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Review

A Co-Citation Analysis on Thermal Comfort and Productivity Aspects in Production and Office Buildings

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Academic Editor: Cinzia Buratti

Received: 15 January 2017; Accepted: 25 April 2017; Published: 1 May 2017

Abstract: In this work, the literature about the relationship between thermal comfort and productivity in workplaces is reviewed and explored by means of a co-citation analysis—i.e., a factor analysis applied to the mutual citations of the most relevant contributions. A structure of three main clusters of papers describing the relationships between workers' thermal comfort and productivity were identified according to the factor analysis and then confirmed with a multidimensional scaling. Results indicate that comfortable indoor thermal conditions can have beneficial impacts on workers' well-being and productivity, such as higher operational rates, lower production losses, fewer sick leaves, and reduced health related costs. Some authors proposed analytical and empirical expressions for the quantification of the impact of thermal comfort on productivity; nevertheless, due to the broad spectrum of activities and their applicability, the literature is still far from reaching a general consensus on the potential impact of comfort/discomfort on productivity and proposed models can vary significantly in the different studies.

Keywords: thermal comfort; productivity; co-citation analysis

1. Introduction

High performance buildings have, as main targets, low or nearly zero primary energy uses and a good indoor environmental quality, *IEQ*, for the occupants. In workplaces, *IEQ* has an impact not only on people's comfort, health, and safety, but also on their satisfaction and productivity [1]. Workers spend between 20 and 60 h per week in offices or factories [2] and, where an adequate *IEQ* is ensured, a reduction of their complaints, sick leave, and absenteeism is expected, with an economic return for the company [3]. This is true especially in developed countries, since workers' salaries are generally higher than building operating costs [4] and, in this concern, comfort achievement can be seen as a key-factor for better business performance. Indeed, besides the characteristics of the productive system, three main parameters contribute to productivity [5]: (i) building system features (e.g., age of the building, envelope and heating, ventilation and air conditioning, HVAC, system performance, operation strategy and maintenance level), (ii) environmental conditions (e.g., thermal conditions, air quality, and acoustics) and (iii) human perceptual and affective responses. Consequently, absenteeism can be lowered by means of interventions in the building system but the results depend also on workers' characteristics, e.g., age, gender, job satisfaction, personal qualities, and educational level, in relation to the kind of activity. Occupants' interaction with the working space is considered important as well [5–7].

This paper aims at investigating a specific research domain of *IEQ*, i.e., thermal comfort, and its impact on productivity, in order to understand the current state of development of the research in this field. The review has been supported by a statistical technique, namely a co-citation analysis, which has been used to cluster the different contributions into thematic groups and disentangle the intellectual scheme subtended by the literature on the topic. The co-citation analysis has been conducted, focusing on the scientific contributions about thermal comfort and productivity in workplaces highly cited or published in the last 15 years. Three main clusters of papers, highlighting various aspects related to occupants' comfort, performance, health, and productivity, have been identified and discussed. Specific attention has been paid to those contributions presenting simplified models attempting to express quantitative relationships between thermal comfort and productivity, which have been described in the final sections of this work. These correlations can be used to simulate the economic impact of measures or interventions aimed not only to improve the energy efficiency of the productive buildings but also the quality of the workplace environment. Finally, the findings from the most recent research works in the literature—and therefore not available for the co-citation analysis—have been discussed.

2. Methods

With the purpose of characterizing the research domain defined in the introduction, its sub-topics, and the way in which the different contributions in the literature are related to each other, a bibliometric technique, namely a co-citation analysis, has been adopted. Those studies proposing quantitative correlations between workers' thermal comfort and productivity or those too recent to be included in the co-citation analysis have been discussed in detail in dedicated sections.

2.1. Motivation for the Chosen Methodology

According to the current state of the art in the literature review in the research field of building energy performance, the classification and the analysis of different contributions and topics are generally driven by the authors' experience and previous knowledge. However, this approach is not the most efficient solution when clear trends in the progress of achievements and methods are not easy to detect. For this reason, quantitative statistical techniques performed on the bibliometric indexes can be exploited to support the review activity. In particular, the co-citation analysis can be adopted to cluster the papers and drive the review by considering not only similarity in contents but also interconnections among contributions. According to this approach, the most relevant aspects in the studied research field can be analyzed in an unbiased way and a robust schematization of the links among the main contributions can be identified.

2.2. Search Settings

The search of papers started by consulting the Scopus database (https://www.scopus.com/). A multi-step query has been written: first, the papers including "thermal comfort" in the title, abstract, or keywords, have been identified and then the search has been limited to those including (1) "productivity" *OR* "performance" *AND* (2) "human" *OR* "work*" *OR* "occupant" *OR* "people" *OR* "person" as further keywords. English was selected as the language and only scientific articles, reviews, and conference proceedings were considered. Two time periods were set: the first one (i.e., from 2000 to 2015) was used to identify the papers for the co-citation analysis while the second one (i.e., publication year later than 2015) was expected to focus on the most recent developments discussed in Section 4.4, but which were too recent to be co-cited. These periods were selected to intercept the boost of public and scientific interest in energy efficiency and indoor environmental quality.

A preliminary analysis on the search outcomes has allowed excluding those works mainly focused on different topics and those only marginally focused on the connection between thermal comfort and productivity. The reference lists of the remaining papers have been used to look for other contributions not included in the query output, such as works not indexed in Scopus or published prior than 2000, but that are relevant for this review and the co-citation analysis. A total of 56 papers have been identified as the core set to proceed with the co-citation analysis method.

2.3. Analysis of the Set of Papers

The approach adopted to implement a co-citation analysis on the core set of 56 papers is shown in Figure 1. The first step regards the construction of a *citation matrix* to analyze the connections among the publications. The citation matrix is a square matrix of citing and cited articles, respectively in rows and columns: if the paper i is cited by paper j, the cell a_{ij} is equal to 1. Then, a *co-citation matrix of frequency* is prepared calculating the *co-citation index*, i.e., the number of times the two works are cited together by at least another document. The elaboration of the *co-citation matrix* of frequency allows us to recognize the so called "intellectual structure". Afterwards, the number of papers in the matrix is reduced, discarding all articles (1) neither cited nor citing any other article or (2) without any co-citation. This latter step is performed since it is assumed that the more often two articles are cited together, the more likely it is that they are related to the same aspects of a topic [8], which can then be identified more easily. Accordingly, the core set of papers in this work has been reduced from 56 to 45.

