curitiba PR, Brazil
2 – Industrial and Systems Engineering Graduate Program – PPGEPS

Nathan Mendes [1,3]
3 – Mechanical Engineering Graduate Program – PPGEM
Thermal System Laboratory – LST

cassiana.fagundes@pucpr.edu.br
roberto.freire@pucpr.br
nathan.mendes@pucpr.br

Abstract. *The world's energy demand has raised concerns about supply difficulties, depletion of natural resources and environmental impacts such as destruction of ozone layer, global warming, climate change, among others. Recent studies indicate that energy consumption in buildings represents more than 40% of the world's energy consumption, with more than half attributed to air conditioning systems. Specific regulations and control strategies for heating, ventilation and air-conditioning (HVAC) systems should provide acceptable thermal comfort and reasonable indoor air quality. The evolution of researches in these areas can be evaluated by the organization of scientific production up to now. The objective of this study is to analyze quantitatively what was produced in terms of optimization associated to both energy savings and thermal comfort in buildings. This bibliometric analysis, based on Science Direct and IEEE Xplore databases, correlates common adopted terms to quantify how optimization, especially those associated computational intelligence, are influencing on building projects where thermal comfort and energy saving are taken into account. This research assumes a sample of 76 articles, and provided a statistical evaluation considering authors identification, and both articles and journals that were more cited by researchers in this area.*

Keywords: *bibliometric analysis, buildings, energy savings, thermal comfort.*

1. INTRODUCTION

Efforts to reduce the energy consumption associated with both use and design of buildings have direct relation to energy efficiency policies created by many governments. Most of these efforts are focused on heating, ventilation, and air conditioning (HVAC) systems that are receiving great attention from both scientific and industrial areas.

In the HVAC context, it is necessary not only to reduce energy consumption but also to guarantee indoor air quality and thermal comfort to the occupants. The majority of HVAC systems available in the market are just based on temperature regulation (Hao, Lin, Kowli, Barooah, & Meyn, S. (2014) and do not take into account additional variables that can be used to optimize thermal comfort and to avoid energy waste, e.g. the relative humidity.

In (Freire, Oliveira & Mendes, 2008), the authors propose an advanced control strategy for reducing energy consumption and maintaining the indoor conditions in an acceptable thermal comfort range, minimizing the energy consumption. Similar research in this area can be found in (Acosta, A., González, A. I., Zamarreño, J. M, & Álvarez, V. (2016); Ahn, J., Cho, S. (2017); Hazyuk, Ghiaus, Penhouet, (2014); Zhai, Soh, (2017). As an alternative to optimize thermal comfort in the building environment and reduce energy demand, the multiobjective optimization techniques, those that involve several parameters and control variables simultaneously, are been providing promising results.

Some works involving multiobjective optimization in buildings stand out (Ferreira et al., 2012; Khoroshiltseva, Slanzi & Poli, 2016; Morales-Valdés, Flores-Tlacuahuac & Zavala, 2014; Hamdy, Hasan & Siren, 2011; Yang and Wang, 2012), among others.

Another way to work with several parameters that are related to thermal comfort and energy consumption is through the integration of multiobjective optimization and whole-building simulation. Some specific software capable to perform whole-building simulation are EnergyPlus (Crawley et al., 2001), WUFI®plus (Fraunhofer, 2010), Trnsys (Trnsys, 2010) and Domus software (Domus, 2013).

From this perspective, of associating building simulation and multiobjective optimization, the purpose of this work is to analyze the scientific development in parameters optimization focusing on thermal comfort and energy efficiency in buildings in a quantitative way, serving as base for a doctoral thesis. The methodological approach used is a systematic review of the specialized literature, this based on the bibliometric data collected from two databases ScienceDirect and IEEE Xplore. This two database have been chosen because they represent a considerable amount of journals relating those two previous mentioned areas: *i*) both thermal comfort and energy savings associated to buildings; and *ii*) parametric optimization.

This paper is organized as follows. Section 2 specifies the methodology adopted in the study. Section 3 presents a background of the literature on thermal comfort, energy efficiency and optimization. Section 4 discusses results, and finally, section 5 addresses conclusions and future works.

2. METHODOLOGY

This work initiates with the theoretical constitution of the research – background on thermal comfort, energy efficiency and metaheuristic optimization (section 3), starting by an explanation of the bibliometric analysis in section 2.1.

