sustainability

MDPI

Article

Flight Path 2050 and ACARE Goals for Maintaining and Extending Industrial Leadership in Aviation: A Map of the Aviation Technology Space

Rosa Maria Arnaldo Valdés [1,*], Serhat Burmaoglu [2], Vincenzo Tucci [3], Luiz Manuel Braga da Costa Campos [4], Lucia Mattera [3] and Víctor Fernando Gomez Comendador [1]

1 Departamento de Sistemas Aeroespaciales, Transporte Aéreo y Aeropuertos, Escuela Técnica Superiór de Ingeniería Aeronáutica y del Espacio, Universidad Politécnica de Madrid, Plaza Cardenal Cisneros nº3, 28040 Madrid, Spain; fernando.gcomendador@upm.es

2 Department of Management, Katip Celebi University, Havaalanı Şosesi Cd. Aosb No:33 D:2, Çiğli, 35620 İzmir, Turkey; serhatburmaoglu@gmail.com

3 UNISA Department of Information Engineering, Electrical Engineering and Applied Mathematics (DIEM), Università degli Studi di Salerno, Via Giovanni Paolo II 132, 84084 Fisciano (SA), Italy; vtucci@unisa.it (V.T.); lmattera@unisa.it (L.M.)

4 Instituto Superior Técnico, Campus Alameda, Morada, Av. Rovisco Pais, Nº 1, 1049-001 Lisboa, Portugal; luis.campos@tecnico.ulisboa.pt

* Correspondence: rosamaria.arnaldo@upm.es; Tel.: +34-636708530

Received: 24 February 2019; Accepted: 4 April 2019; Published: 7 April 2019

Abstract: In the last 40 years, the aeronautical industry has managed to move from a specialized sector to a worldwide leading industry. Companies, governments and associations all over the world acknowledge the importance of the aviation industry in supporting global development and the economy. However, aviation will be facing new challenges related to sustainability and performance in a technological environment in evolution. To succeed, the aeronautical industry must keep innovation as one of its main assets. It must master a wide range of technologies and then collaborate to integrate them into an aircraft design and development program. A collaborative approach to innovation is key to achieve these goals. The main purpose of this paper is to analyze the structure of technological innovation networks in the aviation industry and to characterize the map of the "Aviation Technology Space". Two different approaches and methods are used. In one approach, we performed a bibliometric network analysis of aviation research scientific publications using a keyword co-occurrence analysis method to map the aerospace collaboration structures. Complementarily, we performed a patent analysis to evaluate the innovation capacity of the aviation industry in the cutting-edge technologies previously identified. From the results of this analysis, the paper provides recommendations for future innovation and research policies to allow the sector to fulfill the demanding goals by the year 2050.

Keywords: ACARE; aviation; innovation; sustainability; technology space; co-occurrence analysis; patent analysis

1. Introduction

In the last 40 years, aviation has become a strong driver of economic and social development. It generates around 62.7 million jobs (equivalent to the size of the UK population) and 2.7 trillion USD in global economic activity, which is 3.6% of the world's gross domestic product (GDP) [1]. Aviation improves local access to global markets, creates opportunities for social interchange and development, and supports humanitarian responses to emergencies.

Prospects for the growth of the sector are optimistic. Aircraft manufacturers' most recent estimates (Boeing [2], Airbus [3], Bombardier, etc.) foresee a 4.3% increase in air travel demand per year over the next 20 years.

However, challenges and opportunities populate the horizon of the industry's evolution. The main challenge is to determine how to ensure the sustainable growth of the sector. Technological innovation is at the root of aviation's sustainable growth. Breakthrough and emerging technologies will continue to be the main development differentiator, and sustained efforts in R&D are essential to ensure sustainable growth.

Strategic responses are being prepared by governments and international institutions. ICAO (International Civil Aviation Organization), in collaboration with ACI (Airports Council International), CANSO (Civil Air Navigation Services Organization), IATA (International Air Transport Association), and ICCAIA (International Coordinating Council of Aerospace Industries Associations), has produced a checklist for maximizing long-term aviation benefits and supporting the future of aviation in a sustainable manner [1]. Figure 1 summarizes some of the main challenges and goals envisaged for the sector by the year 2050.

Figure 1. Challenges and goals for aviation in 2050.