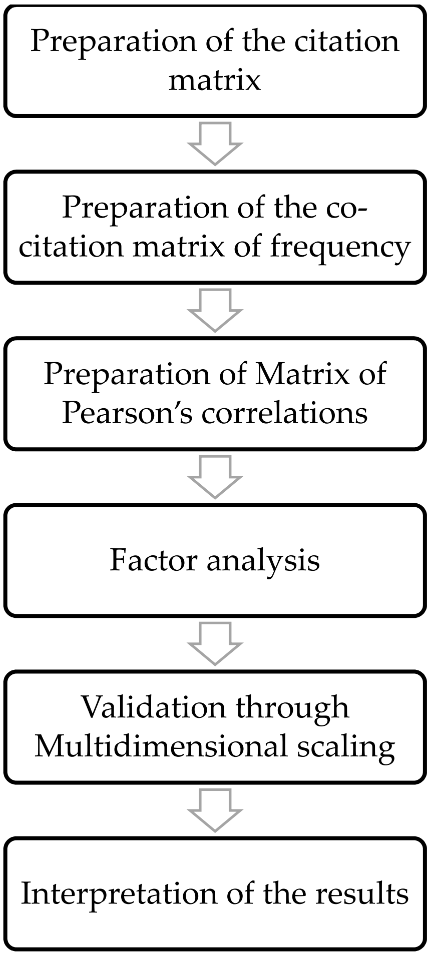

Figure 1. Flow chart of the development of the co-citation analysis.

The following step requires the conversion of the final *co-citation matrix of frequency* into a *matrix of Pearson's correlations*. The Pearson's correlation is a statistical measure of the linear correlation between paired data—the higher the positive correlation, the higher the perceived similarity between the two papers [9,10].

In this work, the social network software UCINET [11] was employed to calculate the Pearson's correlations and then to perform an exploratory factor analysis, whose goal is to reproduce the space described by the correlation matrix with a few orthogonal factors F, without a priori assumptions. Given p random observable variables x_i, with i from 1 to p (i.e., $x_1 \ldots x_p$), whose p means correspond to $\mu_1 \ldots \mu_p$, the factor analysis develops the following model:

$$x_i - \mu_1 = l_{i1} F_1 + \ldots + l_{ik} F_k + \varepsilon_i \quad (1)$$

where F_j are k *Factors* (with j from 1 to k and $k < p$) influencing all observable variables x_i, l_{ij} are unknown constants, named *Factor Loadings*, and ε_i is the unobserved stochastic error. Equation (1) can be written also in the matrix form:

$$\boldsymbol{x} - \boldsymbol{\mu} = \boldsymbol{L} \cdot \boldsymbol{F} + \boldsymbol{\varepsilon} \quad (2)$$

Assuming n observations, $\boldsymbol{x}$, $\boldsymbol{L}$, and $\boldsymbol{F}$ are matrixes with dimensions equal to $n \times p$, $p \times k$, and $k \times n$, respectively. $\boldsymbol{F}$ is assumed independent of $\boldsymbol{\varepsilon}$, with the null expected value and covariance matrix equal to the identity matrix (i.e., all factors are uncorrelated and independent or, in other words, orthogonal).

Given a solution with k factors $\boldsymbol{F}$ for Equation (2), the covariance has to be same for both equation members, i.e., $Cov(\boldsymbol{x} - \boldsymbol{\mu}) = Cov(\boldsymbol{L} \cdot \boldsymbol{F} + \boldsymbol{\varepsilon})$. However, since $\boldsymbol{L}$ does not vary with the observations and $Cov(\boldsymbol{F}) = \boldsymbol{I}$, it can be expressed as:

$$Cov(\boldsymbol{x} - \boldsymbol{\mu}) = \boldsymbol{L} \cdot Cov(\boldsymbol{F}) \cdot \boldsymbol{L}^T + Cov(\boldsymbol{\varepsilon}) = \boldsymbol{L} \cdot \boldsymbol{L}^T + Cov(\boldsymbol{\varepsilon}) \quad (3)$$

This means that each combination of factors and factor loadings can undergo orthogonal transformations. For example, if $\boldsymbol{Q}$ is an orthogonal matrix, $\boldsymbol{L}$ can be written as $\boldsymbol{L} = \boldsymbol{L} \cdot \boldsymbol{Q}$ and $\boldsymbol{F} = \boldsymbol{Q}^T \cdot \boldsymbol{F}$ since:

$$Cov(\boldsymbol{L} \cdot \boldsymbol{Q} \cdot \boldsymbol{Q}^T \cdot \boldsymbol{F} + \boldsymbol{\varepsilon}) = Cov(\boldsymbol{L} \cdot \boldsymbol{I} \cdot \boldsymbol{F} + \boldsymbol{\varepsilon}) = Cov(\boldsymbol{L} \cdot \boldsymbol{F} + \boldsymbol{\varepsilon}) \quad (4)$$

As seen in the previous equations, each factor represents a dimension of this space, which corresponds to a research topic or subtopic in the co-citation analysis, and each paper can be clustered according to them. The attribution of a given article to a cluster can be performed by means of the factor loadings, since the squared factor loadings express the percent of variance explained by a factor for a given variable. However, the factor loadings maximize the variance for the very first factors and this makes the interpretation and clustering processes more difficult. For this reason, exploiting the property shown in Equation (4), an orthogonal transformation is usually applied and factor loadings are rotated, defining the *rotated factor loadings*. In this case, the rotated factor loadings were found by means of the varimax rotation. Rotated factor loadings larger than 0.4 were considered to attribute a given article to a cluster, with a special regard to cases larger than 0.7, representing the strongest correlations.