The definition of the sample in the Science Direct and IEEE Xplore databases and both organization and treatment of the collected records are presented in the sequence, followed by the analysis and interpretation of the results.

2.1 Bibliometric – The Method

Bibliometric research is a technique used to map the main authors, periodicals and keywords of a given topic. In (Pilkington & Meredith, 2009), it is defined as the research technique that aims to analyze the size, growth, and distribution of the bibliography in a given field of knowledge.

In (Ensslin et al., 2010), bibliometric research is described as a qualitative process of disclosure of statistical data, a set of articles, for the management of information and scientific knowledge of a given topic performed by means of a count of documents.

As presented in (Araújo, 2006) bibliometrics was developed based on empirical laws on the behavior of literature. For this, it is necessary to know its three basic laws: Zipf's law that makes it possible to measure the frequency of occurrence of words; Lotka's law that deals with authors' productivity; And, finally, Bradford's law, which highlights the productivity of journals (Bufrem & Prates, 2005).

In this context, the bibliometric laws adopt mathematical and statistical analysis of data to extract information and quantify the scientific publication on a certain theme.

2.2 Sample Definition and Organization

The sample of research works considered in this paper comes from two international scientific databases: IEEE Xplore and Science Direct. IEEE Xplore is a database that indices both scientific and technical work published by the Institute of Electrical and Electronics Engineers (IEEE). Approximately 3 million full-text documents are available in more than 160 scientific journals, as well as 1,200 event annals and more than 3,800 technical standards. In the Science Direct database, the electronic publications of more than 1,800 journals from Elsevier and other scientific publishers with more than 10 million articles covering the most diverse areas of knowledge are available, such as the Sciences of Earth Sciences, Humanities and Literature and Arts, Health Sciences, among others.

The articles sample was define from the two databases mentioned above, the identification of the keywords and the determination of the types of published documents were performed as shown in the flow chart presented in Figure 1. The main idea in including the heuristic term was to consider the use of stochastic methods that already proved their efficiency in solving complex problems.

For the classification of the Journals the impact factor (IF) was selected. This rank is available and presented by SCImago (SCImago, 2007) with quartile rankings, where Q1 or Q2 were selected for this research. Quartile rankings are associated to each journal according to categories divided by subjects of research. In this case, Q1 denotes the top 25% of the IF distribution, Q2 for middle-high position (between top 50% and top 25%), Q3 middle-low position (top 75% to top 50%), and Q4 the lowest position (bottom 25% of the IF distribution).

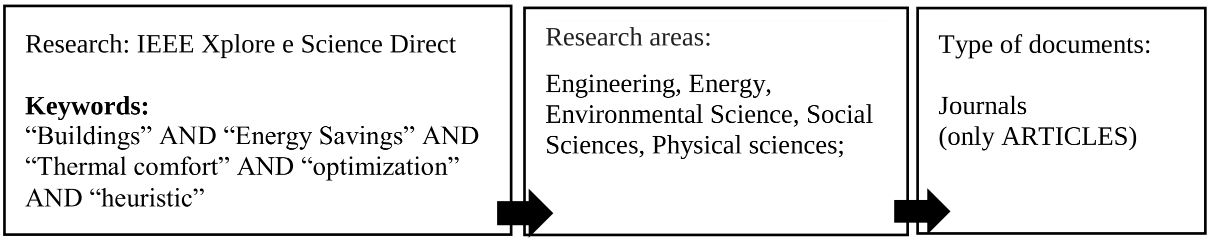

Figure 1. Flowchart of the sample definition process defined in January 2017

Regarding the determination of publication type , considering books, patents, articles, annals of congresses, among others, it was decided to consider only peer-reviewed articles, since this type of publication generally precede books, and are considered relevant sources for research, and must present methodological rigor to be accepted for publication.

The composition of the sample was considered from 2006 to 2016, due to the fact that it is desired to evaluate the last 10 years of researches in these areas. Initially, a total number of 84 articles was obtained, and after the refinement of the journals according to the SCImago criterium, a reduced sample of 76 articles were selected to be analyzed.

The bibliometric treatment of the articles is presented through a descriptive statistical analysis, obtained through illustrative tables and graphs generated using Microsoft Excel software.

3. BACKGROUND

In the literature, several studies can be found associating thermal comfort, energy efficiency, and optimization applied to the buildings. Some of these works are presented in the sequence of this section.

