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Original Research

Thematic Clusters in the field of Gas Turbine Thermal Management: A Co-word Analysis during a Century

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Abstract

The research aims to visualize and analyze the co-word network and thematic clusters of the intellectual structure in gas turbine thermal management during 1919-2020. The study is applied research in terms of the purpose, which is conducted with a descriptive approach, scientometrics indicators, techniques of co-word, and social network analysis. Data analysis and visualization of the co-word network were represented by VoSViewer, SPSS, UCINet, and python Software. The top scientific products in the last century were related to engineering subject area and published by the USA country. Seven main clusters were identified for the index keywords, and 20 main clusters were recognized for the author keywords in Scopus regarding the network structure and thematic clusters based on the co-occurrences. Moreover, 38 clusters were identified based on the hierarchical clusters. The clusters, namely heat flux calculations and radiation effects, thermal performance optimization, and operational considerations, have central and major positions in this field and have more potential to maintain and develop themselves in the future. The future of Research and Development (R&D) activities in the area will be focused on novel cycles, heat map development, and Techno-Economic and Risk Analysis (TERA) by utilizing systematic approaches for the identification of heat sinks and sources, fluid modeling, and environmental considerations. In addition, the emerging contributors in the field will be advanced manufacturing and material considerations.

Keywords: Gas Turbine Thermal Management, Intellectual Structure, Co-Word Analysis,

Thematic Clusters, Hierarchical Clustering, Strategic Diagram.

Introduction

Co-word Analyses like co-authoring, bibliographic coupled analysis, and co-citation are considered among the most commonly used bibliometric and scientific methods. Co-occurrence is a type of keyword relationship, and the analysis unit deals with keywords or extracted terms from the title and abstract of the documents)Cobo, Lopez-Herrera & Herrera-Viedma, 2011). Introduced the co-word analysis in the 1980s, the use of standard terms in two or more documents indicates the proximity of those texts to each other, which can delimit structure, concepts, and the components of a scientific field. This method helps to visualize the structure of fields and scientific areas (Whittaker, 1989) to identify hidden and outstanding patterns and concepts' internal and external relationships (Osareh, Soheili & Mansouri, 2016). It also predicts emerging trends and determines the hierarchical relationships of concepts to develop ontologies of specialized knowledge. The technique aids in clustering the concepts of scientific fields and makes the policy of science and knowledge.

Additionally, the conceptual network of co-word analysis implies that if two terms are used together in a document and their frequencies are high, and these two words have more semantic relationships (Ahmadi & Osareh, 2017). In other words, the more common words of the two articles, the more content and semantic relevance similarity can be found between them (Noyons & van Raan, 1998). The cognitive relation between documents can be uncovered (Salemi & Koosha, 2014).

This technique also identifies science's movement and dynamics (Callon, Courtial & Turner, 1986). Moreover, it helps to answer some questions about the surveyed field, such as: what areas will likely focus on in the future? What kind of evolution has passed so far? And are there any conceptual relationships between fields and conceptual subfields (Ahmadi & Osareh, 2017)? It also allows us to reveal emerging thematic clusters and develop them to predict future research paths (Soheili, Sha'bani & Khasseh, 2016; Lee & Su, 2010). Note that co-word analysis is an example of a graphical modeling approach using relationship analysis techniques (Neff & Corley, 2009). Co-word analysis is a co-occurrence analysis used to map the relationships between concepts, thoughts, and keywords in the basic and social sciences. Moreover, it is a powerful tool for tracking structural changes and perceptual and social networks (Makkizadeh, Hazeri, Hosininasab & Soheili, 2016).

State-of-the-art aircraft and propulsion systems designs are increasingly complex to deal with the vast demands for power generation and emission reduction. These demands result in hotter fluids, higher engine components' temperatures, and higher heat generation, which means critical thermal management issues for aircraft and gas turbine aero-engines (Jafari & Nikolaidis, 2018). These issues could not address just through marginal improvement in aircraft and engine technology and design. So, it is time to think differently about managing the thermal loads in modern gas turbine engines. The Thermal Management System (TMS) plays a crucial role in dealing with this heat to limit payload size and enhance engine performance. The TMS utilizes engine fluids to transfer excess heat from the engine heat sources like bearings, accessory gearbox, pumps, generators, constant speed drive, and power gearbox in new geared turbofans (Van Heerden, Judt, Lawson, Jafari, Nikolaidis & Bosak, 2020). The TMS structures for aircraft engines aligned with gas turbine designs and development changed in the last century. Addressing the future research challenges in the field of TMS design there requires a comprehensive and critical analysis of its history. Therefore, examining these changes and challenges over a hundred years indicates the importance and necessity of this study. As a result, policymakers, designers, and developers of the relevant technology, as well as engine designers and manufacturers, might utilize the results as a thematic policy map. The findings may also be used to discover theme gaps, avoid repeat research, uncover underlying trends, and predict future core topics of the discipline.

Therefore, the present study aims to visualize and analyze the intellectual structure in the field of gas turbine thermal management during 1919-2020 using co-word analysis techniques and tries to answer the following questions:

1- What are top scientific productions in gas turbine thermal management in terms of document, affiliation, funder, publication year, author, country, and subject area?

2- How is the intellectual structure of gas turbine thermal management analyzed in terms of the network structure and thematic clusters <u>for index keywords</u> based on co-occurrence? What is their status in terms of frequency, link numbers, and total link strength?

3- How is the intellectual structure of gas turbine thermal management analyzed in terms of the network structure and thematic clusters <u>for author keywords</u> based on co-occurrence? What is their status in terms of frequency, link numbers, and total link strength?

4- How is the intellectual structure of gas turbine thermal management analyzed in top co-word pairs, co-occurrence matrix, and hierarchical clustering (HC)?

5- How are clusters of gas turbine thermal management visualized and analyzed by the strategic diagram (SD) in maturity and development?

Literature Review

The literature review is classified into two fields and subjects: various information-related fields and thermal management. Finally, a conclusion is written.

Various information-related fields

Co-word analysis, visualizing and analyzing the intellectual structure by using co-word networks are used in different fields like iMetrics (Khasseh, Soheili, Moghaddam & Chelak, 2017), information security and knowledge management (Sedighi & Jalalimanesh, 2014), information retrieval (Ding, Chowdhury & Foo, 2001), information management (Khademi & Heidari, 2016), institutional repository (Cho, 2014), internet of things (Yan, Lee & Lee, 2015). The results of these studies identified trends and main thematic areas and recognized developed, developing, and evolving topics in the mentioned fields.

Thermal management field

Moreover, a study by Borri, Zsembinszki and Cabeza (2021) investigated a comprehensive review and a detailed bibliometric analysis of thermal energy storage (TES) technologies applied to various levels of the built environment in the Scopus database. The research focused on three main categories: buildings, districts, roads, and bridges. The study concluded that the USA was the top country to publish relevant studies on applying TES to buildings, mainly to reduce the cooling demand through optimal control techniques remaining the main research trend. Results related to the keyword analysis identified two main categories of studies. The first refers to heat transfer study mainly on hydronic heating pavements, while the second is related to the inclusion of phase change material into pavements or lightweight aggregate through various techniques such as impregnation or microencapsulation. Results also showed that future research trend is expected to mostly depend on factors such as the legislation, policies, and funding available for the different countries/territory. Because of the high investments in energy efficiency, Europe is leading the research with the highest number of papers in the literature.

Another study by Afgan and Bing (2021) analyzed bibliometric data from 304 research and review articles from 1993 till 2020. Results showed a rapid publication in 2007, with a sharp increase in 2010 and a mild declination in the preceding year. Moreover, a sharp increase was observed in the past 10 years in the number of publications, with substantial increments each year since 2011 - 2020. Applied Thermal Engineering was referred to as the top five influential research journals in the field of thermal energy storage. It also concluded that grey areas for future research work to develop guidelines and standards for novel material preparation, modification of encapsulation strategies, and implementing nano, micro, and macro technologies. Additionally, the keyword analysis showed that Phase change material, Phase change materials, Thermal energy storage, Mechanical properties, Thermal Properties, Microstructure, and compressive strength were the top co-occurred author keywords.

Bortoluzzi, Correia de Souza and Furlan (2021) conveyed research to identify patterns in the use of key performance indicators (KPI) and multicriteria decision-making models (MCDM/A) in the field of renewable energy technologies (RET) by bibliometric review techniques of 142 papers selected from the Web of Science database. The results showed that the important role of MCDM/A models is in achieving the Sustainable Development Goals present in the 2030 United Nations Agenda. Moreover, the results suggested implications in other areas of study by identifying political and technical aspects beyond the already known Triple Bottom Line (TBL). Policymakers and managers can be guided by the main KPI and MCDM/A categorized by this research analysis.

In conclusion, no studies were found in the gas turbine thermal management field. It is concluded that the research originality and novelty of the present study consider using various techniques simultaneously by VOSViewer software, visualizing based on the density of clusters, SNA, and HC. Moreover, the study contains an interdisciplinary background and context in the gas turbine thermal management field.

Materials & Methods

Data gathering & data cleaning

The research community includes all the keywords extracted from all documents in Scopus during 1919-2020 as all documents in English. The database search via a researcher-made query including prominent words and phrases related to the field in advance search in title, abstract, and keyword (TITLE-ABS-KEY) fields on February 8th, 2021 in Scopus:

TITLE-ABS-KEY ("Thermal management" OR "Thermal management system*" OR "Thermal load*" OR "Thermal load management" OR "Heat load*" OR "Lubrication system*" OR "Oil system*" OR "Oil cooling" OR "Oil*cooled" OR "Fuel*oil system" OR "Fuel*cooled" OR "Fuel cooling" OR "Secondary air system*" OR "SAS" OR "Cooler" OR "Air cooling" OR "Air*cooled" OR "Cooling" OR "Cooling system*" OR "Blade cooling" OR "Turbine blade cooling" OR "Internal cooling" OR "External cooling" OR "Film cooling" OR "Heat source*" OR "Heat sink*" OR "Heat transfer" OR "Heat soakage" OR "Heat exchange" OR "Heat exchanger*") AND TITLE-ABS-KEY ("gas turbine*" OR "turbo*jet" OR "jet engine*" OR "turbo*prop*" OR "aircraft engine*" OR "gas turbine engine*" OR "industrial gas turbine*" OR "turbo*fan" OR "turbo*shaft" OR "Full*electric propulsion" OR "All*electric propulsion" OR "Electrified*propulsion" OR "More*electric propulsion" OR "Hydrogen*powered propulsion" OR "Mini* jet engine*" OR "micro*jet engine*" OR "small jet engine*" OR "aero*engine*" OR "marine gas turbine engine*" OR "airplane engine*" OR "aircraft propulsion" OR "hybrid*electric propulsion" OR "parallel hybrid*electric propulsion" OR "series hybrid*electric propulsion" OR "Geared*turbofan" OR "Rotorcraft engine*" OR "Aircraft thruster" OR "Aircraft propulsor" OR "Heavy duty gas turbine*" OR "Marine propulsion") AND (EXCLUDE (PUBYEAR , 2021)) AND (LIMIT-TO (LANGUAGE , "English"))

As a result, 18674 documents were retrieved. After reviewing the index keyword column, 1706 documents did not include keywords that were removed. On the other side, in comparison with the author keyword column, 12774 were blank. As a result, for the final analysis, there were 16968 documents for the index keywords and 5900 documents for the author keywords. Moreover, the keyword column was unmixed, refined, and cleaned. Singular and compound words were converted into a singular form. The final data from this section led to answering the first question.