Among the alternative extraction methods for factor analysis, the Principal Component was selected. In order to determine the number of factors to extract, we analysed the eigenvalues that measure the variance explained by each factor considering all variables. Specifically, the Kaiser's criterion, i.e., the rule of eigenvalues greater than 1 [12], along with a Scree test [13], were used. Moreover, consistent with the chosen methods, the sum of the squared rotated factor loadings is larger than one for all significant extracted factors. In order to facilitate the analysis of the clusters, each one was given a specific name according to the main topics discussed in the papers belonging to it. Indeed, even though exploratory factor analysis can be used to identify the number of different categories, as well as the elements in each one, the attribution of the specific meaning is up to the researcher and requires a direct analysis of the elements in the clusters.

Finally, Multidimensional Scaling, *MDS*, was adopted to check the results of the factor analysis [14]. The aim of *MDS* is to build a visual representation of the pattern of similarities among a set of objects (i.e., the papers in the co-citation analysis). This result is achieved through an iterative algorithm which moves the set of objects in a m-dimensional space with the aim of minimizing a statistic index named *stress* (Equation (5)) and identifying the corresponding set of m-dimensional vectors, whose matrix of Euclidean distances d are as close as possible to a monotonic function f of the matrix of input data.

$$Stress = \sqrt{\frac{\sum_i \sum_j \left(f(x_{ij}) - d_{ij}\right)^2}{\sum_i \sum_j d_{ij}^2}} \quad (5)$$

In this work, the matrix of Pearson's correlations was used as the input matrix and *m* was set equal to 2, in order to have a 2-dimensional map where the position and proximity of papers showing conceptual similarities are easier to identify [15]. The axes in the *MDS* map are meaningless and similar to the names of the clusters in the factor analysis, labels can be given in order to facilitate interpretation. In this case, after analysing the positions of the papers in the 2-dimensional chart, label titles were defined.

3. Results

3.1. Factor Analysis

The systematic research in the literature helped to classify the methods, models, and experiments about the relationship between workers' thermal comfort and productivity. Four clusters were found from the data, explaining 89% of the variance in the correlation matrix, with the first three clusters accounting for 85.8%, as shown in Table 1. Based on the largest absolute value of the rotated factor loadings, 24 papers were assigned to the cluster *F*1, 9 to cluster *F*2, 11 to cluster *F*3, and a single paper to cluster *F*4 (Table 2). Considering the content of the included papers, the three main clusters were named as follows: "*F*1*: Impact of the environment conditions on workers' performance and productivity*", "*F2: Workers' environmental perception*" and "*F3: Workers' health*". *F*1 includes the most important references discussing the relationship between workers' thermal comfort and productivity, which is also discussed in *F*2 and *F*3, even if the focus is put mainly on other aspects (i.e., thermal quality and health of the workplace).

Table 1. Results of the factorial analysis with the principal components extraction method.

Factor	Eigenvalue	Percentage [%]	Cumulative Percentage [%]
1	19.29	42.9	42.9
2	10.25	22.8	65.7
3	9.05	20.1	85.8
4	1.46	3.2	89.0

Table 2. Rotated factor loadings of the core set of papers grouped by cluster: the loadings with absolute value larger than 0.4 are in italics, those larger than 0.7 are in bold. The publication year is underlined if prior than 2000. Regarding the type of study: "A" indicates conceptual and theoretical studies, "B1", "B2", and "B3" are experimental studies performed, respectively, in the field, in the laboratory, and through surveys, "C" is a literature review, and "D" are simulation analyses.

Papers	Year	Rotated Factor Loadings				Type of Study
		*F*1	*F*2	*F*3	*F*4	
Papers Assigned to Cluster *F*1						
Berglund et al. [16]	1990	***0.946***	−0.069	−0.087	0.012	A/B1
Brager and de Dear [17]	1998	*−0.684*	−0.043	*0.563*	0.198	C
Frontczak and Wargocki [18]	2011	*−0.635*	−0.367	*0.530*	0.158	A
Jensen et al. [19]	2009	***0.785***	0.180	0.198	−0.215	B1/B3
Kosonen and Tan [3]	2004	***0.925***	0.299	0.064	−0.060	A
Kroner and Stark-Martin [20]	1994	*0.557*	−0.242	*−0.446*	0.373	B1/B3
Lan and Lian [21]	2009	***0.950***	−0.233	−0.036	0.092	B1/B3
Lan et al. [22]	2009	***0.973***	−0.146	−0.004	0.033	B1/B3
Lan et al. [23]	2011	***0.959***	−0.239	0.072	0.07	B1/B3
Lorsch and Abdou [24]	1994	*0.662*	0.330	0.098	−0.365	A
Loveday et al. [25]	1995	***0.958***	−0.226	0.028	−0.052	A/D
Nicol and Humphreys [26]	2002	*−0.686*	−0.145	*0.494*	0.028	A
Roelofsen [27]	2001	***0.929***	0.258	0.022	−0.063	A
Schiavon and Zecchin [28]	2008	***0.943***	−0.251	0.047	0.097	A