3.1 Thermal Comfort

For most of the international standards (ISO 7730, 2005), (ASHRAE55, 2005) and according to (Fanger, 1970), thermal comfort can be defined as “that condition of mind which expresses satisfaction with the thermal environment”. The best-known thermal comfort index is the Fanger’s Predicted Mean Vote (PMV) Model, which combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people.

In terms of thermal comfort measurements, the most used index in the evaluation of internal environments PMV. It is an index that predicts the average value of a large group of people, according to the scale of sensations of 7 points (very hot, warm, slightly between, neural, slightly cold, cold, very cold). It was created through statistical analyzes according to results obtained by (Fanger, 1970) in studies in Denmark in climatized chambers. In these studies, people recorded their votes on the seventh scale, which points from very cold to very hot.

As there may be conflicts among users in relation to the thermal comfort of an environment, thermal comfort indices were developed to measure thermal comfort sensation in a given environment. Among other indices of comfort most disseminated in the literature are the Effective Temperature (ET) and Standard Effective Temperature (SET*).

The Effective Temperature can be defined as the dry bulb temperature index combination, (Moran & Shapiro, 2000) with barometric pressure and air velocity, in order to inform the sensation of the Thermal comfort of the people occupying the interior of a certain environment. This ET concept was introduced in 1923 (Houghten & Yaglou, 1923). The SET* index was developed in order to design a set of standard conditions to be represented in situations common to certain types of environments.

Through these definitions and criteria, it can be noticed that the thermal comfort sensation may vary from person to person in the same environment. In this way, one of the main difficulties of HVAC systems designers is how to attend to different profiles of people considering their preferences regarding the indoor climatic conditions. As a solution to this problem, it is observed that analyzing only one variable to estimate thermal comfort is not the best solution.

Recent examples can be found in (Hamilton, et al., 2001), where only temperature control is considered in the design of air conditioning systems. Most of these projects are due to the fact that temperature is one of the most relevant variables in estimating the sensation of thermal comfort (Trebien, Mendes & Oliveira, 2007) and, when combined with relative humidity, good levels of comfort can be reached when control of indoor thermal conditions considering these two quantities is properly performed (Mba, Meukan & Kemajou, 2016). In the last decades, numerous researches were developed in order to evaluate thermal comfort of indoor environments, and for this reason, a large number of comfort indices has been established.

3.2 Energy Efficiency

Global energy consumption is growing rapidly (Quaschning, 2016), and concerns about supply difficulties, depletion of energy resources and environmental impacts are constantly in evidence. Buildings from commercial and residential sectors have a considerable contribution associated to the energy demand, reaching between 20% and 50% in developed countries, surpassing the large industrial and transport sectors (Pérez-Lombard, Ortiz & Pout, 2008; Peruzzi et al., 2014; Soares et al., 2013).

According to (Dakwale et al., 2011), to achieve energy efficiency, it is necessary to raise awareness about energy consumption through training and education, to formulate patterns of energy consumption, to adopt an integrated approach by selecting the best option for energy generation in terms of cost and environmental impact, to use renewable energy sources, to modernize technology related to the generation of non-conventional energy, and finally to cancel subsidies for obsolete technology and subsidize modern technology.

Through these definitions, it can be noticed the need for an improved government regulation that standardizes and specifies practices of energy efficiency that result in buildings with less environmental impact and greater substantiality.

By analyzing th international context, several countries are applying or promulgating laws, incentives or classification methods that promote the design and the construction of buildings with low environmental impact. As an example, the WordGBC Council was created in 2000, consisting of eight countries, the United States, Australia, Spain, the United Kingdom, Japan, Russia, Canada and Arabia, whose mission is to accelerate the transformation of built environments in search of sustainability. In this way, labeling and its minimum criteria of energy efficiency, as described by Word Energy Council (2004), can be the high performance solution in obtaining practical improvements.

In Brazil, PROCEL EDIFICA - National Program for Energy Efficiency in Buildings was instituted in 2003 by ELETROBRAS / PROCEL and works together with the Ministry of Mines and Energy, the Ministry of Cities, universities, research centers and entities in the governmental, technological, economic development, and civil construction areas. This program aims to raise awareness of the rational use of electricity in buildings, for this it provides actions to encourage and conserve the efficient use of natural resources: water, ventilation and light, reducing environmental impacts and waste. Called Brazilian Labeling Program (PBE), it contributes to the rationalization of energy use through information on the energy efficiency of equipment available in the market.