The accomplishment of the goals envisaged for a future sustainable aviation implies impressive achievements across the full range of aeronautical products, particularly:

- Establishment of leading-edge technologies in all the sectors contributing to the design of aeronautical vehicles;

- Collaboration to integrate all of these cutting-edge technologies into efficient aircraft production, certification, and service support programs.

To analyze the fulfillment of those goals, initiated by the partners of the European Union-funded project "PARE—Perspectives for Aeronautical Research in Europe" [4], research is being conducted. The aim of PARE projects is to determine the level of progress, gaps, and barriers for a sustainable growth of aviation and to develop recommendations for the elimination of the latter two.

In particular, one of the research tasks in the PARE project is to characterize a map of the "Aviation Technology Space" and to provide hindsight into two complementary issues:

I. The analysis of the capacity of the aviation industry to master key technological areas and to innovate within them.
II. The assessment of the aerospace collaboration structures and their ability to cooperate effectively and aggregate the knowledge and efforts that have gone into the innovation path.

These two factors are considered key for the sustainable development of aviation, and they are analyzed in this paper from the perspective of the technology network's structures. Aviation is a complex system involving highly interrelated technologies whose relations can be mapped as a network. The structure of this network, if mapped with precision, can help us to understand the properties and research of these technologies. Indicators of innovation in aviation, as in other sectors, are the patents in related subjects, collaborative projects, and publications. A technology network analysis was carried out in this study from patents, publications, and collaboration data using several databases and graphical analysis of proximity and interrelationships [5]. To achieve any of the set goals by the year 2050, measures to promote collaborative networks and research structures need to be taken now. For this reason, this paper focuses on the technological innovation networks in aviation and aims to generate recommendations that will allow the sector to fulfill the demanding goals by the year 2050.

2. Materials and Methods

As pointed out by Silverberg and other authors, "technological invention can be considered as navigating a space of technologies" [6]. Various kinds of technologies are related to each other in many complex ways [7,8]. Additionally, technologies relying on similar or related knowledge are connected and proximate in the technology space [9]. Consequently, the space of technology and innovation can be described and analyzed using networks. An analysis of the Aviation Technology Space as a network will open the door to an understanding of how the aerospace collaboration structures behave as a whole and whether the aviation industry can master key technological areas and innovate within them. The methodology applied in this work relies on the following three pillars:

I. Identification of key technological areas that are essential for future industrial leadership.
II. Selection of innovation indicators and proper data.
III. Assessment of the technology network's structures.

2.1. Key Technological Areas

The competitiveness of the aerospace industry depends on mastering cutting-edge technologies in a wide range of subjects. The design of a successful aircraft does not tolerate anything less than first-rate solutions in an extensive range of 11 technologies [10], which are illustrated in Figure 2. Since the substandard mastery of only one of these technologies can cripple an aircraft design and doom its market prospects, it is imperative to remain at the forefront of all 11 technologies to avoid being caught off guard by a competitor. In addition, these technologies must be ready for integration into new competitive products at any time deemed necessary to maintain market leadership in a new development program.