Seppänen [29]	2005	*−0.578*	−0.315	*0.504*	0.201	A/D
Seppänen et al. [30]	2006	***0.970***	−0.168	0.021	0.067	A/D
Tanabe et al. [31]	2007	*−0.635*	−0.367	*0.530*	0.158	B1/B2/B3
Tham [32]	2004	***0.763***	0.177	*−0.497*	−0.038	B1/B3
Tham and Willem [33]	2010	***0.977***	−0.159	0.035	0.053	B2/B3
Wargocki and Djukanovic [34]	2005	*0.677*	−0.298	*−0.620*	0.156	A
Wargocki and Wyon [35]	2006	***0.959***	−0.239	0.072	0.07	B1
Wargocki et al. [36]	2000	*0.675*	−0.083	*−0.658*	0	B1/B3
Wyon and Wargocki [37]	2005	***0.916***	−0.163	−0.276	0.104	A
Wyon et al. [38]	1975	***0.901***	0.263	−0.159	−0.028	B2/B3
Papers Assigned to Cluster *F*2						
Chiang and Lai [39]	2002	−0.063	***0.994***	0.037	−0.029	A/B1
Clements-Croome and Baizhan [40]	2000	−0.085	***0.881***	*−0.402*	−0.047	B3
Hameed and Amjad [41]	2009	−0.063	***0.994***	0.037	−0.029	B3
Haynes [1]	2008	−0.063	***0.994***	0.037	−0.029	C
Kawamura et al. [42]	2007	−0.063	***0.994***	0.037	−0.029	B2/B3
Seppänen et al. [43]	2005	−0.063	***0.994***	0.037	−0.029	A/D
Seppänen and Fisk [44]	2006	0.370	***0.837***	−0.082	0.181	A
Wargocki [45]	2007	−0.063	***0.994***	0.037	−0.029	A
Wong et al. [46]	2008	−0.213	***0.946***	0.154	0.004	B3
Papers Assigned to Cluster *F*3						
Dorgan et al. [47]	1998	0.155	−0.018	***−0.899***	0.002	A
Fisk [48]	2000	−0.017	0.235	***−0.821***	0.031	C
Fisk and Rosenfeld [49]	1997	*0.402*	−0.121	***−0.753***	0.130	C
Lan et al. [50]	2011	−0.315	−0.303	***−0.821***	0.150	B1/B3
Milton et al. [51]	2000	−0.048	−0.007	***−0.929***	−0.067	B1
Seppänen et al. [52]	2003	−0.031	0.004	***−0.814***	−0.165	A/D
Seppänen et al. [53]	2006	−0.110	−0.226	***−0.925***	0.110	A
Wargocki et al. [54]	1999	*0.481*	0.280	***−0.746***	0.167	B1/B3
Wargocki et al. [55]	2000	−0.164	−0.211	***−0.882***	−0.069	B1
Wyon [7]	1996	*0.575*	0.302	*−0.637*	−0.121	A
Wyon et al. [56]	2000	−0.074	0.100	***−0.945***	−0.095	B1/B3
Papers Assigned to Cluster *F*4						
Clements-Croome and Kaluarachchi [57]	1998	0.027	−0.067	−0.106	***−0.897***	B3

For some references (i.e., [7,17,18,20,26,29,31,32,34,36,40,49,54] in Table 2), the absolute values of the rotated factor loadings are larger than 0.4 for more factors, indicating the tendency to bridge two or more sub-categories [14]. Except for Reference [40], in most cases the connection is between *F*1 and *F*3, suggesting a connection between thermal comfort, health, and productivity because of less health-related absences.

In Table 2, papers are distinguished according to the type of the presented studies: "A" groups are conceptual or theoretical research works, "B" are the experimental works, "C" are the simulation-based works and "D" are the literature reviews. Considering the experimental studies, they are further separated into "B1", "B2", and "B3" (i.e., experiments in the field, in the laboratory, or based on surveys). In most cases, papers have sections that fit with more than one category of study. In *F*1, 12 papers present conceptual or theoretical models ("A"), 3 of which are coupled with a literature review ("D"). The most common experimental activities are performed in the field: 10 papers fit with "B1" and 7 of them also present results from surveys ("B3"). In *F*2, a group of 4 papers belong to category "A" and another 4 papers to "B3". Similarly to *F*1, in *F*3, 4 papers belong to the group of conceptual/theoretical works ("A") and 5 papers belong to the experimental works performed either in situ ("B1") or by means of surveys ("B3"). As a whole, measurements in the field together with collecting data through surveys are the most common experimental approaches.

3.2. Multidimensional Scaling

Figure 2 shows the Multidimensional Scaling map. Along the horizontal axis, i.e., the first dimension, the papers range from studies focused on the relationship between workers' thermal comfort on productivity (on the left, such as [3,23,30]) to those focused only workers' thermal comfort perception and adaptation (on the right, such as [17,26,46]). The vertical axis, i.e., the second dimension, ranges from papers discussing the impact of the indoor conditions on workers' thermal comfort and performance (on the top, such as [57]) to those discussing the impact of the indoor conditions on workers' health (on the bottom, such as [51,55]).

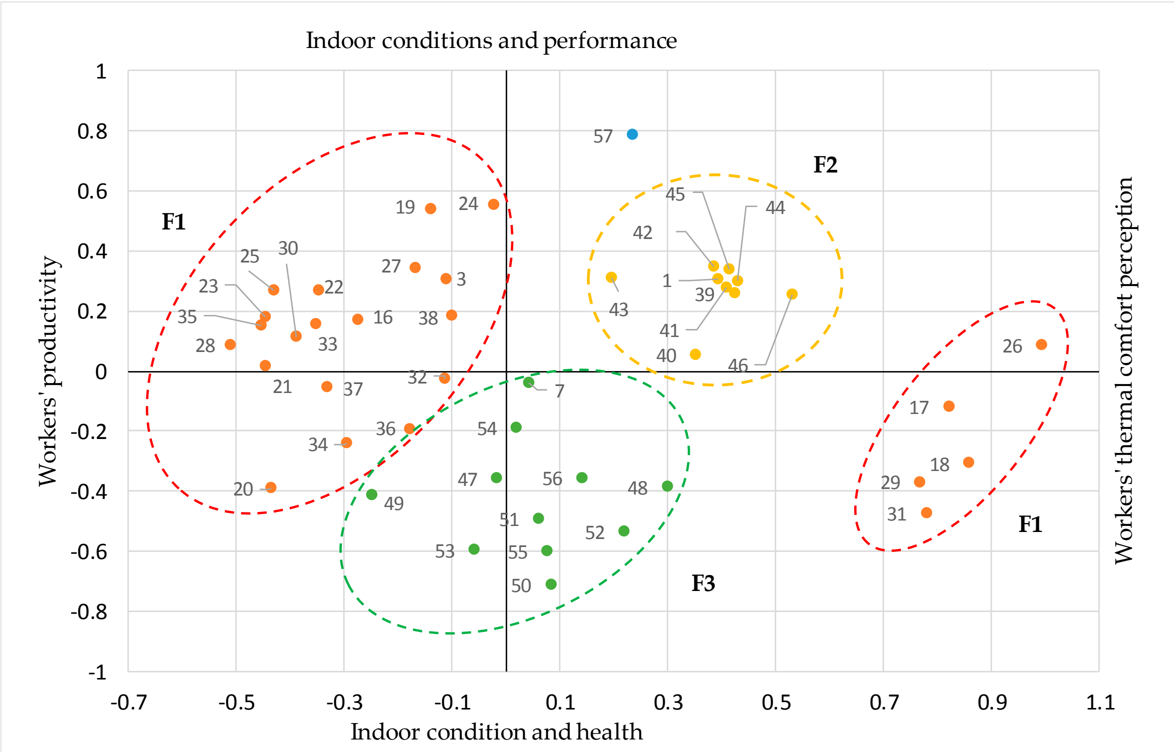

Figure 2. Multidimensional Scaling Map. Circles on the map are drawn according to the main three clusters of Table 2.