Main clusters by co-word analysis

The general links between concepts in clusters can be visualized by using VOSViewer software. The data exported from Scopus, including both columns, namely author keywords (keywords have been assigned and written by authors on the papers) and index keywords (indexers have selected keywords for the papers in Scopus). The threshold value in the software to the test and error was considered ≥ 5 co-occurrence for both author and index keywords. For the column of author keywords and the threshold value ≥ 5, out of a total occurrence of 2000 keywords (of the 47004 keywords, 6831 meet the threshold), forming 7 main clusters. Furthermore, for the index keywords and the threshold value ≥ 5, out of a total occurrence of 706 keywords (of the 11723 keywords, 706 meet the threshold), which resulted in the formation of 20 main clusters. The data from this section led to answering the second and third questions.

Hierarchical clustering

Some techniques, such as hierarchical clustering (HC), can be used for co-word analysis. The dendrogram diagram is represented by the hierarchical clustering technique, focusing on Ward's method, and Squared Euclidean distance. Hierarchical relationships between words in clusters can be represented by mappings in SPSS software,Version 22 (Statistics, 2013), and it is helpful to answer the fourth question.

Social network analysis

In a strategic diagram, the x-axis indicates centrality, and the y-axis stands for density. The strategic diagram includes four quadrants containing various degrees of density and centrality. High centrality indicates that the cluster is more important in the field. As shown in figure 1, quadrant I includes mature clusters placed at the core of the field due to high centrality and density (Hu, Hu, Deng & Liu, 2013). In other words, they have powerful internal correlation and maturation and stand in an expanded and powerful relation with other clusters.

Moreover, quadrant II, known as well-developed but isolated clusters, represents low centrality and high density contain clusters that are not central but well-developed. This implies that these clusters are not axial but are developing (Khasseh et al., 2017). The clusters located in quadrant III include low centrality and low density. It indicates marginal topics (emerging/declining themes) with little attention. They have a relatively discontinuous structure and are underdeveloped. Quadrant IV includes central clusters that are not developed. They are central but immature due to high centrality and low density (Hu et al., 2013). Finally, a square matrix (co-occurrence matrix) and a correlation matrix were created based on the number of keywords for each cluster. Then, each cluster's centrality and density were measured using UCINet (Borgatti, Everett & Freeman, 2002) software, and a strategic diagram was drawn by SPSS software, leading *to answering the fifth question.*

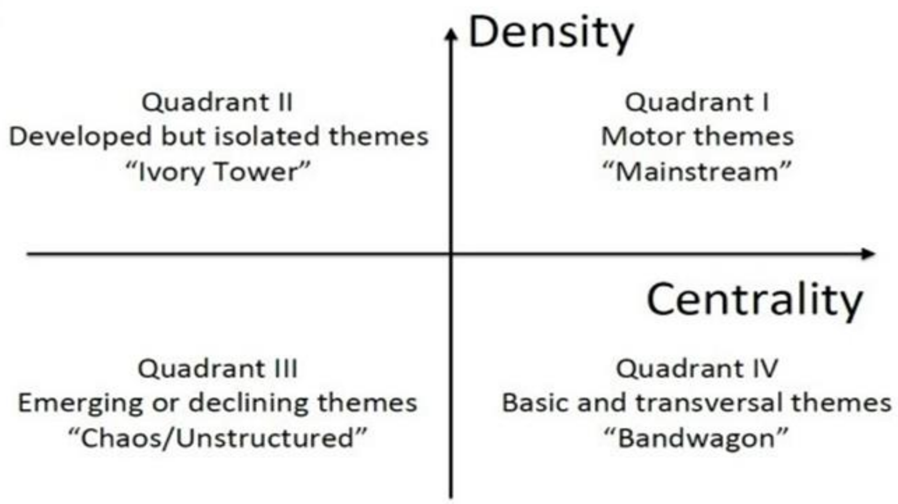

Figure 1: Quadrants in a Strategic Diagram (Afgan & Bing, 2021)

Results

What are the top scientific productions in the gas turbine thermal management field in terms of document, affiliation, funder, publication year, author, country, and subject area?

Table 1
Top scientific productions in the field of gas turbine thermal management from Scopus

Document Type	Conference Paper (10668/ 57.12%)	Article (6987/ 37.41%)	Conference Review (441/ 2.36%)	Review (249/ 1.33%)	Book Chapter (136/ 0.72%)
Top Affiliation	Rolls-Royce plc (356/ 2.64%)	NASA Glenn Research Center (336/ 2.49%)	Texas A&M University (325/ 2.41%)	University of Oxford (318/ 2.36%)	Università degli Studi di Firenze (286/ 2.12%)
Funder	National Natural Science Foundation of China (615/ 20.53%)	Engineering and Physical Sciences Research Council (EPSRC) (149/ 4.97%)	U.S. Department of Energy (130/ 4.34%)	National Aeronautics and Space Administration (NASA) (112/ 3.73%)	Fundamental Research Funds for the Central Universities (89/ 2.97%)
Subject Area	Engineering (15673/ 47.61%)	Energy (4408/ 13.39%)	Physics and Astronomy (2226/ 6.76%)	Chemical Engineering (1653/ 5.02%)	Materials Science (1401/ 4.25%)
Publication Year	2017 (979/ 4.68%)	2019 (975/ 4.67%)	2018 (882/ 4.22%)	2015 (826/ 3.95%)	2020 (825/ 3.95%)
Author	Han, J.C. (241/ 3.72%)	Thole, K.A. (182/ 2.81%)	Facchini, B. (163/ 2.52%)	Bogard, D.G. (111/ 1.71%)	Wittig, S. (110/ 1.70%)
Country	USA (5788/ 27.27%)	China (1803/ 8.49%)	United Kingdom (1721/ 8.11%)	Germany (1467/ 6.91%)	Italy (1040/ 4.90%)

Figure 2 shows the number of documents published in gas turbine thermal management in the last century. The trend of the number of documents is pretty aligned with the historical progress in the development of thermal management systems design, development, and optimization for aerospace applications, as discussed in the literature (Ganev & Koerner, 2013; Huang, Spadaccini & Sobel, 2002). Specifically, there are three main milestones in the figure as follow:

1960: the first change in the slope of figure 2 can be noticed around 1960. This was the start date of the pioneering work phase when theoretical studies and embodiments' presentations were undertaken. This period took two decades and resulted in the generation of the main ideas for the aerospace TMS architecture design (Jafari et al., 2017).

1980: the following slope change in figure 2 is around 1980 when, due to literature (Jafari & Nikolaidis, 2018), the second phase of TMS progress was started to integrate TMS for engine and airframe. So, the number of research studies is increased dramatically to address several research questions and practical challenges in integration airframe/engine TMS architecture design and development.

2000: the last milestone is around 2000, which is the start of the detailed design phase in TMS design when several comprehensive studies started being published addressing thorough testing and real applications of new advanced structures for the TMS, fuel temperature control in TMS, and using different cooling fluids.

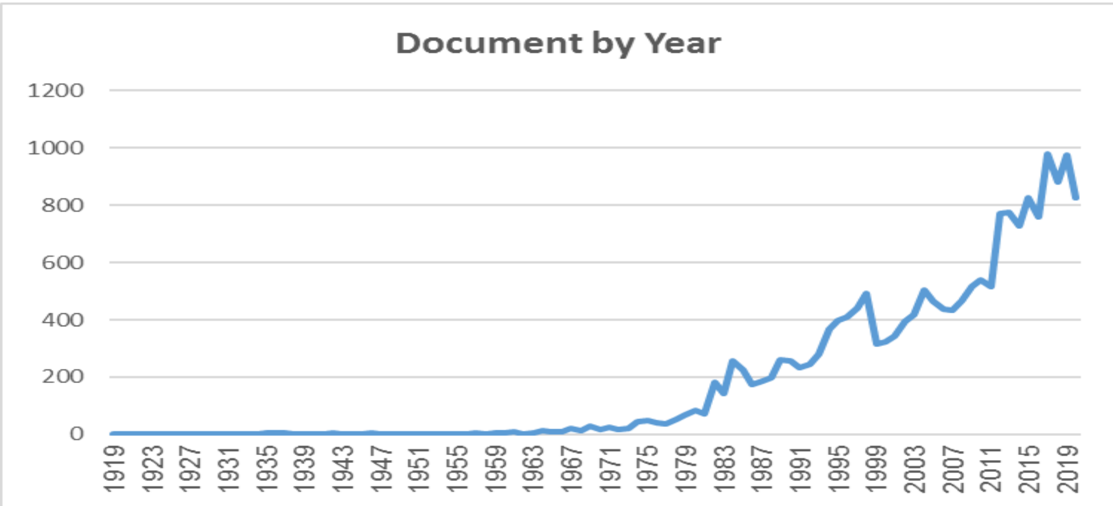

Figure 2: Documents by year in the field of gas turbine thermal management during 1919-2020 from Scopus

How is the intellectual structure of gas turbine thermal management analyzed in terms of the network structure and thematic clusters for the index keywords based on co-occurrence? What is their status in terms of frequency, link numbers, and total link strength?

The final output using algorithms and analysis by VOSViewer software generally includes seven main clusters, including 2000 keywords (selected items), 179573 co-occurrences, 2297608 total link strength, and 680544 links. Table 2 indicates the information on 10 high-frequency keywords of each cluster.