3.3 Optimization

In the last decades, several researches have been carried out in order to find methods that solve the challenge of finding optimal or quasi-optimal solutions of engineering problems.

Optimization problems can be defined as the choice of the best element in a set of possible alternatives, through a specific objective function (such as maximization or minimization) that approaches or presents a desired value.

Alternatively, it is conceivable to enumerate all possible solutions and store the one that presents the best value for the objective function. However, for real problems, this approach can be computationally impracticable due to the exponential growth of possible solutions as a function of the size of the problem.

More elaborate methods, which prioritize the speed in the search for the best possible solution related to a problem, known as metaheuristics, have been developed and used to solve practical optimization problems in engineering. The term metaheuristics was introduced by Glover (1986) and is characterized as problem solving methods that manage local search procedures with higher level strategies in order to create a process capable of escaping from local minimums, and performing a robust search in a pre-defined solution space.

Since these procedures are specific to each metaheuristic and there is no guarantee that the solution is the best solution found by metaheuristics, several techniques can be used to solve optimization problems, where each one can provide best results according to its characteristics and the problem associated. Among well stablished techniques available, Genetic Algorithms (GA) (Goldberg, 1989); Search Tabu (BT) (Glover, 1986); Particle Swarm Optimization (PSO) (Kennedy, Eberhart, 1995); Ant Colony Optimization (ACO) (Dorigo, Stützle, 2004), Differential Evolution (DE) (Storn, Price, 1997), and Harmonic Search (BH) (Geem et al., 2001), are some common strategies adopted to solve engineering problems.

In the case of optimization applied to thermal comfort and energy savings in building, current studies generally pay more attention to the use of heating or cooling systems to improve internal thermal comfort (Freire, Oliveira, & Mendes, 2008; Freire, Oliveira & Mendes, 2008). Focusing mainly on the resolution of the conflict between the energy consumption of the HVAC system and the internal climate condition, most works do not consider how to use building elements to improve these conditions. In this context, the optimization of parameters such as shape, orientation, window-to-wall ratio (WWR), and internal space layout, can significantly influence thermal comfort and energy efficiency of buildings.

In (Yu et al., 2015) a novel multi-featured new multiobjective optimization model that can assist designers of green buildings was presented. In this case, the Pareto solution was used to obtain a set of optimal solutions in building projects, and where a multiobjective genetic algorithm (NSGA-II) was considered as theoretical basis for the multiobjective optimization. The NSGA-II algorithm selected and optimized the design variables based on the prediction of energy consumption and thermal comfort in order to obtain the possible solution. As a result, designers needed to limit the range of input variables and fully leverage the computer to compare different solutions.

Delgarm, Sajadi & Delgarm (2016) presented a powerful simulation-based multiobjective optimization of building energy efficiency and indoor thermal comfort to obtain optimized solutions of the comfort-energy configurations for building envelopes. The optimization method was developed by integrating a multiobjective artificial bee colony (MOABC) technique implemented in MATLAB with EnergyPlus, which is a building and energy simulation tool. The proposed optimization approach is applied to a single office room; and the building parameters, including the room rotation, window size, cooling and heating temperature setpoints, where glazing and wall material properties are considered as decision variables.

In the article presented by Kim et. al. (2016), the objective was to optimize ecological systems. By considering thermal comfort and energy consumption of an educational establishment, optimal design scenarios were analyzed considering their economic and environmental effects. The study was conducted as follows: *i*) first, it was selected project variables and objective function were defined; *ii*) in the sequence, green systems optimization was performed; *iii*) after, comparative analysis of standard and optimal designs were evaluated; *iv*) finally, both economic and environmental evaluation of the project scenarios were performed. In order to compare the thermal comfort of the green systems with that of the existing building, this study used the percentage of dissatisfied predicted (PPD) which is the thermal comfort index based on the Fanger's PMV model.

Other studies focused on the optimization of parameters in thermal comfort and energy efficiency are developed by (Ansione et al., 2016; Nagarathinam et al., 2017; Chen, Wang & Srebric, 2016; Horikiri, Yao & Yao, 2015; Martínez-Molina et al., 2016; Chowdhury, Rasul & Khan, 2016 and Wang et al., 2015).