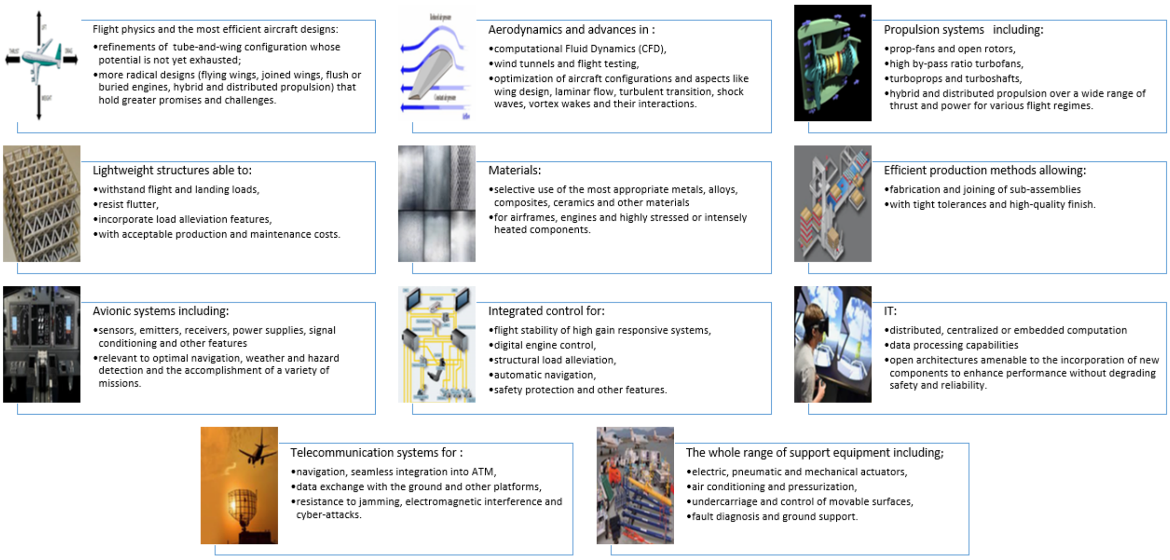

Figure 2. Key technological areas for the competitiveness of the aerospace industry.

2.2. *Selection of Innovation Indicators and Sources of Data*

The technology space can be depicted using patents and publications, as well as the knowledge domains stemming from that information. Patents and publications are classified by domain experts into one of many technology classes. The analysis of this data allows the interrelationship between research structures, as well as the proximity between technology classes, to be derived. This facilitates the identification of gaps in innovation and the derivation of research recommendations on the basis of the technology space network.

In this study, two main databases were used: publications and patents. The first part of the study relied on the analysis of scientific and technical publications. Data on the publications were downloaded from the Web of Science (WoS) Database by using the "WC= ("Aerospace, Engineering")" query covering the 2008–2017 period (downloaded from WoS on 27 December 2017). A total of 57,982 publications under this category that were available from Web of Science and produced in the last decade were analyzed. WoS (previously known as Web of Knowledge) is an online citation indexing service provided by Clarivate Analytics, and it provides an exhaustive search of citations. WoS provides access to multiple databases of interdisciplinary research, allowing a detailed and exhaustive analysis of an academic or scientific discipline and its corresponding specialized subfields. In addition, it is well-known that common sources of scientific literature are PubMed, Google Scholar, Scopus, and WoS. WoS and Scopus were compared in terms of journal coverage by Mongeon and Paul-Hus [11]. The analysis revealed that both databases are affected by some biases, and therefore, both should be used carefully for comparative research evaluation. Although the research did not identify big differences between the two databases in terms of journal coverage, it highlighted that the data retrieved from both databases should be handled with caution. Accordingly, our study applied a data preprocessing step to remove duplicates and irrelevant files. All visuals in this study for publication analysis were prepared by using VOSviewer software [12].

The second analysis focused on the evaluation of patents. Patents are one of the main outcomes of R&D that denote the features of a technology. A vast amount of recent technical knowledge is condensed into an accessible electronic patent database, increasing the need for exploiting this knowledge [13]. Patents are a treasured source of data for determining the temporal, geographical, sectoral, and technological distribution of inventions [14].

In this analysis, the Derwent Innovations Index Database was used as a data source. In this database, patents are classified into 20 broad categories and three overall areas: Electrical and Electronic Sections (S–X), Engineering Sections (P–Q), and Chemical Sections (A–M). Categories are further split into classes, which are identified by a letter and two digits. For example, Automotive Electrics is designated as X22. The search term 'aviation' in the topic field of patents resulted in 23,508 patents. Since this study is configured as explanatory, filters were not applied to limit the data corpus at first. Data were retrieved from the database and then cleaned for further analysis. Some pre-specified thesauruses and fuzzy clustering algorithms were applied in this stage. The patent analysis was performed with VantagePoint software [15].

2.3. Assessment of Technology Network's Structures

Two different approaches and methods were used in this study to analyze the structure of the technological innovation networks in European aviation:

i. Publication analysis.
ii. Patent analysis.

On one side, by considering the co-occurrence of keywords to map aerospace collaboration structures, we performed a bibliometric network analysis of scientific publications reporting aviation research.

Bibliometric analysis has been applied in several domains for understanding the dynamics of a scientific field [16]. Co-word analysis, introduced at the end of the 1970s by French bibliometric scientists [17], is the most widespread. This method is based on the following principle: specialized keywords have a relevant relationship if they represent a particular research theme and are present in the same technical document [18]. The more the coincidence, the closer their relationship. A general co-occurrence analysis scenario can be performed as in Figure 3.