Table 2
High co-occurrence index Keywords in 7 Main Clusters from VOSViewer Software

The first cluster: 683 keywords/ total co-occurrences: 53451/ links: 246033/ total link strength :721116				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	heat exchangers	1335	1747	15502
2	cooling systems	1315	1731	16045
3	turbine	1004	1781	15246
4	compressors	820	1323	8983
5	efficiency	805	1441	10425
6	waste heat	785	1195	11861
7	temperature	699	1459	9216
8	design	675	1573	8848
9	optimization	658	1341	7750
10	thermodynamics	642	1248	7533
The second cluster: 661 keywords/ total co-occurrences: 71325/ links: 234070/ total link strength :945140				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	heat transfer	5545	1954	59184
2	cooling	4161	1969	50752
3	turbomachine blades	2645	1747	33164
4	reynolds number	1991	1416	26460
5	computational fluid dynamics	1887	1719	24655
6	turbine components	1540	1608	20581
7	aerodynamics	1013	1445	12528
8	coolants	997	1291	12709
9	heat transfer coefficients	942	1184	12659
10	film cooling	741	1059	8867
The third cluster: 497 keywords/ total co-occurrences: 33401/ links: 144755/ total link strength :374777				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	aircraft engines	2321	1810	24733
2	engines	1586	1824	19438
3	turbomachinery	1133	1813	15858
4	mathematical models	677	999	5912
5	fighter aircraft	476	1196	5878
6	finite element method	363	912	3890
7	machine design	357	970	3908
8	propulsion	355	1042	3807
9	temperature distribution	344	897	3576
10	rotors	335	745	3488
The fourth cluster: 147 keywords/ total co-occurrences: 13031/ links: 50946/ total link strength :162048				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	combustion	1600	1711	19934
2	combustors	1344	1574	15610
3	computer simulation	926	1447	9619
4	combustion chambers	517	1352	6907
5	air	464	1368	6147
6	operating condition	392	1324	5282
7	fuel	365	1099	5131
8	gas turbine combustor	282	883	3682
9	drops	275	917	3753
10	nitrogen oxides	253	745	2910

Table 2. Cont.
High co-occurrence index Keywords in 7 Main Clusters from VOSViewer Software

The fifth cluster: 8 keywords/ total co-occurrences: 8088/ links: 3239/ total link strength :90971				
Rank	Keyword	Co-occurrence	Link	Total Link Strength
1	gas turbine	7741	1966	87418
2	blade	83	267	809
3	films	75	212	741
4	calculations	66	261	694
5	correlation methods	52	242	557
6	thermal variables measurement	42	181	450
7	crossflow	29	110	302
8	gas turbine	7741	1966	87418
The sixth cluster: 3 keywords/ total co-occurrences: 115/ links: 802/ total link strength :1530				
Rank	Keyword	Co-occurrence	Link	Total Link Strength
1	coolant temperature	48	312	673
2	temperature and pressures	45	310	546
3	turbine cooling systems	22	180	311
The seventh cluster: 1 keywords/ total co-occurrences: 162/ links: 699/ total link strength :2026				
Rank	Keyword	Co-occurrence	Link	Total Link Strength
1	ionization of gas	162	699	2026

According to the semantic concepts in the clusters and based on the views of experts, these five main clusters were named (Table 3).

Table 3
Names of the 5 main clusters for index keywords

Cluster	***Name***
The 1st cluster	Heat Map Development
The 2nd cluster	Secondary Air System
The 3rd cluster	Thermal Models Development
The 4th cluster	Combustion and Emission Considerations
The 5th cluster	Heat Flux Correlation Development
The 6th cluster	Architecture Design and Coolant Selection
The 7th cluster	Ionization of Gas

Figure 3 shows the *network structure* in the gas turbine thermal management field, including 2000 high co-occurrence keywords that are visualized using VOSViewer (Version 1.6.16.) As shown in Figure 3, the network consists of seven main clusters in different colors.

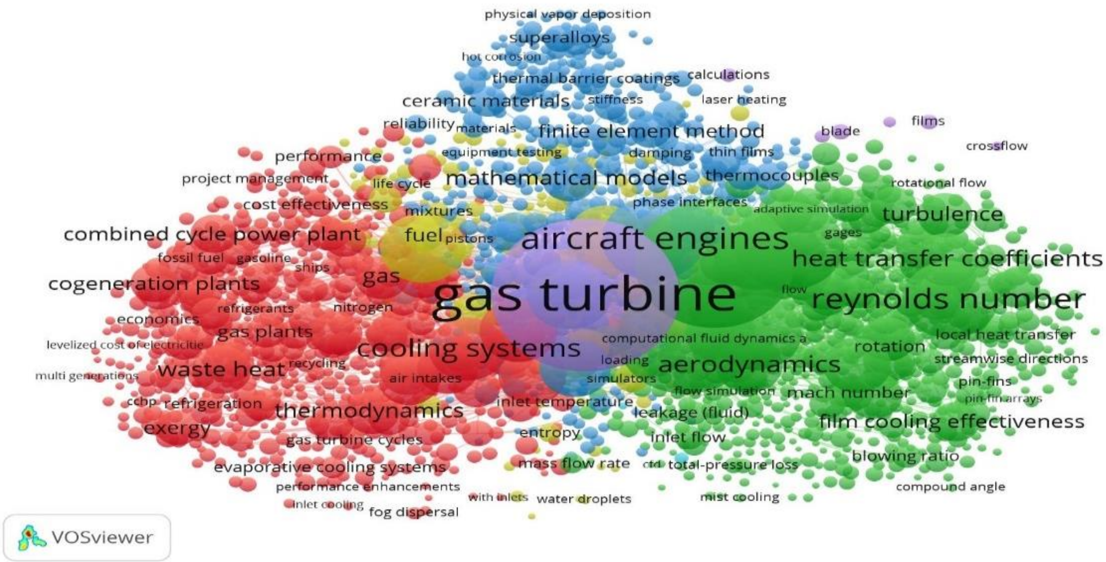

Figure 3: The Network Structure of the index keywords in the field of gas turbine thermal management by using VOSViewer Clustering

Figure 4 illustrates the *Overlay visualization* of the network in this field. The colors of this map are determined by their weight in the network. Blue has the lowest score, green indicates the average, and yellow has the highest score. It means that movement from blue to yellow indicates the greater score and the importance of the keyword in the network (Van Eck & Waltman, 2018). A color bar is drawn in the bottom right corner of the visualization in figure 4. The color bar is shown if scores of items determine only colors. Changes have been seen from low weight to high from 2006 to 2014. The year 2014 has more weight and importance in the network and includes more relevant and prominent keywords in the field.

The gas turbine TMS utilizes engine fluids as heat sinks to transfer excess heat from the engine heat sources. Due to the increasingly complex design of gas turbine engines and the severe regulations set by organizations for environmental considerations, there are limitations and constraints in the state-of-the-art of TMS design and implementation, including the volume and weight of the components and architecture, temperature, pressure limitations, etc. These constraints limit the heat sink capacity of the TMS and highlight the requirement for a smart, optimized TMS design for modern GTEs. In addition, an optimized TMS should enhance engine performance by using the engine's excess heat rather than wasting it. That’s why the development of detailed physics-based mathematical models concentrated on advanced topics like film cooling effectiveness, techno-economic risk analysis, novel cycles, two-phase cooling, and refrigeration are becoming more popular during the last decades, as shown in figure 4.

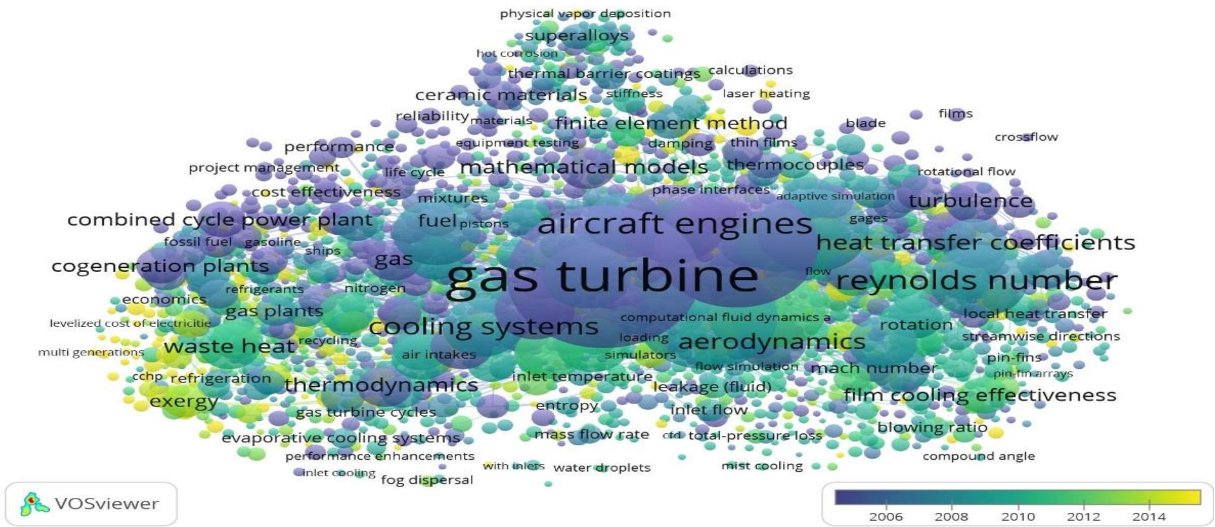

Figure 4: Overlay visualization of the index Keyword Network in the field of gas turbine thermal management from VOSViewer Software

How is the intellectual structure of gas turbine thermal management analyzed in terms of the network structure and thematic clusters for the author keywords based on co-occurrence? What is their status in terms of frequency, link numbers, and total link strength?

In general, the final output using algorithms and analyzing by VOSViewer software includes 20 main clusters, 706 keywords (selected items), 11102 co-occurrences, 24542 total link strength, and 14046 links. Table 4 indicates the information of 10 high-frequency author keywords of each cluster**.** According to the clusters' semantic concepts and based on the views of experts, these 20 main clusters were named and labeled as represented in Table 5. Moreover, Figure 5 shows the network structure in the gas turbine thermal management field, including 706 high co-occurrence author keywords that are visualized by utilizing VOSViewer (Version 1.6.16.) As shown in Figure 5, the network consists of 20 clusters in different colors.

Table 4
High co-occurrence author Keywords in 20 Main Clusters from VOSViewer Software

The 1st cluster: 151 keywords/ total co-occurrences: 2606/ links: 3737/ total link strength :5888				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	optimization	124	141	261
2	exergy	118	133	362
3	combined cycle	110	107	258
4	cogeneration	95	111	223
5	organic rankine cycle	72	87	191
6	solid oxide fuel cell	70	86	164
7	exergy analysis	63	74	131
8	micro gas turbine	62	75	108
9	inlet air cooling	55	56	122
10	biomass	48	61	154

The 2nd cluster: 110 keywords/ total co-occurrences: 1194/ links: 1533/ total link strength :2148				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	thermal barrier coating	82	77	148
2	turbine blade	76	86	174
3	microstructure	34	41	57
4	modeling	32	60	76
5	thermal barrier coating	30	35	50
6	finite element analysis	29	35	54
7	blade	27	50	84
8	oxidation	27	31	49
9	numerical analysis	26	34	59
10	additive manufacturing	23	22	29
The 3rd cluster: 73 keywords/ total co-occurrences: 1352/ links: 1553/ total link strength : 3070				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	heat transfer	409	276	947
2	heat transfer enhancement	71	63	171
3	internal cooling	57	61	137
4	turbulence	41	48	99
5	gas turbine cooling	39	37	66
6	convective heat transfer	32	41	65
7	piv	30	33	75
8	48usselt number	28	48	72
9	pressure drop	25	30	57
10	gas turbine blade cooling	23	18	31
The 4th cluster: 62 keywords/ total co-occurrences: 12601/ links: 1339/ total link strength :2895				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	film cooling	361	186	819
2	numerical simulation	100	86	177
3	conjugate heat transfer	95	81	172
4	gas turbine blade	67	72	142
5	film cooling effectiveness	48	46	105
6	cooling effectiveness	40	43	96
7	blowing ratio	37	40	101
8	turbine blade cooling	29	39	54
9	leading edge	23	39	79
10	endwall	22	35	77

Table 4. Cont.
High co-occurrence author Keywords in 20 Main Clusters from VOSViewer Software