Papers on the *MDS* map are grouped according to the clusters found in the factor analysis. It is possible to observe that cluster *F*1 is split into two subclusters: the main group of 19 papers in quarters 2 and 3, on the left part of the map, and a minor group of 5 papers [17,18,26,29,31] in quarters 1 and 4, on the right. Looking at the two other main clusters, *F*2 is located in quarter 1, on the left of the map, and *F*3 is between quarter 3 and 4, on the bottom. As a whole, considering the meaning that we attributed to the two *MDS* dimensions after analyzing the relative positions of the papers in the map and the proximity of the papers belonging to the different clusters, the groups found by means of the factor analysis can be considered confirmed and validated by *MDS*. However, *F*1 reveals a poor homogeneity and the presence of a small group of 5 papers remarkably different from the rest belonging to the first cluster. To some extent, this aspect was observable also in factor analysis: indeed, these 5 contributions have absolute values of the rotated factor loadings larger than 0.4 and close for both *F*1 and *F*3.

4. Discussion

4.1. The Three Main Clusters

4.1.1. *F*1: Impact of the Environmental Conditions on Workers' Performance and Productivity

The first cluster covers 24 papers corresponding to 42.9% of the variance. Most of the papers in cluster *F*1 present models, correlations, or statistical tests on either experimental and numerical data about the relationship between environmental conditions and workers' performance and productivity. Besides that, some contributions in *F*1 are related to workers' thermal adaptation and perceived individual control as well as the economic results from the improvement of the indoor conditions.

Measurement of productivity is dealt with by a number of authors in the literature, at different environmental conditions, by taking into account several performance tasks. For example, Wyon et al. [38] measured in a climatic chamber the subjects' performance in numerical addition and memory tasks and in a test of cue-utilization, as well as their self-rated effort, arousal, fatigue, and the freshness of the air. Lan and Lian [21] performed computerised tests to assess some neurobehavioral functions, such as visual perception, working memory, reasoning, and executive functions.

Some authors discussed the relationship between thermal environmental conditions and productivity, such as [3], who underlined that productivity loss is correlated to the rate of change in thermal conditions, and Wyon and Wargocki [37], who observed that some air temperature ranges can lower arousal, elevate Sick Building Syndrome (*SBS*) symptoms, reduce manual dexterity, and affect learning performance [35]. As a general result, in many works, productivity loss is reported when people feel warm [23] and in non-neutral comfort conditions [21], but not in the same way for the different performance tasks, since the dominant hemisphere and portions of the brain cortex involved are not the same [22]. For example, Kosonen and Tan [3] found optimal productivity at around 24 °C and with a predicted mean vote equal to 0.21. Seppänen et al. [30] quantified a performance decrease of 2% per each degree Celsius of air temperature increase in the range of 25–32 °C and recommended 22 °C as the optimal temperature. Tham [32] reported a workers' performance maximized at 24.5 °C in a call centre in Singapore with a ventilation rate of 10 L s^{-1}-per person; but in a further simulation analysis, Tham and Willem [33] concluded that air temperature around 20 °C can improve mental arousal and performance in activities requiring attention. Tanabe et al. [31] studied the effect of moderately high temperature on task performance and fatigue with 40 college-age subjects, showing an increase of fatigue and decrease in deoxygenated haemoglobin at an operative temperature of 33 °C. Wargocki et al. [36] showed benefits for health, thermal comfort, and productivity in the case of higher ventilation rates: for example, the authors found a significant improvement in typing and in creative thinking at a ventilation rate of 10 L s^{-1} per person compared to 3 L s^{-1} per person. Confirming that tasks requiring concentration and alertness are affected by temperature and air quality, Lorsch and Abdou [24] remarked that lower air temperature and better air quality can also diminish the industrial accident rate.

As already observed in Sections 3.1 and 3.2, some contributions included in cluster *F*1 can be considered a subcluster focused mainly on comfort perception of the workplace, thermal adaptation, and workers' individual control, which can enhance performance and reduce complaints [20]. For example, Nicol and Humphreys [26] remarked that occupants' control over the environment can contribute to the adaptive mechanisms for achieving the desired comfort condition and Brager and de Dear [17] highlighted that thermal comfort evaluations in naturally ventilated buildings are influenced by differences in levels of the perceived control. Frontczak and Wargocki [18] focused on the influence of different non-environmental factors on the overall *IEQ* evaluation. This study found that factors such as country of origin, education level, type of job, psychosocial atmosphere, and time pressure do influence the overall satisfaction with *IEQ*, while, on the contrary, personal characteristics (e.g., occupants' age, health, self-estimated environmental sensitivity, menstruation cycle, pattern of smoking and coffee drinking, job stress) do not. Roelofsen [27] statistically derived an equation for calculating the loss of performance, coupled with the equivalent temperature model by Berglund [16], who predicted productivity decrements as dependent on thermal conditions. Loveday et al. [25] derived a multiple regression model of productivity and thermal sensation votes relating temperature, relative humidity, and the velocity of indoor air.