4. RESULTS

The first descriptive analysis of the publications on the selected areas was dedicated to identify trends of growth or decay of interests in studies considering energy efficiency, thermal comfort and optimization applied to buildings. By classifying the articles of the sample according to the year of publication, it was possible to establish the comparison presented in Figure 2. The volume and publications presents a cyclical character with peaks of volume of publications in the years 2012 to 2016 for the Science Direct base and in the years from 2012 to 2015 for the IEEE Xplore, with periods of lower volume in previous years.

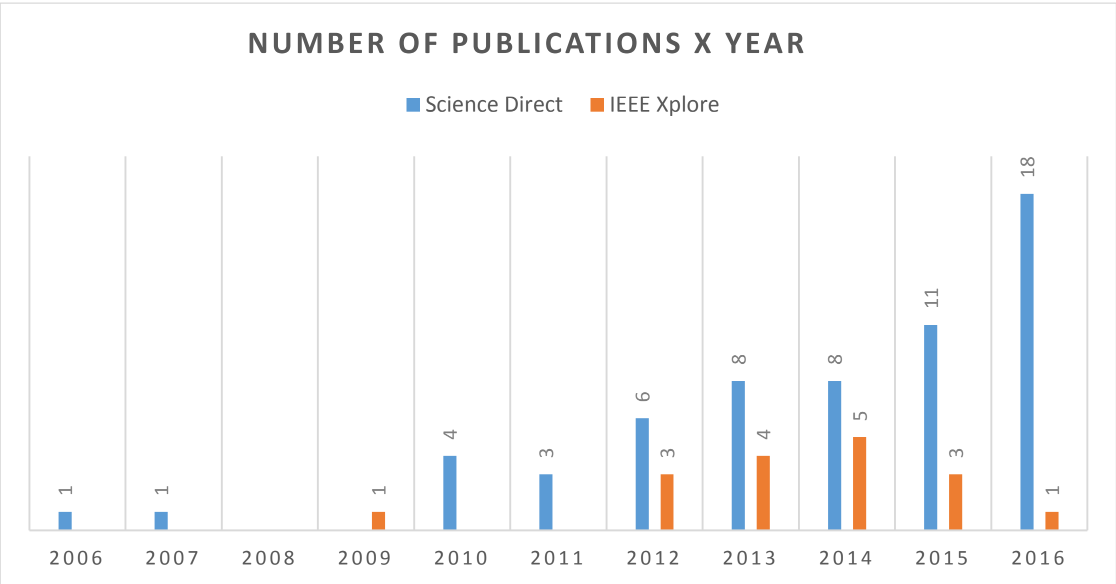

Figure 2. Evolution of publications over the last decade

The second descriptive analysis has the objective of evaluating the dispersion of the research works found during the analyzed period. In order to identify the main authors and periodicals in volume of publications Figures 3 and 4 represent the distribution of works in the selected areas according to authors, countries and journals, respectively.

With regard to the distribution of works by author, the analysis of the sample revealed that the authors with the highest number of papers were Zhu Wang, Wang Lingfeng, Mohamed Handy Jan LM Hansen, Ali Ghaharamani and Burcin Breick-Gerber, with 3 publications. Then, the other authors with 2 publications were Shengwei Wang, Rui Yang, Anastasios i. Dounis, Panagiota Karava,, Jianjun HU, Ali Malkawi and Xiwang Li .

The stratification of publications by country of origin shows a marked predominance of publications originating in the United States, with publication of 26 articles. Then there are China, Australia, Canada and Italy, with number of publications of 12, 9, 5 and 5 articles, respectively.