The 5th cluster: 55 keywords/ total co-occurrences: 666/ links: 889/ total link strength :1314				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	heat exchanger	81	102	181
2	combustion	63	65	117
3	computational fluid dynamics	55	72	117
4	large eddy simulation	27	29	53
5	aero engine	23	31	54
6	combustion instability	18	12	18
7	experiment	18	37	44
8	centrifugal compressor	17	16	22
9	adiabatic effectiveness	16	23	38
10	aircraft	15	16	19
The 6th cluster: 38 keywords/ total co-occurrences: 481/ links: 899/ total link strength :1423				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link strength**
1	efficiency	88	122	284
2	energy	43	69	152
3	compressor	32	54	89
4	steam turbine	30	53	91
5	design	21	29	40
6	combustion chamber	20	39	57
7	power	18	40	70
8	hydrogen production	16	28	35
9	temperature	16	44	73
10	fuel	10	25	31
The 7th cluster: 38 keywords/ total co-occurrences: 515/ links: 692/ total link strength :1024				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	cooling	87	127	251
2	heat transfer coefficient	48	61	100
3	gas turbine engine	47	65	86
4	aeroengines	34	42	56
5	aircraft engine	27	32	37
6	discharge coefficient	26	27	47
7	jet impingement	19	18	25
8	secondary air system	17	19	29
9	gas turbine heat transfer	15	14	23
10	rotating	14	19	35
The 8th cluster: 32 keywords/ total co-occurrences: 338/ links: 544/ total link strength :778				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	simulation	38	63	88
2	performance	33	51	81
3	heat recovery steam generator	32	44	87
4	computational fluid dynamics (cfd)	20	22	45
5	thermal efficiency	19	35	41

6	supercritical carbon dioxide	14	29	36
7	bottoming cycle	12	23	29
8	gas-steam combined cycle	10	11	21
9	entropy generation	8	10	10
10	environment	7	14	18

Table 4. Cont.
High co-occurrence author Keywords in 20 Main Clusters from VOSViewer Software

The 9th cluster: 28 keywords/ total co-occurrences: 492/ links: 587/ total link strength :1064				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	cfd	174	155	404
2	combustor	32	52	82
3	power augmentation	26	24	58
4	high temperature	24	25	29
5	gas turbine combustion	23	15	23
6	modelling	23	39	56
7	emissions	20	26	36
8	wet compression	20	21	44
9	fogging	19	27	49
10	water injection	17	32	52
The 10th cluster: 17 keywords/ total co-occurrences: 1143/ links: 773/ total link strength :2505				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	gas turbine	947	480	2064
2	evaporative cooling	24	25	45
3	turbine cooling	23	38	49
4	air cooling	22	24	48
5	steam cooling	20	30	55
6	transpiration cooling	19	22	35
7	intercooling	13	25	34
8	reheat	13	31	44
9	recuperation	11	21	29
10	gas turbine performance	10	16	18
The 11th cluster: 16 keywords/ total co-occurrences: 168/ links: 241/ total link strength :359				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	cooling system	21	23	38
2	jet engine	19	29	37
3	thermodynamics	19	43	58
4	mass transfer	18	24	41
5	les	17	23	43
6	thermal radiation	13	19	34
7	naphthalene sublimation	11	12	24
8	radiation heat transfer	8	10	11
9	computational fluid dynamic	6	10	15
10	electric aircraft	6	5	5
The 12th cluster: 16 keywords/ total co-occurrences: 134/ links: 199/ total link strength :311				

Rank	Keyword	Co-occurrence	Link	Total Link Strength
1	impingement cooling	42	42	95
2	impinging jet	10	14	18
3	full-coverage film cooling	7	15	23
4	numerical	7	10	11
5	thermal protection	7	15	19
6	vortices	7	16	26
7	combustor liner	6	20	24
8	heat transfer augmentation	6	7	14
9	jets	6	10	17
10	pin fins	6	12	15

Table 4. Cont.
High co-occurrence author Keywords in 20 Main Clusters from VOSViewer Software

The 13th cluster: 16 keywords/ total co-occurrences: 151/ links: 206/ total link strength :374				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	blade cooling	44	59	105
2	thermoeconomics	11	15	23
3	coal gasification	10	12	13
4	cost of electricity	8	16	24
5	exergetic efficiency	8	15	17
6	exergoeconomics	8	15	24
7	hybrid cycle	8	10	17
8	hybrid plants	8	8	25
9	air film cooling	7	11	15
10	total cost rate	7	14	19
The 14th cluster: 15 keywords/ total co-occurrences: 172/ links: 230/ total link strength :356				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	recuperator	26	38	60
2	turbomachinery	23	38	56
3	aeroengine	21	25	33
4	unsteady flow	19	20	43
5	hot streak	14	12	26
6	intercooler	14	21	29
7	rotating cavity	9	7	12
8	urans	9	11	20
9	buoyancy	6	7	12
10	small gas turbine	6	4	5
The 15th cluster: 13 keywords/ total co-occurrences: 118/ links: 235/ total link strength :316				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	convection	15	35	52
2	boundary layer	13	16	25
3	regenerator	13	23	28
4	rans	12	33	44
5	radiation	10	18	29
6	transition	10	16	24
7	stirling engine	9	17	19

8	heat exchange	8	16	16
9	conduction	7	12	17
10	cht	6	14	21
The 16th cluster: 10 keywords/ total co-occurrences: 190/ links: 248/ total link strength :483				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	turbine	97	132	265
2	forced convection	36	46	91
3	fluid dynamics and heat transfer phenomena	10	10	23
4	measurement techniques	10	14	28
5	unsteady	8	13	17
6	flow transition	7	4	12
7	heat transfer and film cooling	7	12	18
8	infrared	5	8	11
9	transonic	5	2	6
10	wakes	5	7	12

Table 4 Cont.
High co-occurrence author Keywords in 20 Main Clusters from VOSViewer Software

The 17th cluster: 8 keywords/ total co-occurrences: 52/ links: 71/ total link strength :84				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	vibration	11	16	16
2	working fluid	8	8	15
3	irreversibility	6	15	16
4	labyrinth seal	6	6	6
5	stability	6	8	8
6	closed cycle gas turbine	5	5	9
7	flutter	5	3	3
8	numerical study	5	10	11
The 18th cluster: 4 keywords/ total co-occurrences: 42/ links: 46/ total link strength :114				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	film-cooling	25	24	61
2	cylindrical hole	6	8	18
3	dilution hole	6	7	19
4	trench hole	5	7	16
The 19th cluster: 2 keywords/ total co-occurrences: 13/ links: 7/ total link strength :13				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	temperature measurement	8	6	9
2	thermal history sensor	5	1	4
The 20th cluster: 2 keywords/ total co-occurrences: 15/ links: 17/ total link strength :23				
Rank	**Keyword**	**Co-occurrence**	**Link**	**Total Link Strength**
1	uncertainty quantification	10	14	20
2	proper orthogonal decomposition	5	3	3

Table 5

Names of the20 main clusters for author keywords

Cluster	***Name***
The 1st cluster	Novel Cycles
The 2nd cluster	Advanced Manufacturing
The 3rd cluster	Heat Flux Correlation Development
The 4th cluster	Secondary Air System
The 5th cluster	Heat Sources and Sinks
The 6th cluster	Alternative Fuels
The 7th cluster	Integration and System Architecture Design
The 8th cluster	Thermal Models Development
The 9th cluster	Combustion and Emission Considerations
The 10th cluster	Advanced Cooling Mechanisms for High Heat Fluxes
The 11th cluster	Radiation Effects
The 12th cluster	Heat Exchangers
The 13th cluster	Techno-economic Analysis
The 14th cluster	Fluid Modelling
The 15th cluster	Boundary Layer
The 16th cluster	Heat Loads Measurement
The 17th cluster	Stability Analysis
The 18th cluster	Turbine blade Cooling
The 19th cluster	Heat Map Development
The 20th cluster	Uncertainties and Implementation Considerations

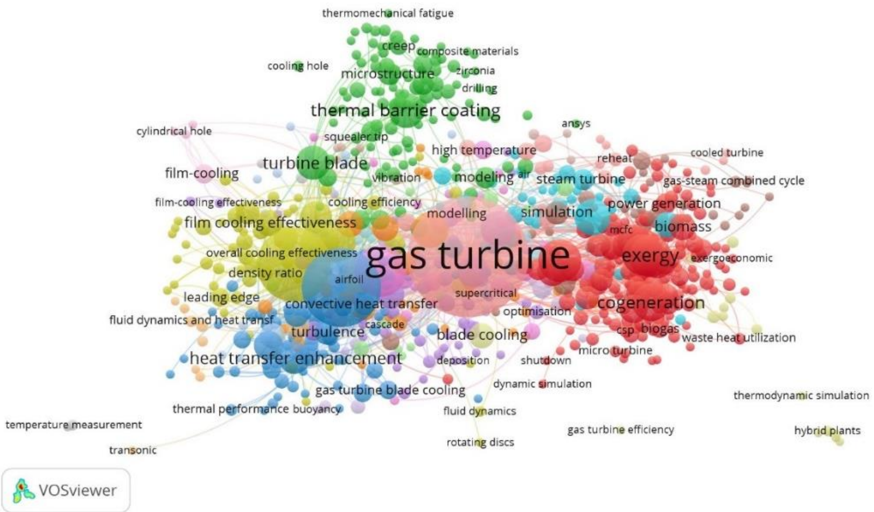

Figure 5: The Network Structure of the author keywords in the field of gas turbine thermal management by using VOSViewer Clustering

Figure 6 illustrates the Overlay visualization of the network in this field based on the author's keywords. Changes have been seen from low weight to high from 2008 to 2016. The year 2016 has more weight and importance in the network and includes more relevant and prominent keywords in the field. The overlay visualization of the author's Keyword Network shown in Figure 6 illustrates the importance of advanced topics in developing the gas turbine thermal management field during the last decade. Like Figure 4, film cooling effectiveness and thermodynamic simulation are the main elements of this figure. This figure also highlights the more advanced topics related to recent development in propulsion systems like alternative fuels and electrified propulsion systems.

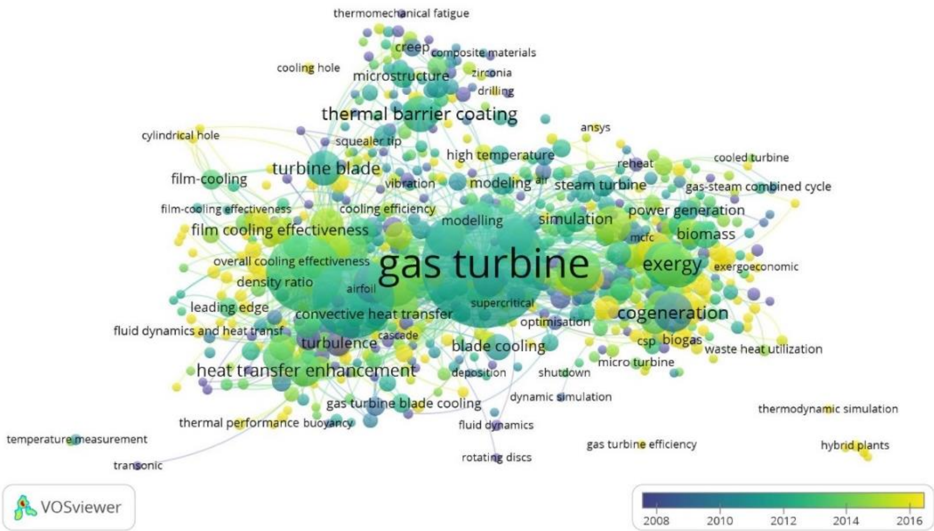

Figure 6: Overlay visualization of the author Keyword Network in the field of gas turbine thermal management from VOSViewer Software

How is the intellectual structure of gas turbine thermal management analyzed in terms of top co-word pairs, co-occurrence matrix, and hierarchical clustering (HC)?