Finally, some authors concentrated on the economic implication of better environmental conditions. Jensen et al. [19] analysed the relationship between thermal sensation votes and workers' performance in different building designs through a Bayesian Network Approach and adopted a performance index to assess the economic impact of indoor environmental conditions, with particular attention to the effects of temperature on mental performance. Schiavon and Zecchin [28] underlined the importance of accounting for the relationship between *IEQ* and workers' performance in cost-benefit analyses, estimating that an increment of 1% of the work performance can payback the running annual energy cost. The life-cycle cost analysis by Wargocki and Djukanovic [34] showed productivity benefits from a better indoor air quality up to 60 times higher than the increased costs. After highlighting that poor indoor conditions are commonly related to *SBS* symptoms, respiratory illnesses, sick leave, reduced comfort, and losses in productivity, Seppänen [29] concluded that improvements in the indoor environment can show potential financial benefits, such as reduced medical care cost and sick leave, better work performance, lower turn-over of employees, and lower cost of building maintenance due to fewer complaints about indoor air quality and climate.

4.1.2. *F*2: Workers' Environmental Perception

The second cluster covers 22.8% of the variance with 9 papers. Most of them describe comfort models and those aspects that workers would like to improve first or consider the most important ones. Other topics, such as the influence of thermal comfort on performance and possible improvements achievable by means of proper ventilation strategies, are also included in this cluster.

Chiang and Lai [39] elaborated a global Indoor Environment Index, *IEI*, using an analytical hierarchical process to consider subjective evaluation on thermal comfort, indoor air quality, visual comfort, acoustic aspects, and electromagnetic conditions. Some authors, instead, studied the relative importance of the different environmental aspects. Analyzing the literature, Haynes [1] observed that occupants are mainly dissatisfied with temperature and ventilation. After an experimental survey in a climatic chamber, Kawamura et al. [42] stated that occupants' priority is improving thermal and acoustic comfort conditions, rather than lighting conditions. Wong et al. [46] developed a multivariate-logistic model to estimate the indoor environmental quality acceptance, based on almost 300 questionnaires on office conditions in Hong Kong: also in this case, thermal conditions were the most important aspect, followed by indoor air quality, noise, and lighting levels.

Other authors in cluster *F*2 are focused more on the productivity implications of various thermal comfort and environmental conditions than on the occupants' perception. Clements-Croome and Baizhan [40] elaborated three multiple regression models correlating office productivity to unsatisfactory characteristics of the indoor environment (e.g., thermal conditions, sick syndrome building symptoms), job dissatisfaction, and crowding rate of the workplace. The authors estimated a possible increase of productivity in offices of about 4 to 10% after improving the environmental conditions. Hameed and Amjad [41] proposed a regression correlating productivity with temperature, noise, and lighting conditions, as well as with the type of furniture and spatial arrangements.

Another group of authors concentrated their efforts on the impact of ventilation rate strategies on productivity and workplace comfort perception. Wargocki [45] observed that it is possible to promote health, comfort, and a better performance in office work by means of a better ventilation rate. Seppänen and Fisk [44] expressed the illness-caused absence as a function of the ventilation rate and they linked the work performance to the ventilation rate, air temperature, and perceived air quality. Moreover, as already observed in [30] in *F*1, Seppänen et al. [43] estimated a decrease in productivity equal to 2% when the temperature rises above 25 °C.

4.1.3. *F*3: Workers' Health

The last main cluster includes 11 papers corresponding to 20.1% of the variance. Excluding a small group of papers discussing the relationship between thermal comfort and productivity and presenting the findings already seen in *F*1 and *F*2 [7,50,52], the main topic in this group is health in workplaces and its impact on productivity, with a particular focus on the influence of indoor air quality.

Wyon [7] distinguished overall work force productivity and individual performance, stating that productivity is affected by absenteeism, health costs, capital and running costs of a building, and performance by workers' control over their thermal conditions, physical environmental variables, motivation, comfort, and healthy buildings. He also remarked that performance is negatively affected by vertical temperature differences, as a condition opposed to human health requirements. Dorgan et al. [47] observed that medical costs and productivity losses can be reduced by improved indoor air quality. Fisk and Rosenfeld [49] argued that the costs of improving indoor environments are comparable with the value of potential productivity gains and savings in health care costs. In a further study, Fisk [48] estimated the U.S. national medical cost savings at 6–14 billion $ for the reduction of respiratory illness, 2–4 billion $ for allergy and asthma, 10–30 billion $ for *SBS* symptoms, and compared them to the potential energy savings for space conditioning and lighting achievable through the refurbishment of commercial, institutional, and residential buildings (i.e., 20–160 billion $). Wargocki et al. [54] assessed the relationship between human comfort, *SBS* symptoms, and productivity, and the advantages arising in the case of low-polluting buildings. Seppänen et al. [53] evaluated the potential work performance benefits in increasing ventilation, considering that the ventilation rate influences workers' performance indirectly through its impact on short-term sick leave, *SBS* symptoms, or dissatisfaction with air quality. Similarly, Milton et al. [51] found correlations between sick leaves and lower rates of outdoor air supply and *IEQ* complaints and estimated the health costs and lost productivity attributable to inadequate ventilation. Thanks to an analysis of the effect of airborne dust levels in a central-London office, Wyon et al. [56] confirmed that better indoor air can reduce *SBS* symptoms and increase self-estimated productivity. Wargocki et al. [55] performed a field experiment and quantified that performance can increase on average by 1.5% for every 10% decrease in the percentage of persons dissatisfied with the air quality.

4.2. *Papers of the Core Set Excluded from the Co-Citation Analysis*

This section analyses those contributions belonging to the core set of papers discarded during the steps of the co-citation analysis, because they were either not-cited, not citing, or without co-citations (Table 3).

Table 3. Papers of the core set excluded from the co-citation analysis. The publication year is underlined if prior than 2000. Regarding the type of study: "A" indicates conceptual and theoretical studies, "B1", "B2", and "B3" are experimental studies performed, respectively, in the field, in the laboratory or through surveys, "C" is a literature review, and "D" are simulation analyses.