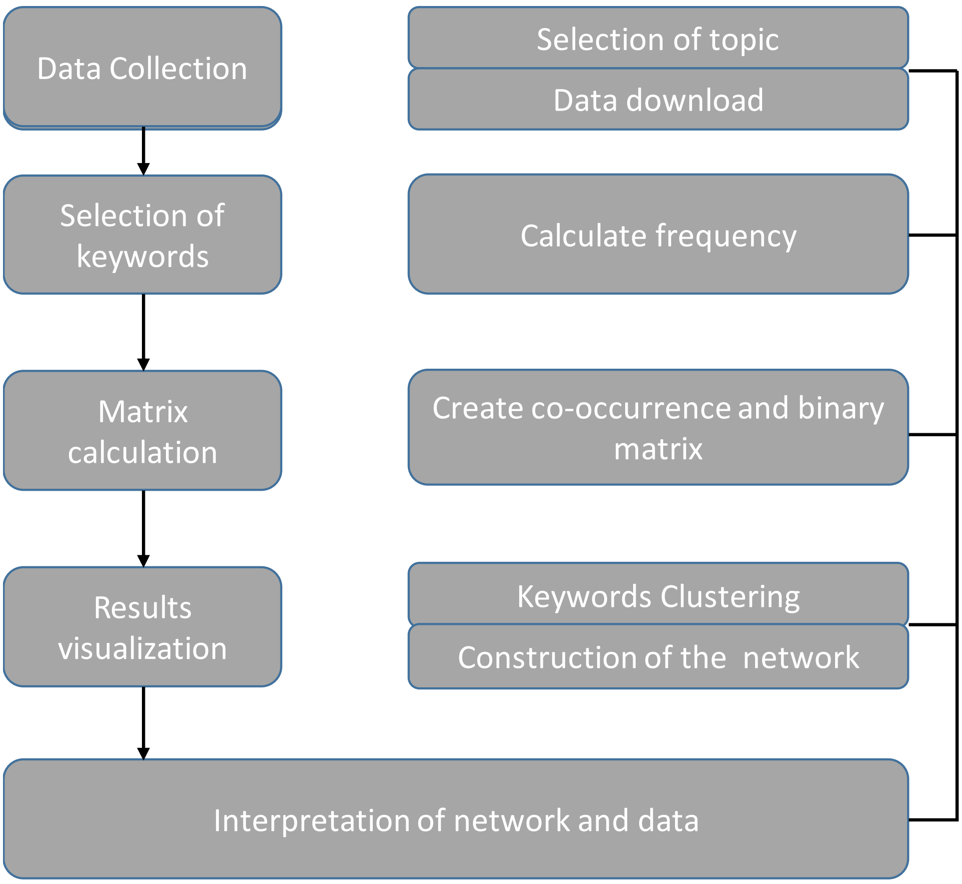

Figure 3. Typical keyword co-occurrence analysis.

Keyword co-occurrence analysis has been applied in several domains for understanding the dynamics of a scientific field. Dehdarirad et al. scrutinized almost a thousand articles from the Scientometrics journal using word analysis and text data mining to reveal the intellectual logic applied by the journal [19]. In Reference [20], research trends were studied by the analysis of keyword co-occurrence at co-funded projects. Other subjects analyzed with this technique include robotics [21], gender differences, libraries [22], etc. However, its application in aviation and aerospace is limited. In reference [23], 12 years of aerospace engineering articles from Web of Science were analyzed with CiteSpaceII to study the co-occurrence network at Chinese research organizations. The authors built a knowledge map of aerospace engineering in China, studied its evolution throughout a 12-year period, and demonstrated the existence of many research organizations, but they found very little co-operation among them. They also identified that tangent orbit and hypersonic inlet had been key research areas since 2000. In reference [24], the technique was applied to reveal cooperation networks of engineering aerospace educational institutions.

On the other side, a European Technology map was completed with the patent analysis. Patent analysis has been widely used to assess knowledge dissemination and to hand over processes in R&D [25]. Patent analysis can be classified into micro- and macro-level research. Micro-level research of patents usually focuses on the diffusion [26] or forecasting [27] of a particular technology, or it is used for competitor analysis [28]. In the macro-level analysis of patents [29], the topics are technological innovation and technological competitiveness between regions or nations. Patent analysis has also been intensively used to

(i) Understand the invention processes [30],
(ii) Better stimulate innovation,
(iii) Analyze the time lag between the allocation of research funds and patent issues [31],
(iv) Assess innovation diffusion [32],
(v) Predict the future directions of technological development [33].