The analysis of this question focuses **only on the author's keywords**. Due to the excessive volume of data (keywords) to answer this question, only the keywords of the author column are used. However, we also had to create a time series to reduce this column's data. On this line, the software could process the data to export adjacency matrices as co-occurrence square matrices. Therefore, the data of these hundred years were divided based on the output volume of the square matrices to the periods, including 1919-2000, 2001-2010, 2011-2015, and 2016-2020. A code exported the matrices in the NumPy and Panda libraries in Python (version 2.7) (Rossum, 1995) As a result, the total numbers of co-words of all the scientific outputs from WOS were recorded in square matrices in Excel files. Table 6 implies top and high-frequency co-word pairs in various time series. Table 7, table 8, table 9, and table 10 indicate labels of the identified clusters based on the Hierarchical clustering as depicted in the appendix (Figure A1-A4).

Table 6
Top and High Frequency Co-Word Pairs in the Field

Time series	*The Square Matrix*	*Ten Top Co-occurrence of keywords*
1919-2000	916*916	Gas turbine* Gas turbine (83)
		heat transfer* heat transfer (36)
		forced convection* forced convection (21)
		turbine* turbine (20)
		film cooling* film cooling (19)

Time series	*The Square Matrix*	*Ten Top Co-occurrence of keywords*
		Gas turbine* heat transfer (12)
		Combustion*combustion (11)
		Gas turbine*film cooling (11)
		Cogeneration*cogeneration (10)
		Turbine*forced convection (9)
2001-2010	3966*3966	Gas turbine* Gas turbine (273)
		Heat transfer*Heat transfer (125)
		Film cooling*Film cooling (94)
		CFD*CFD (38)
		thermal barrier coating* thermal barrier coating (47)
		Turbine*Turbine (40)
		Cogeneration* cogeneration (38)
		Cooling*Cooling (36)
		combined cycle* combined cycle (34)
		Optimization* optimization (30)
2011-2015	3853*3853	gas turbine*gas turbine (283)
		film cooling*film cooling (105)
		heat transfer*heat transfer (99)
		Exergy*exergy (44)
		Cfd*cfd (42)
		Efficiency*efficiency (36)
		Optimization*optimization (35)
		conjugate heat transfer*conjugate heat transfer (35)
		heat transfer enhancement*heat transfer enhancement (34)
		combined cycle*combined cycle (34)
2016-2020	6439*6439	gas turbine*gas turbine (404)
		heat transfer*heat transfer (187)
		film cooling*film cooling (172)
		Cfd*cfd (89)
		heat transfer*gas turbine (76)
		numerical simulation*numerical simulation (64)
		Exergy*exergy (62)
		Optimization*optimization (58)
		film cooling*gas turbine (57)
		organic rankine cycle*organic rankine cycle (53)

Table 6 shows changes in high-frequency Co-word pairs in the field. Before 2000, research studies were focused on the fundamentals and rationale behind gas turbine thermal management. Thermodynamic simulations play an essential role in the development and growth of the topic during this period. With the emergence of advanced manufacturing technologies, the studies focused on thermal barrier coating, blade design methods, and CFD analysis between 2000 and 2010. It results in more detailed research on heat transfer coefficient and cooling effectiveness in these new technologies between 2010 and 2015. Finally, the literature last 5 years is replete with ideas on optimization, integration, and novel cycles that could be the game-changer in the gas turbine thermal management systems field.

Table 7
Numbers and Names of the Clusters during 1919-2000 based on Hierarchical Clustering

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
11 clusters during 1919-2000	1	Effects of Fuel Characteristics	inductively coupled plasma, rde aes, aes, gfass, icp, fuel analysis, fuel treatment, comparison of analytical techniques, flaas, atomic absorption spectroscopy, atomic emission spectroscopy, aes rotating disc electrode, analytical procedures, high temperature corrosion
	2	Effects of Thermal Inertia	Sulphates, uns n06603, acidic dissolution, internal corrosion, nickel base alloys, chlorides, fluxing, alloy603gt, basic dissolution, alkali salts, hot corrosion
	3	Waste Heat Recovery	thermophysical properties, waste heat, absorption chiller, stack, system, mathematical expressions, recovery, heatpipe loop, modelling, energy
	4	Heat Transfer Characteristics	surface shear stress, wind tunnel, mechanical engineering, shear stress, surface shear, heat flux, turbo machinery, automotive, liquid crystal, heat transfer coefficient.
	5	Combined Cycles	combustion chamber cooling, reheat, closed loop cooling, combined cycle gas turbine, inter cooling, turbine cooling, air cooling, steam cooling.
	6	Boundary Layer	Optimal operation, system engineering, design engineering, cogeneration, distinct heating and cooling, power plant, compound angle holes, film effectiveness, film cooling, convective heat transfer, boundary layers, blade, two dimensional injection, cascade, super alloy, micro structure, ribs, heat exchangers, blade cooling, combustion, low nox, steam injection, water injection, full cover age film cooling, cooling effectiveness, recuperator, performance, mcraly, economics, cogeneration systems, gasturbine
	7	Heat Sources and Sinks	Vapor pressure, volatility, aerospace lubrication, high temperature lubricants, oxidation - lubr. Degradation, gas turbine oil, gas turbine engine, aviation jet engine, deposition of tribo materials.
	8	Thermal and Fluid Modelling	Stress distribution, thin sheet, buckling, monitoring systems, stress, heat sink, moire fringe techniques, distortion, numerical analysis, aerospace.
	9	Two-phase Cooling	sauter mean diameter, spray coneagle, droplet distribution, impact pinnozzle, relative span, fluid viscosity, free stream air velocity, droplet size, fluid pressure, atomization.
	10	Heat Flux Calculations and Radiation Effects	Forced convection, turbine, flow transition, wakes, turbulence, impingement, swirling, rotating, mass transfer, rotating flow, control, flow, transition, leading edge, periodic wake, unsteady flow, monte carlo method, jet engine, combustion chamber, thermal radiation, cooling blade, heat transfer, turbulent, optimization, turbine blade, multidisciplinary.

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
	11	Heat Map Development and System Architecture Design	Exhaust gas, oxidation behavior, amorphous sio2, crystallization, cvdsic, cogeneration system, dual fluid cycle, efficiency, exergy, process synthesis, steam network, chp, electricity, gasification, energy production, biomass, coal gasification, coal combustion, fossil fuel, pollution, Brayton cycle, energy recovery, power generation, thermos dynamic analysis, co2, combined cycle, part load, steam turbine, heat exchanger, creep, regenerator, heat pipe, thermal efficiency, gas turbine engine, heat transfer enhancement, turbulent flow, flow visualization, internal cooling, vortices, stirling engine, thermal generator, regenerative gas turbine, off peak air conditioning, , aircraft engine, cooling, gear, temperature distribution, thermal barrier coating, cyclic oxidation, tribology, welding, radiative heat transfer, impinging jet.

Table 8
Numbers and Names of the Clusters during 2001-2010 based on Hierarchical Clustering

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
4 clusters during 2001-2010	**12**	Novel Cycles and Disruptive Cooling Technologies	horizontal turbo-machine layout, pre cooler, mass transfer, two phase flow, blowing ratio, leakage, absorption refrigeration, hydrogen production, heat recover system generator, co2 capture, energy saving, finite time thermos dynamics, zirconia, turbine cooling, hybrid system, porous media, turbulence model, film, thermos mechanical fatigue, reliability, aerodynamics, plasma spray, applications, high temperature heat exchanger, external firing, carbon, heat treatment, exergy efficiency, jet engines, liquid metals, smart materials and structures, optimal approximation, galerkin projection, ferroelastic dynamics, von karman vortex street, unsteady interaction, steam film cooling, internal convection cooling, fuel utilization efficiency, post combustion control, surface film, droplets plashing, pressure ratio, after cooling, nickel base super alloy, inlet air cooling, evaporative cooling, pyrometry, unsteady flow, coal, heat carrier, fluidbed combustion, total acid number, online sensors, fluid contamination, oil condition monitoring, steady and unsteady measurements, rotating cascade, correlation, micro combustion, pde, measurement techniques, flow, secondary flows, liquid crystal, combustor exit temperature, droplets diameter, total pressure loss, static pressure recovery coefficient, gas turbine combustion, gas reheater, improving efficiency, gas treatment

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
			combined cycle, Brayton cycle test-loop, Brayton test, streams, material change, displacements, crack length, young's modulus, power cycle, trigeneration_A, combustion chambers, high temperature materials, pche, joule, thermal fatigue, combustion chamber, uncertainties, discharge coefficients, impingement cooling, les, hybrid, preliminary design, fouling, urans, rans, stabilization, efficiency optimization, finite thermal capacity rate, electromagnetic radiation, dual pressure, corrosion, power plant, micro gas turbine_A, concave surface, power optimization.
	13	Thermal Models Development	technologies for two-stage-to-orbit vehicles, optimal trajectories for hypersonic vehicles, flight mechanics and control, convection and conduction, tbc top coats, thermo economics, turbulent combustion, turbo charger, semi closed gas turbine, aircooling_A, cooling efficiency, velocity ratio, film cooling effectiveness_A, adiabatic effectiveness, evaporative after cooling, micro turbojet engine (mte), stability, pemfc, steam rankine cycle, spray deposition, rotating channel, gas turbine heat transfer, aspect ratio, alumina, failure mechanism, waste heat recovery, acoustic absorption, titanium alloys, wear, transpiration, pressure drop loss, microhardness, noise, process simulation, molten carbonate fuel cell, entropy generation, combustion in stability, fuel injection, inlet fogging, droplete vaporation, combined system, film cooling_A, cycle performance, stress analysis, computer modeling, performance enhancement, second law efficiency_A, renewable, heat recovery steam generator (hrsg), gasifier, second law analysis, hat cycle, injected water, spark discharges, global warming, constant temperature, closed cycle, performance matching, power system, linear programming.
	14	Thermal Performance Optimization	Volume fraction, serration, dilatometry, vapeur, systemic absorption, chaleur, cogeneration, closed loop steam cooling, cogeneration_A, centrifugal compressor, power generation, piv, microstructure, aircraft propulsion, genetic algorithm, creep, model reduction, topping cycle, mcfc, radiation, heat flux, organic rankine cycle, flow visualization, conjugate heat transfer, bend, deanvorlex, visualization, separation, compressor station, procurement, piping, fast track, engineering, safety, sufficiency, helium, maintenance, closed bray

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
			tone cycle, combined heat and power, heat recovery, thermal efficiency, thermos dynamic optimization, recuperator, distributed generation, refrigeration, optimization, natural gas, modeling, thermal analysis, grain boundaries, trailing edge, internal cooling, cooling, combustor, thermal barrier coating, simulation, ceramics, combustion, rotation.
	15	Advanced Manufacturing	co2 recovery by liquefaction, deposition, surface curvature, rotating blade, test facility, media, filter, monthly analysis, sofc hybrid, robust control, shrouded turbine vane, secondary flow field, transient, ducts, vacuum brazing, moment methods, frequency averages, colorless combustion, partflow cycle, cogeneration system, crossflow, vacuum freeze drying, parabolic pde, paint injection, heat treatment of coatings, microturbine_B, buoyancy, high rotating number.