Papers	Year	Type of Study
Carrer et al. [58]	2015	C
Clements-Croome [59]	2008	C
de Dear and Brager [60]	2002	B1/B3
de Dear et al. [6]	2013	C
Fisk et al. [61]	2011	A/D
Humphreys and Nicol [62]	2007	B1/B3
Jin et al. [63]	2012	A/D
Kumar and Fisk [64]	2002	A
Rupp et al. [65]	2015	C
Sensharma et al. [5]	1998	C
Wyon [66]	2004	B1

Generally, these contributions discuss topics already presented in Section 4.1 or confirm the findings of the papers included in the factor analysis. For example, as underlined in *F*1, papers [5,6,60,62,65] stress the importance of workers' control over the environment to increase thermal acceptability. Indeed, as stated by de Dear and Brager [60], a search for a general optimization should be avoided. This study suggested that the occupants should be provided with a variety of means for controlling internal conditions at their own individual discretion. Consistently with the studies cited in Sections 4.1.2 and 4.1.3, Carrer et al. [58], Clements-Croome [59], and Kumar and Fisk [64] confirmed the advantages of higher ventilation rates for increasing the indoor air quality, health, and productivity. Additionally, regarding the economic aspects, approaches and findings are in agreement with those presented in the discussion of clusters *F*1 and *F*3. For instance, Fisk et al. [61] underlined the potential annual economic benefits in improving *IEQ* in U.S. offices, by estimating savings for different scenarios. Jin et al. [63] optimized some façade design options studying the economic value of the resulting *IEQ*. Wyon [66] concluded that interventions to improve indoor air quality can have a payback time of 2 years because of the high cost of labor per unit floor area.

4.3. Models and Equations Related to Thermal Comfort and Productivity

Within the core of papers analyzed, only a few studies attempted to derive a model on the influence of workers' thermal comfort on their productivity. In this section, nine models are presented.

Roelofsen [27] expressed the performance loss (*PL*) in offices as a function of the Predicted Mean Vote (*PMV*): the larger the distance from thermal neutrality, the larger the performance loss. The model combines the study of Berglund et al. [16] with the *PMV*, distinguishing between discomfort by cold and hot sensations (Table 4):

$$PL = b_0 + b_1 \cdot PMV + b_2 \cdot PMV^2 + b_3 \cdot PMV^3 + b_4 \cdot PMV^4 + b_5 \cdot PMV^5 + b_6 \cdot PMV \quad (6)$$

Table 4. The values of the regression coefficients, b_0–b_6, in Equation (1).

Regression Coefficients	*PMV* < 0	*PMV* > 0
b_0	1.280207	−0.15397397
b_1	15.995451	3.8820297
b_2	31.507402	25.176447
b_3	11.754937	−26.641366
b_4	1.4737526	13.11012
b_5	0.0	−3.1296854
b_6	0.0	0.2926092

Additionally, Kosonen and Tan [3] modeled productivity loss [%] in office activities (i.e., typing and thinking tasks) with respect to the *PMV*. The two equations, respectively, for typing tasks (PL_{typ} in Equation (7)) and thinking tasks (PL_{th} Equation (8)), can be used in an operative temperature range of 20–27 °C:

$$PL_{typ} = -60.543PMV^6 + 198.41PMV^5 - 183.75PMV^4 - 8.1178PMV^3 + 50.24PMV^2 + 32.123PMV + 4.8988 \quad (7)$$

$$PL_{th} = 1.5928PMV^5 - 1.5526PMV^4 - 10.401PMV^3 + 19.226PMV^2 + 13.389PMV + 1.8763 \quad (8)$$

Jensen et al. [19] and Lan et al. [50] elaborated relative performance (*RP*) models based on subjective thermal sensation (*tsv*). Jensen et al. [19] studied the responses to addition tasks (RP_{add}) of 12,700 occupants in 124 buildings and proposed Equation (9):

$$RP_{add} = -0.0069tsv^2 - 0.0123tsv + 0.9945 \quad (9)$$

Lan et al. [50] focused on text typing, addition, and calculation tasks ($RP_{typ+add+calc}$), proposing the model in Equation (10):

$$RP_{typ+add+calc} = -0.0351tsv^3 - 0.5294tsv^2 - 0.215tsv + 99.865 \quad (10)$$

Loveday et al. [25] developed a multiple regression model on the effect of thermal comfort on productivity, PL [%]. The model assumes a constant metabolic rate equal to 1 met, a clothing level of 0.6 clo, and mean radiant temperature equal to the air temperature. It was validated considering the air temperature t_a in the range from 15–35 °C, relative humidity RH equal to 12%, 55%, and 100%, air velocity v lower than 0.5 m s^{-1}, and productivity P between 64% and 100%.

$$PL = ß_0 + ß_1\, t_a + ß_2\, RH + ß_3\, v + ß_4\, t_a^2 + ß_5\, t_a\, RH \quad (11)$$

Berglund et al. [16] estimated the performance loss of mental tasks, PL_{th} [%], related to thermal discomfort, by integrating the Gagge et al. [67] model with the Mackworth [68] research. This model was validated under air temperatures between 29.4 and 40.6 °C, relative humidity between 63% and 70%, exposition time of 3 h, and considering a range of discomfort level, x, in Equation (12), between 0.14 and 11.4:

$$PL_{th} = -7.5851 + 27.138x - 6.754x^2 + 0.85945x^3 \quad (12)$$

Seppänen et al. [43] developed a simplified model with a linear performance loss PL [%] as a function of air temperature. The model assumes no performance loss between 21 and 25 °C and for temperatures higher than 25 °C it considers a decrement of 2% per each degree Celsius until 33 °C:

$$PL = 2t_a - 50 \quad (13)$$

Other studies attempted to derive an equation using data obtained via self-assessment questionnaire of productivity and environmental parameters. For instance, Clements-Croome and Baizhan [40] carried out a survey in offices: their questionnaires ranked the overall dissatisfaction of the indoor environment (En evaluated in a 7-point scale), the job dissatisfaction (JD evaluated in a 7-point scale), the crowded working space (CS evaluated in a 7-point scale), and the self-assessed productivity (SP evaluated in a 9-point scale). The following equation was obtained using multiple regression analysis of the questionnaire data:

$$SP = 6.8510 - 0.3625En - 0.1542JD - 0.1.329CS \quad (14)$$

Hameed and Amjad [41] surveyed employees of 13 banks in Pakistan and proposed a regression equation, by taking into account furniture (F), noise (N), lighting (L), temperature (T), and spatial arrangements (SA), with all those variables measured in a 5-point scale:

$$SP = -0.645 + 0.015F - 0.068N + 0.739L + 0.021T + 0.162SA \quad (15)$$

As can be seen, the approaches adopted to quantify the change in specific performance tasks or overall productivity are different, can involve different quantities (e.g., predicted mean votes, thermal sensation votes, temperature, relative humidity, or other environmental variables) and, consequently, propose different evaluations of the impact of indoor conditions on the potential productivity losses.