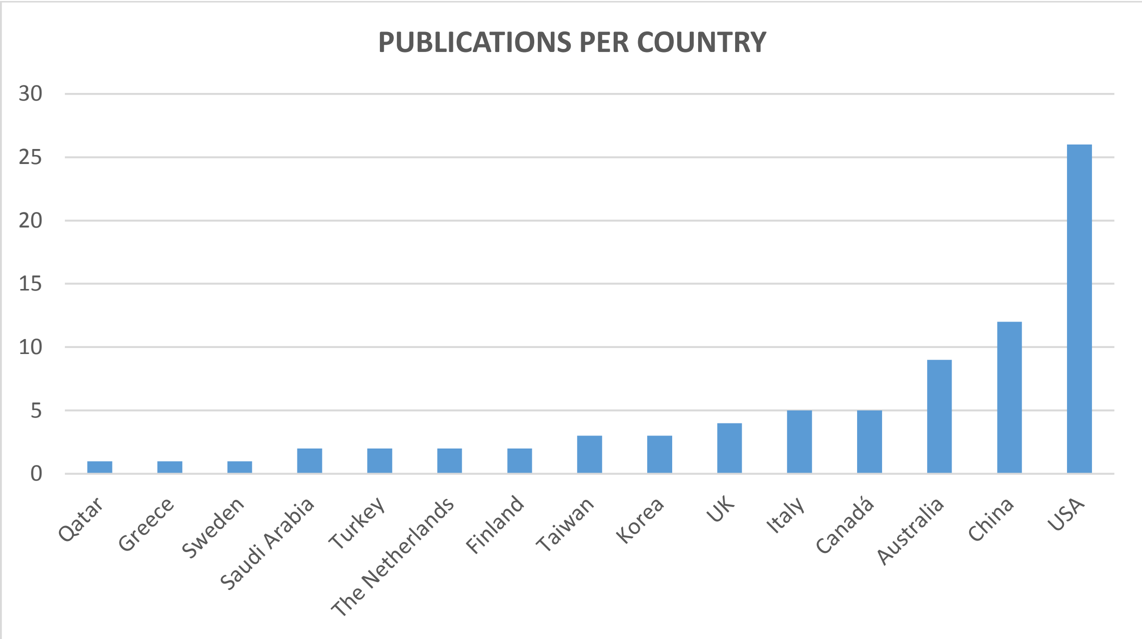

Figure 3. Sample distribution by country of origin

Regarding the distribution of articles by peer-reviewed journals, it can be observed that Energy and Buildings with 27 publications is the most prominent periodical in volume of (Figure 4). Next, we highlighted Building and Environment and Applied Energy, with 10 and 6 publications, respectively. These publications represent 56% of the total sample and tare concentrated mostly in 2015 and 2016 years for the first journal, showing the recent interest by researchers in this area.

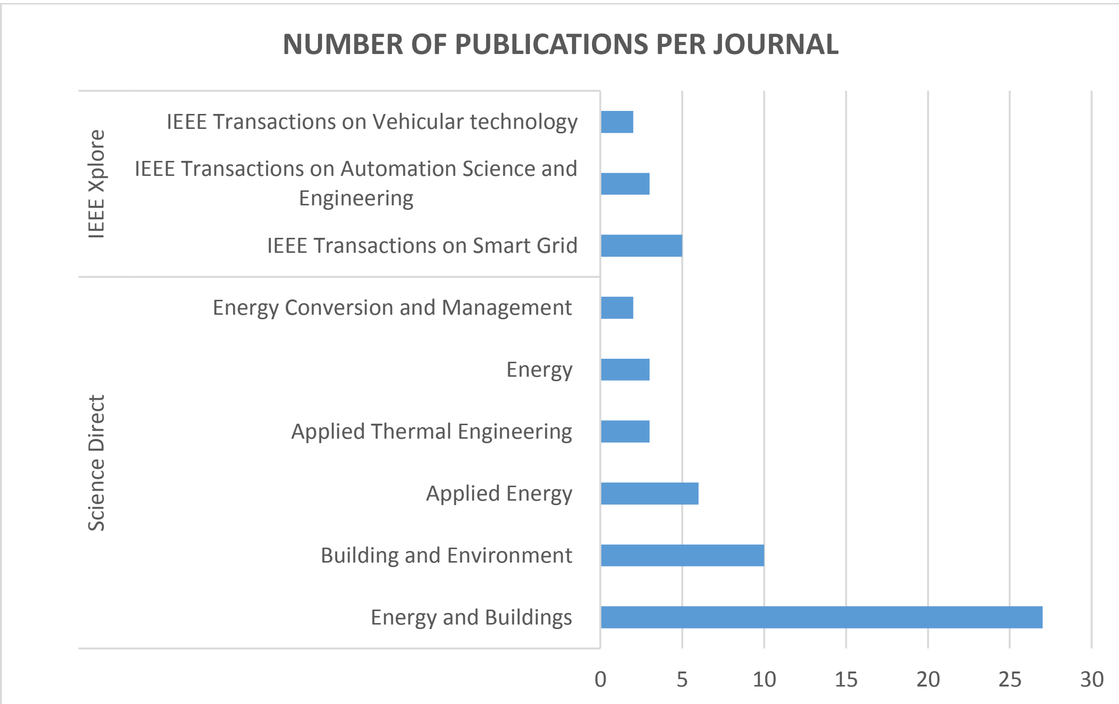

Figure 4. Comparison of the distribution of articles by the main journals

The impact factor, the classification of the journal (best quartile) and the H index according to SCImago, of the journals with the highest number of publications in the two databases can be observed in Table 1.