Table 9
Numbers and Names of the Clusters during 2011-2015 based on Hierarchical Clustering

Numbers of the Clusters in the Time series	***Number of the cluster***	***Name of the cluster***	***Words in clusters***
14 clusters during 2011-2015	**16**	Operational Considerations	Electric power, boiler recover, gas, compressor, air, gas turbine unit_A, operating mode, pressure, gas turbine unit, coatings, combined cycle power plant_A, efficiency, performance indicator, boiler utilizer, parameters, steam.
	17	Advanced Manufacturing	Rapid quenching, alloy, melt, copper, amorphousalloy, ceramics, nickel.
	18	Advanced Cooling Mechanism and Secondary Air System	synthetic-eddy method, adm, kidney vortex, approximate deconvolution model, double row, les, shower head cooling, aero dynamic loss, turbulence promoting rib, adiabatic film cooling effectiveness, micro film cooling, net heat flux reduction, film cooling, double jet, anti-counter-rotating vortices, jet interaction phenomena, tlc measurement, full cover age film cooling, heat transfer coefficient, cooling effectiveness, adiabatic effectiveness, tlc, cooling efficiency.
	19	Stability Analysis	Solid rotor, api, rotor dynamics, magnetic bearings, high speed, direct drives.
	20	Novel Cycles	simple and combined cycle efficiency, 450 scenario, operational flexibility, hybrid cycles, fuel flexibility, igcc.
	21	Integration with Control System	Smart nodes, data concentrators, redundancy management, ht electronics, fadec.

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
	22	Advanced Measurement Techniques	Turbine cavity, dynamic temperature measurement, strut, optical fiber temperature measurement, temperature field, flow field.
	23	Thermal Models and Correlations Development	Reduced order modelling, numeric, integro-differential equations, radiative heat transfer.
	24	Fluid Modelling and Techno-economic Analysis	Cooling system, synchronous generator, more electrical engine, forced convection, rotor casting, transonic turbine, thermal stress, convection, heat transfer, Reynolds number, Coriolis force, rough surfaces, unsteady flow, endwall cooling, rib turbulator, computational fluid dynamics (cfd), vortices, impingement cooling, heat transfer enhancement, flow, pin fin, friction factor, upstream leakage, purge flow, secondary flow, thermal conductivity, fluent, wake, convection cooling, thermal analysis, impingement, leakage flow, numerical simulation, tip wall, eddy viscosity, rans solver, Coriolis, trailing edge, secondary system, pressure recovery, internal air system, separation, gas turbine blade cooling, gas turbine heat transfer, tip clearance, turbulence, finite volume, backward facing step, flow control, turbine vane, experiment, blade trailing edge, blade leading edge, radial deformation, scanning electron microscopy (sem), fan blade, dimple rupture, finite elements, micro structural stability, ad730, cooling rate, disk, friction, bearing, seal, waste, district, heating, micro gas turbine, phase change material, energy flow, heat loss, tetrafluoro methane, closed cycle gas turbine, organic rankine cycle, single shaft gas turbine, co2, oxy fuel, jet engine_A, cooling fluid, control, vortex breakdown, flow instabilities, ammonia-water mixture, gtmhr, cooled gas turbine, combined cycle, combined heat and power, optimization, noise, acoustics, engine, air craft engine, thermal paints, thermal history sensor, intercooling, regeneration, reheat, porous media, aero engine_A, lubrication, photo voltaic, microgasturbine_B, absorption heat pump, cchp system, micro gas turbine_A, steam cycle, waste heat, oxidation, oxides, thermal stability, flng, specific thrust, cascade waste heat recovery, particles warm optimization, gas turbine engine, gthtr300, power unit, improving power, desiccant cooling, discrict heating, economic analysis, biofuel, fuel cell, chp, high pressure, high temperature, fuel-lubricating oil heat exchanger, centrifugal compressors, methodology, casting, thermal barrier coating (tbcs), distributed combustion, gas turbine combustion, finite time thermodynamics, turbo charger, gas turbine gt, flame let model, penetration, control

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
			method, diffusion flame, tbc, distributed energy system, emission, compact heat exchanger, propulsion, mode transition, deformation, solar, energy conservation, jet engine, energy saving, jet impingement cooling, power generation, exergy analysis, cost of electricity.

Table 9 Cont.

Numbers and Names of the Clusters during 2011-2015 based on Hierarchical Clustering

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
14 clusters during 2011-2015	**25**	Thermal Performance Analysis	Variable heat-to-power ratio, profitability, networks, heat load following, fixed heat to power ratio, distributed energy systems, operating strategy, greenhouse gas emission.
	26	Combustion and Emission Considerations	Reforming, high-temperature heat exchangers, topping cycle, emissions control, pre combustion control, carbon capture, steam turbine, hrsg.
	27	Alternative Fuels	Vam, carbon credits, methane mitigation, ghg, coal mine methane, ventilation.
	28	Hybrid Cycles	Spher, direct absorption, solar simulator, Brayton cycle, concentrated solar power, cylindrical hole, dilution hole, trenched holes, cooling hole, gasturbine, naphthalene sublimation, internal cooling, piv, liquid crystals, rib, density ratio, leading edge, double swirl chambers, evaporative cooling, inlet air cooling_A, hat cycle, humidification, friction characteristics, rectangular channel, thermal storage, concentration solar power, solid oxide fuel cell, distributed generation, power plant, nusselt number, porous coating, multi objective optimization_A, blade cooling, humid air, evaporative cooler, single phase flow, emissions, exergoeconomic analysis, renewable energy, natural gas pressure drop station, steam injection, wet compression, power augmentation.
	29	Heat Exchangers and Turbine Blade Cooling	Inorganic fibres, alumina, fire performance, ceramic fibres, silicon carbide, super critical carbon dioxide, genetic algorithm, exergy, ejector, Brayton, bio mass gasification, exergy destruction, absorption refrigeration, natural gas, sewage sludge, biogas, gasification, gt, cogeneration, air heat exchanger, turbine blade cooling, industrial turbomachinery, air cooling, tiptiming, transpiration cooling, turbine cooling, cycle performance, regenerative, thermos dynamic analysis, sofcgt, chemical absorption, guidevane, distortion, dome, leakage performance, fuzzy logic, modelling, energy storage, hot corrosion, thermal barrier coating, thermos mechanical fatigue,

Numbers of the Clusters in the Time series	***Number of the cluster***	***Name of the cluster***	***Words in clusters***
			stress analysis, off design performance, cchp, operation strategy, solar energy, thermos dynamic optimization, sensitive analysis, coal, turbine inlet temperature, fault detection, district cooling, energy efficiency, ethanol, heat integration, fluid flow, hydrogen, regenerator, condensation, heat exchanger.

Table 10
Numbers and Names of the Clusters during 2016-2020 based on Hierarchical Clustering

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
9 clusters during 2016-2020	30	Performance Analysis	Water, gtp, turbine entry temperature, power.
	31	Advanced Manufacturing	silicon nitride-titanium nitride, Rsm, electrical discharge machining, response surface methodology.
	32	System Characteristics	Adjustment range, flow part, expansion.
	33	Thermal Modelling and Heat Loads Measurement	Turbulent combustion, numerical simulation, experimental measurement, end wall heat transfer, turbine vane, cylindrical hole, impingement vortex, passage vortex, thermal mechanical analysis, nozzle guide vane, coanda effect, leading edge, cut back, density ratio, effectiveness, jet in cross flow, chp, orc, biomass, environmental analysis, anaerobic digestion, anaerobic digester, multi objective optimization, thermal power plant, maisotsenko cycle, exergetic analysis, irreversibility, desalination, exergo economic analysis, compression, oxy fuel combustion, combined heat and power, combined cooling, turbo fan, humid air turbine, biofuel, cchp system, off design performance, thermos dynamic simulation, distributed generation, simple, ecop, exergy, fog coller, exergy loss, thermodynamic cycle, efficiency, heat pump, exergo economic_A, thermal efficiency, parametric analysis, fuel, economic, environmental, variable solar irradiance, hybrid plants, ultimate, printed circuit heat exchanger, turbine over speed, endwall contouring, aero dynamic losses, liquid fuel, flow field, hyper sonicaire craft, swirl, regenerator, convective heat transfer, liquid crystal thermography, computational intelligence, rotating, secondary flow, cross flow, heat transfer coefficient, wind turbine, coal, syngas, heat flow, engine, actloss, fins, dynamics magorinsky model, high speed contact, tip leakage flow, air craft engine, fatigue, alumini decoating, oxidation, heat treatment, micro structure, single crystal, hotisostatic pressing, cutting, jet engines, wet compression, transmission loss, aero acoustics, turbo charger, control, supersonic flow, stator, jet engine,

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
			energy conversion, gt, integration, fuel cell, characteristics, tool life, Inconel 718, transient process, experiment, counter rotating turbinecrt , cars, entropy waves, gas foil bearing, electro chemical machining, residual stress, concentrated solar power, solar fuel, dynamic model, heat engines, numerical calculation, thermal cracking, oil system, radial flow turbine, reliability analysis, cogeneration system, regenerative heat exchanger, ablation, gasturbine blade cooling, crack propagation, fea, vibration, time series, precooled engine, pressure pulsations, titanium alloy, power systems, life cycle assessment, thermos dynamic performance, cfd analysis, cost, combined cycle gas turbine, zirconia, environmental barrier coating, laminated cooling, mass flow ratio, thermal radiation, tbc, combustion chamber, emission reduction, thermal stresses, cooling efficiency, high temperature, labyrinth seal, thermal design, peak value, lct, topology optimization, numerical study, stability, mass flow rate, des, pulsedetonation engine, thermal protection, vortex generator, dns, nano fluids, nusselt number, bearing chamber, high power factor, double rotor, electric air craft, aerospace engineering, electric machines.
	34	Material Considerations	Tool, ratio, factor, damage, superalloy.
	35	Operational Considerations	Weld repair, tensilet testing, nimonic 263, metallurgical evaluation, heynes282.
	36	System Integration	Thermos dynamic potential, sofchybrid, nernstvoltage, heat engine, cell voltage, system integration.
	37	Fluid Modelling	Entropy, natural convection, rotation, impingement, rib, infrared thermography, thermochromic liquid crystals, convection, thermal performance, friction factor, vortex cooling, misalignment, tip clearance, experimental study, boundary layer, cooling, mist cooling, free stream turbulence, mist, unsteady, film cooling, piv, adiabatic film cooling effectiveness, uncertainty quantification, swirling flow, internal air systems, unsteady flow, unsteady wake, gas turbine, end wall, simplified transition piece model, squealer trip, dimples, shround, blade tip, riborientation.
	38	Novel Cycles and Techno-economic Analysis	turbomachinery aerodynamics, experimental methods, capacity, turbine heat transfer, evolutionary algorithm, impingement/effusion cooling, mist steam cooling, numerical, environmental impact, adiabatic effectiveness, economy, thermos dynamic optimization, cooling system, ammonia mass fraction, combined power cycle, absorption cooling system, exergy analysis, heat recovery steam generator, combined cycle, energy management, emission, thermos dynamic analysis, simulation, cascade waste heat recovery, stirling engine, Humphrey cycle, reheating, coolant precooling, structured experiments, soot, swirl

Numbers of the Clusters in the Time series	*Number of the cluster*	*Name of the cluster*	*Words in clusters*
			flame, liner, hybrid cycle, basic gas turbine, cost of electricity, energetic efficiency, discharge coefficient, aero dynamic design, heat recovery system generator (hrsg), surface roughness, gas turbine efficiency, rotating cavity, recuperator, additive manufacturing, temperature distribution, experiments, pump, multiphase flow, turbine blade, pressure ratio, turbo machinery, electrical efficiency, hydrogen production, shut down, cold energy, waste heat, turbine cooling, thermos economic analysis_A, genetical algorithm, biogas, organic rankine cycle, cchp, cathode air flow.