4.4. Recent Works on Comfort and Productivity

As observed in the methods section, the co-citation analysis does not include the latest articles since these papers are generally without co-citations. In this last section, the most significant papers published in 2016 about thermal comfort and productivity are discussed.

According to Al Horr et al. [69], among the eight most influencing environmental variables affecting productivity in offices are indoor air quality and ventilation, thermal comfort, lighting and daylighting, and noise. Moreover, the economic increment in productivity can be higher than the annual energy and maintenance costs [69]. Al Horr et al. [70] studied also workers' health and well-being in offices, concluding that *SBS* and thermal, visual, and acoustic comfort cannot be neglected in green building design. Kim et al. [71] suggested that users' control over spatial variables can be a key aspect affecting people's satisfaction, self-reported productivity, or health in workplaces. Lamb and Kwok [72] examined the effects of environmental stressors on workers' well-being and productivity, collecting 2261 online surveys on occupants' thermal comfort perception, visual and acoustic disturbance, individual state of work performance, and well-being. The survey showed that in most situations, environmental stress is responsible for a reduction in performance of 2.4–5.8%. Finally, Wargocki and Wyon [73] asserted that both thermal environments and indoor air quality have a similar impact on the performance of mental work.

5. Conclusions

In this study, a co-citation analysis has been deployed in order to review the scientific literature regarding the relationship between workers' thermal comfort and productivity in production and office buildings. After selecting 56 papers through a keyword search and content check, the applied methods allowed the identification of three clusters, describing the intellectual structure and scheme of the studies published on this topic. The main group of 24 papers refers to the cluster *F*1, which describes the effects of environmental conditions on productivity. Nine papers relate to cluster *F*2, which can be correlated in particular to the workers' environmental perception, and 11 to cluster *F*3, which deals with workers' health. The results of the grouping activity through the factor analysis prescribed in the co-citation method have been compared to clustering with multidimensional scaling techniques. The three main clusters, as well as the main themes discussed within the review topic, were confirmed, even if for the largest group, i.e., *F*1, the multidimensional scaling revealed some inhomogeneity, identifying a subcluster of papers focused mainly on thermal comfort in workplaces and less on the productivity implications.

This study found that:

- Even if the topic has been investigated for some decades, the development of the literature on the link between thermal comfort and productivity is in many respects still at its early stages. This can be due to a number of reasons, ranging from the complexity of the relationship itself because of the many interactions and stressors that are concurrently contributing, as seen for example in those contributions discussing the relative importance of the different environmental solicitations, to the variety of workplaces and job tasks which have to be investigated. In comparison with productive buildings, many steps forward have been made for office buildings. This is proved, for example, by the number of models aimed at predicting losses in typical office tasks, such as typing and calculations, as well as for the number of surveys in office or equivalent buildings. Among the possible motivations, we can suggest a larger standardization of office tasks and jobs, a higher centrality of the workforce with respect to the production systems in terms of added value, as well as the opportunity of more easily conducting experimental activities through surveys on the workplace—or even in climatic chambers reproducing this kind of environment because of the narrower range of possible conditions—can explain the difference.
- According to many authors, a productivity loss can be registered if workers feel warm and, broadly speaking, in non-neutral thermal comfort conditions. Nevertheless, its amount depends on the kind of performance task, as well as on other environmental characteristics and, above all, the air quality. To that extent, many researchers observed that higher ventilation rates can be beneficial in workplaces.
- There is no agreement in the literature about the potential productivity improvement if indoor conditions are optimized. Indeed, various approaches and models have been proposed in the literature, based on different quantities and kinds of correlations. Some authors gave special consideration to workers' thermal adaptation and to the opportunity of workers' control on the workplace conditions as key strategies to improve the thermal perception of the working environment and, thus, the productivity.
- When economic advantages are accounted for, all authors agree that benefits can overcome the costs of the investment for a better indoor environment as well as the larger energy running costs, though the estimation of their magnitude can be significantly different. In some cases, social advantages given by lower healthcare costs were also considered and projected as potential savings at national levels.

- While some authors focused on the productivity loss with respect to optimal indoor thermal comfort conditions, others concentrated on the advantages arising from lower risks for workers' health. In this regard, better thermal conditions mean less short-term sick leaves, reduced *SBS* symptoms, and diminished work accidents.
- In a limited number of cases, some empirical statistically-derived equations were proposed to quantify the performance loss in doing a specific task with respect to neutral comfort conditions. Performance loss is often referred to office activity (e.g., typing) and proposed as a function of either Fanger's predicted mean vote, thermal sensation votes, Gagge's discomfort level or, simply, ambient temperature. Starting from the survey data, some authors included also the effect of and the interaction with other environmental variables, such as noise, or the workers' job dissatisfaction.
- Even though these examples of correlations have some limitations that prevent a general applicability, they can be considered a significant initial step towards an integrated modelling of office and productive buildings, allowing possible outcomes in multi-objective optimizations of economic, energy, and thermal comfort performance.

Acknowledgments: This study has been funded by the project "Klimahouse and Energy Production" in the framework of the programmatic-financial agreement with the Autonomous Province of Bozen-Bolzano of Research Capacity Building.

Author Contributions: Mariantonietta Tarantini performed the literature review and implemented the co-citation analysis. Giovanni Pernigotto defined the methods and supervised its application and the analysis of the results. Andrea Gasparella identified the aims of the research and supervised the study. All authors contributed in writing, editing, and structuring the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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