Papers appear in the Journal IEEE Transactions on Vehicular Technology, even though these have no direct relationship with the buildings, but it is observed in the literature that comfort thermal comfort and efficiency in energy consumption is also treated in the automotive sector.

Table 1. Journals Impact Factor

Title Journal	**SJR**	**SJR Best Quartile**	**H index**
Energy and Buildings	2.073	Q1	103
Building and Environment	2.121	Q1	86
Applied Energy	2.998	Q1	99
IEEE Transactions on Smart Grid	4.784	Q1	66
IEEE Transactions on Automation Science and Engineering	1.832	Q1	48
IEEE Transactions on Vehicular Technology	1.203	Q1	116

Regarding the keywords of these publications, it can be observed in Figure 5 that the keywords adopted in this research: energy consumption, optimization and HVAC were cited 14, 12, 11 and 10 times, respectively.

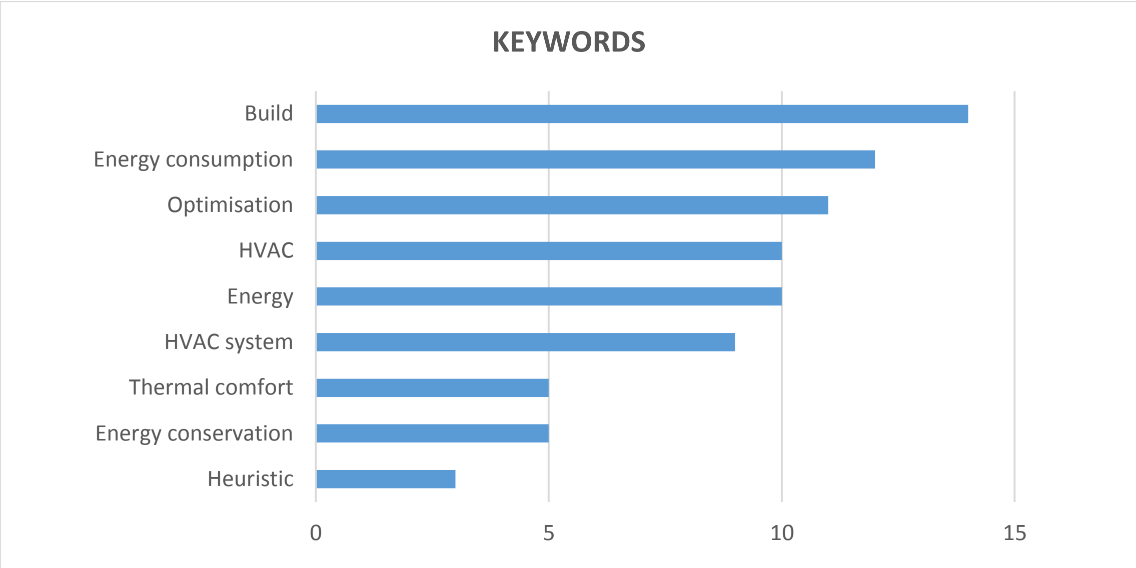

Figure 5. Keywords most cited in the sample

5. CONCLUSION

The organization of data related to the scientific publication on energy savings, thermal comfort and optimization applied to buildings can contributes to the consolidation of the available knowledge and to the development of new visions and concepts. It is necessary, however, to show some limitations of the method and of the data sources that are available for the development of this work.

The platforms chosen for this research, IEEE Xplore and Science Direct, have the predominance of North American publications and English, not contemplating the academic production of many countries, especially those in development. New keywords combinations will be performed with the objective of selecting Brazilian papers relevant to the study, that were not identified by the filter applied in the database.

Another limitation, originated in the sample process, concerns the type of the selected publications. Knowledge that has not been transformed into a scientific article has not been taken into account in this research. What is suggested, then, is the development of an investigation, whose sample consists of articles under evaluation and published in Brazil, although other vehicles of publication are not considered, but it is possible to identify authors and nuclei of Research with relevant production in the country.

Future works will focus on the construction of a network of relationships between existing publications and their co-citations. A systematic evaluation of the bibliography could be performed, classifying the works by: optimization of parameters in thermal comfort, energy efficiency, thermal comfort and energy efficiency in buildings.

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