How are clusters of gas turbine thermal management visualized and analyzed by the strategic diagram (SD) in terms of maturity and development?

A strategic diagram can be represented by SNA indicators such as degree of centrality and density. Moreover, it is also possible to analyze each cluster's maturity and development status. Therefore, the centrality and density of each cluster are measured by UCINet software in each time series.

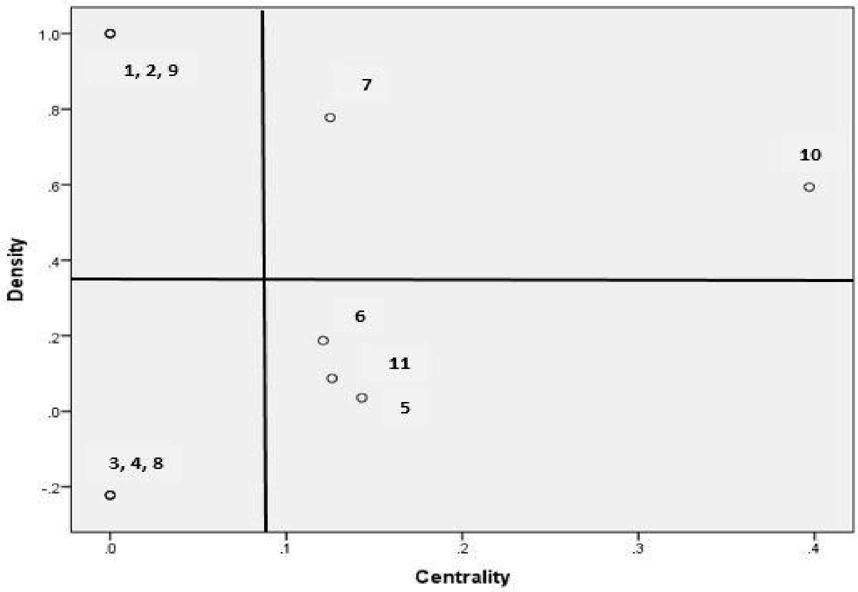

Figure 7. Strategic Diagram of the Clusters during 1919-2000

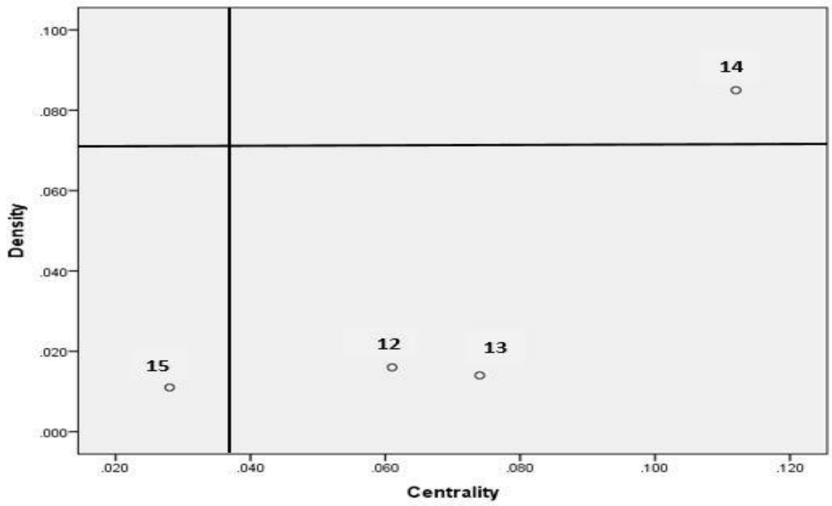

Figure 8. Strategic Diagram of the Clusters during 2001-2010

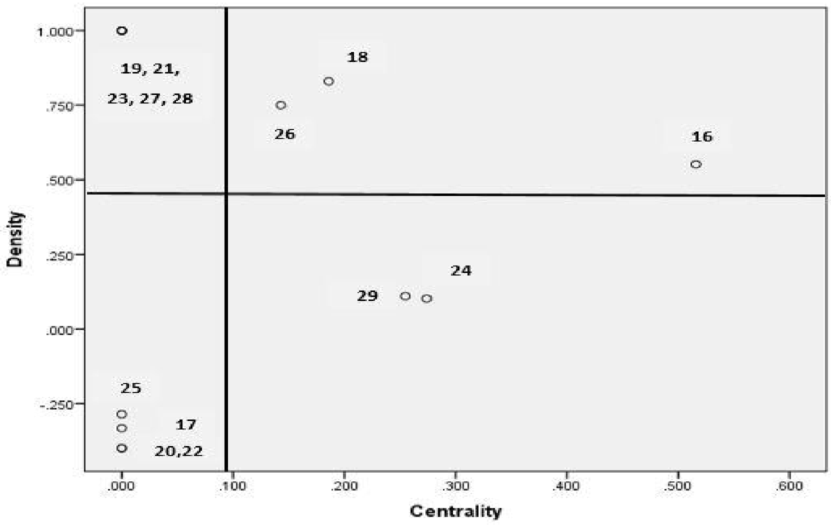

Figure 9. Strategic Diagram of the Clusters during 2011-2015

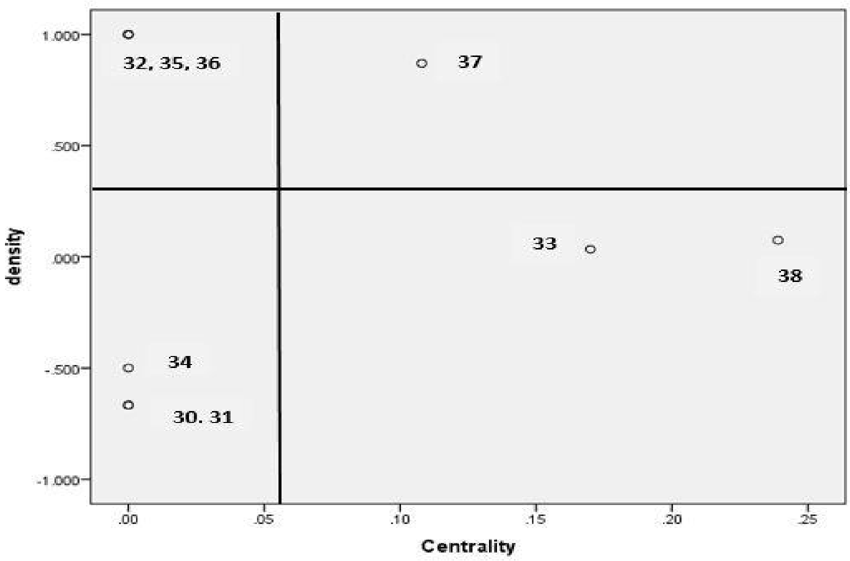

Figure 10. Strategic Diagram of the Clusters during 2016-2020

Discussion

This paper aims to visualize and analyze the co-word network and thematic clusters of the intellectual structure in the field. Its findings align with literature and industry trends concerning thermal management systems design evolution.

The research findings revealed that the top scientific productions in the last century in this field are related to the engineering subject area and published in the USA country. The trends of the number of documents in three main milestones, 1960, 1980, and 2000, align with the historical progress in thermal management systems design, development, and optimization for aerospace applications.

The clusters number 10 (Heat Flux Calculations and Radiation Effects), 14 (Thermal Performance Optimization), and 16 (Operational Considerations) with the highest centrality have central and a significant positions in this field, and especially with the highest density, have more potential to maintain and develop themselves in the future. The mentioned keywords in table 6, as top and high-frequency co-word pairs in various time series, are closely related to this field professionally and scientifically, focusing on research in the field right now and in the future. Generally, they are at the central research positions in gas turbine thermal management. Table 11 summarizes the identified and classified clusters in the strategic diagrams in figures 7-10.

Table 11

Quadrants for identified clusters in gas turbine thermal management

Quadrant II: Ivory Tower	***Quadrant I: Mainstream***
• Effects of Fuel Characteristics • Effects of Thermal Inertia • Two-phase Cooling • Stability Analysis • Integration with Control System • Thermal Models and Correlations Development • Alternative Fuels • Hybrid Cycles • System Characteristics • Operational Considerations • System Integration	• Heat Sources and Sinks • Heat Flux Calculations and Radiation Effects • Thermal Performance Optimization • Operational Considerations • Advanced Cooling Mechanism and Secondary Air System • Combustion and Emission Considerations • Fluid Modelling
Quadrant III: Chaos/Unstructured	***Quadrant IV: Bandwagon***
• Waste Heat Recovery • Heat Transfer Characteristics • Thermal and Fluid Modelling • Advanced Manufacturing • Advanced Manufacturing • Advanced Measurement Techniques • Novel Cycles • Thermal Performance Analysis • Performance Analysis • Advanced Manufacturing • Material Considerations	• Combined Cycles • Boundary Layer • Heat Map Development and System Architecture Design • Novel Cycles and Disruptive Cooling Technologies • Thermal Models Development • Fluid Modelling and Techno-economic Analysis • Heat Exchangers and Turbine Blade Cooling • Thermal Modelling and Heat Loads Measurement • Novel Cycles and Techno-economic Analysis

As can be seen in table 11, the mainstream topics of gas turbine thermal management are located in quadrant I and are defined as the mature and central clusters. In other words, they are the strongest and most mature cluster with central positions in this field. These clusters have the most comprehensive thematic concepts in this field and are more developed than other themes, and the concepts of these clusters are at the heart of the subject of the field. Identify heat sources and sinks, fluid modeling and heat loads calculations, optimization, emissions, and environmental considerations. It makes sense as the European flight path 2050 (Darecki et al., 2011) and governments' net-zero targets are focused on reducing emissions, enhancing performance, and optimizing energy management systems design and development (National Academies of Sciences, 2016).

The clusters in the second quadrant have strong internal relationships and a good level of maturity in this field. They are not axial but developing. In other words, in the second quadrant (Ivory Tower), we have effects of system characteristics (including fuel and thermal characteristics) as well as integration and stability. These are not pivotal but well-developed, important, and isolated clusters. The reason for this isolation is that these clusters are merged with other clusters later on. For instance, hybrid cycles, integration, and two-phase cooling are merged with the novel cycle and techno-economic analysis that could be found in the fourth quadrant as a bandwagon. Fuel, thermal, and system characteristics and alternative fuels will automatically be considered in heat flux calculations (quadrant I) and heat map development (quadrant II). Finally, the operational considerations could be found in the first quadrant as a mainstream.

Quadrant III presents the clusters that are marginal with little attention and are in the phase of transition. They are chaotic due to a lack of internal and external relations. They have a relatively discontinuous structure called underdeveloped. These are not structured because their topics are either new or evolving. For instance, advanced manufacturing in newly developed components and materials and new manufacturing methodology is a hot but unstructured topic. Moreover, the waste heat recovery and fluid modeling clusters that were unstructured before 2000 have been merged in quadrant VI in the last decades.

Quadrant four shows the central, immature, underdeveloped, basic, and transversal themes like heat map development, fluid modeling, and advanced and novel cycles (De Campos, Bringhenti, Traverso & Tomita, 2020). These topics will be extended more in the following years as revolutionary ideas for propulsion systems are widely considered, like hydrogen-powered and hybrid-electric aircraft (Mohammadi, Miran Fashandi, Jafari & Nikolaidis, 2021; Jansen, Bowman, Jankovsky, Dyson & Felder, 2017).

The results also showed four common clusters in comparison between the author and index keywords: *Combustion and Emission Considerations, Heat Map Development, Secondary Air System, and Thermal Models Development*. In other words, the index keywords can potentially show the intellectual structure of knowledge in Scopus in this field in more profound detail over time.

In addition, comparisons between three different clustering techniques indicate that two clusters, namely *Advanced Manufacturing* and *Combustion and Emission Considerations*, are common to all three. Advanced manufacturing has always played a vital role in all aspects of gas turbine engine design and development due to the increasingly complicated designs of the engines. In addition, combustion and emission considerations should always be considered to deal with limitations and targets set by governments and organizations regarding environmental concerns.

Conclusions

It could be concluded that the Research and Development (R&D) activities on gas turbine thermal management systems in the following years and decades will be concentrated on advanced and novel cycles, heat map development, thermal modeling, Techno-Economic and Risk Analysis (TERA), where the backbone of these research will be the identification of heat sinks and sources, fluid modeling, and environmental considerations. It is also expected that applications of advanced manufacturing and material respects will be another contributor to gas turbine thermal management systems design and development.

Finally, the obtained results can be used as a thematic policy map for policymakers, designers, and developers of the related technologies and active organizations in the field, such as the Advisory Council for Aeronautics Research in Europe (ACARE) and the European Union Aviation Safety Agency (EASA) to be well aware in the field. Additionally, based on the provided systematic analysis, engine designers and manufacturers can plan predictably to improve scientific outputs quantitatively and qualitatively to develop the topics in balance for the future. The results also can highlight thematic gaps, prevent repetitive studies, and identify the underlying trends, core topics, and popular areas of the field. In the end, analysis of the intellectual structure of knowledge in the related themes such as novel cycles, heat map development, techno-economic, and risk analysis, advanced manufacturing techniques, and material considerations is highly recommended for future works to identify shared concepts and clusters as well as research gaps in these related fields.

Appendix

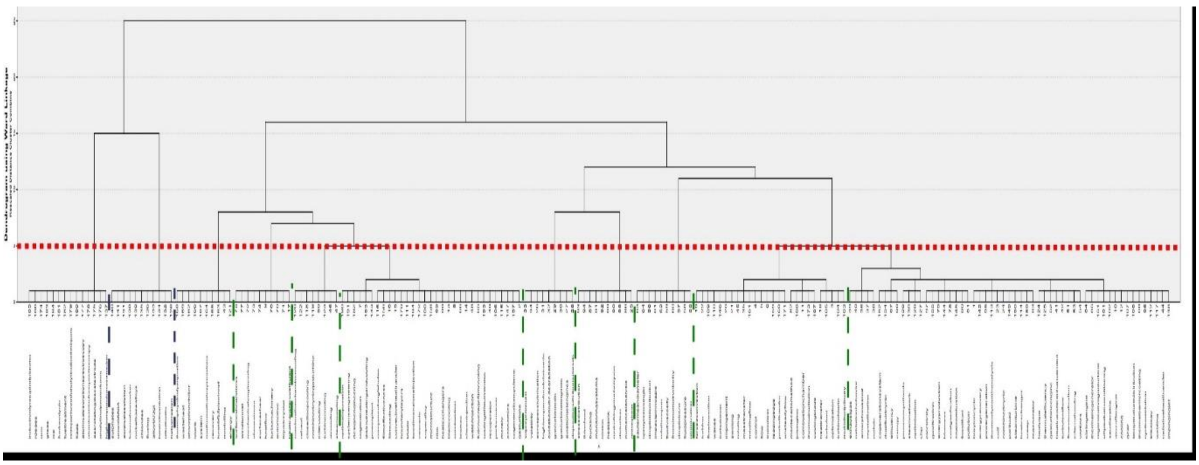

Figure A1: Clusters during 1919-2000 Based on Hierarchical Clustering

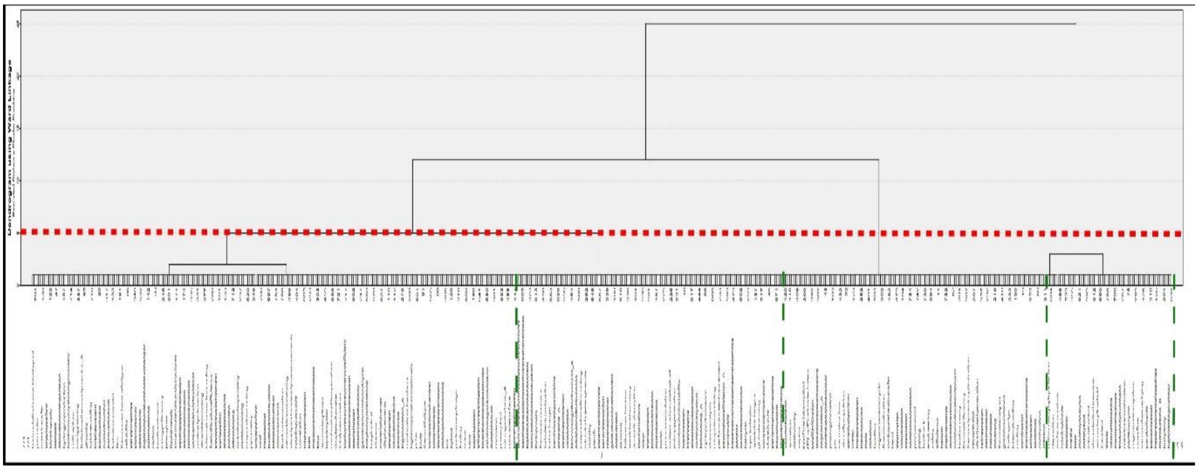

Figure A2: Clusters during 2001-2010 Based on Hierarchical Clustering

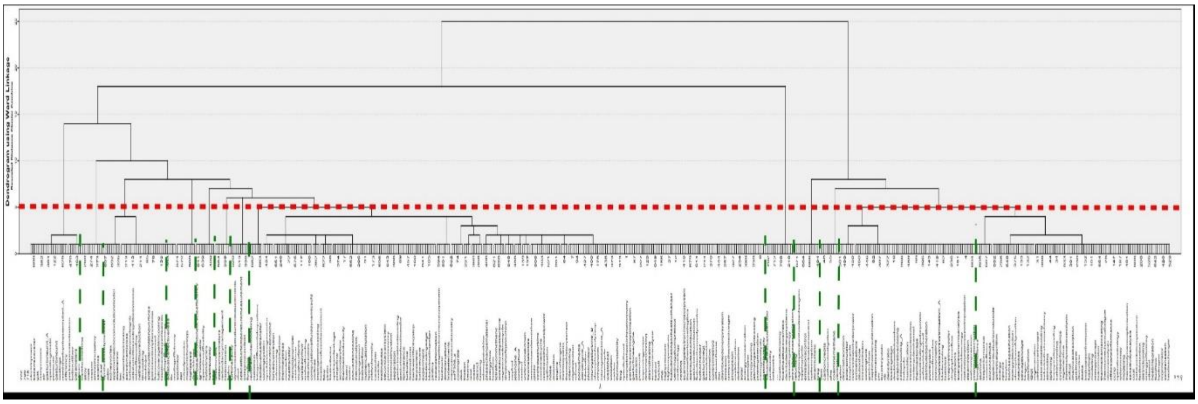

Figure A3: Clusters during 2011-2015 Based on Hierarchical l Clustering

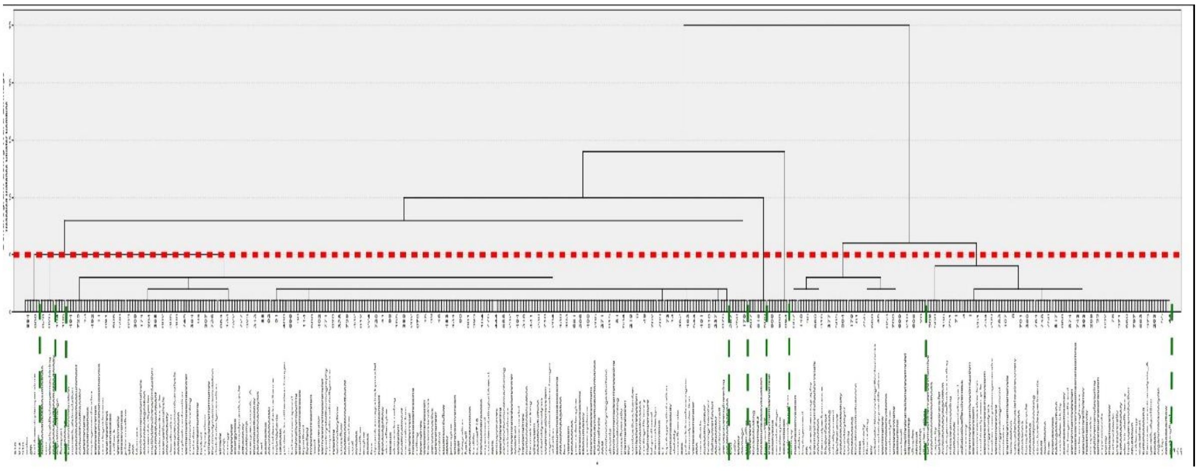

Figure A4: Clusters during 2016-2020 Based on Hierarchical l Clustering

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Thematic clusters in the field of gas turbine thermal management: a co-word analysis during a century

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Regional Information Center for Science and Technology

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