There are two recognized viewpoints in patent technology breakdown: (i) content-based approaches and (ii) citation-based studies. Content-based approaches measure the similarity in content between pairs of documents using text-mining techniques. On the other hand, citation-based studies ignore the patent content and consider the citations between two patents as knowledge flows that allow the discovery of main technological trends [34].

A different approach that overcomes the weaknesses of citation analysis is network-based patent analysis. Network analysis displays the association among patents as a graphical network and consequently helps to grasp the structure of a patent database. As it is based on text mining, it reduces processing time, considers more variation, and generates more significant indicators [35]. The general steps in patent analysis are shown in Figure 4.

There are very few scholarly works to date that have applied this type of technological analysis to aviation technology. One of them is Nakamura's [36] study, which aimed to map aerospace engineering comparatively with citation network analysis by using the patent data of the aerospace industry and Toyota. They found that at the system level, there are similar fields of technology for improvement in both aviation and Toyota. In another study, Kwon and Lee [37] prepared a technology forecast for sustainable (green) aviation by using patent analysis. From the study's findings, they asserted that, in the 2000s, there were continuous technological developments in the fuel cell and noise areas in the green aviation technology field. Finally, they forecasted that the development of new aircraft engines would be expected to focus on new technology for future green aviation.

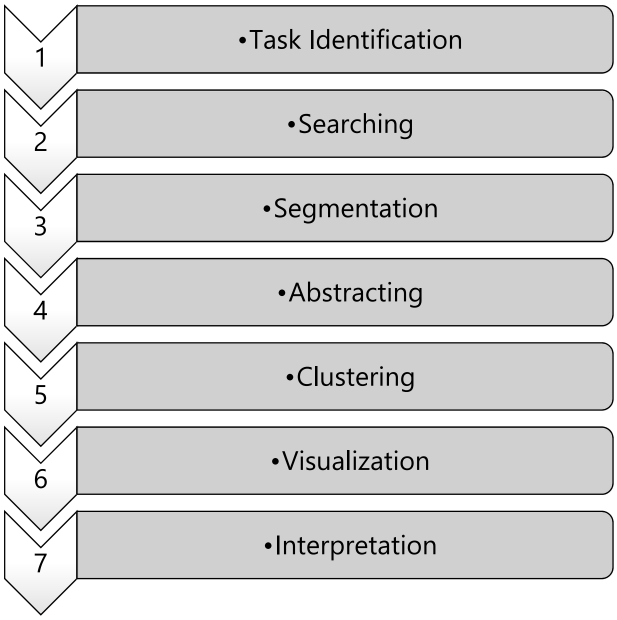

Figure 4. Steps in patent analysis.

3. Results and Discussion

3.1. Assessment of the Aerospace Collaboration Structures on the Basis of Web of Science Database

This section discusses the application of co-occurrence analysis for understanding the dynamics of research in aviation by using country, institution, and Web of Science category fields. This analysis is intended to depict the aerospace engineering field on the basis of three categories:

I. Country,
II. Institution,
III. Web of Science categories.

The analysis demonstrates and identifies the existence of international scientific collaboration networks. These structures are analyzed here according to the nations and institutions involved. The analysis also allows for the identification of the main aerospace subfields of research currently within this international scientific collaboration network.

3.1.1. International Collaboration Networks

The first visual is presented to convey an understanding of the international aviation collaboration network. From the scientific field co-occurrence analysis, six main clusters are identified. The co-word bibliometric network studied is a weighted network. The edges indicate a relation between two nodes, as well as the strength of the relation. In Figure 5, the main clusters of the international collaboration network are indicated with different colors, and the publication frequency is indicated by the size of the node. Figure 5 identifies countries with weighted direct citation links.

In Figure 5, the highest publication frequency takes place in the USA, followed by China and the European Union. USA presents the top Weighted Degree (WD) value; WD = 3217, China accounts for a WD of 1287; and Germany, England, Italy, France, and Netherlands complete the list of the seven top countries with WDs higher than 1200. European countries dominate four of the six clusters; the two exceptions are led by Israel and the USA.

Germany (WD = 1925), England (WD = 1579), France (WD = 1499), Italy (WD = 1333), Netherlands (WD = 1296), Spain (763), Belgium (WD = 431), and Switzerland (WD = 395) can be identified as the main actors in their clusters.

This structure of clusters highlights how the technological capabilities in aerospace engineering are spread or concentrated. Research capabilities and knowledge are homogeneously spread, with a clear geographical correlation, into four highly specialized clusters. However, national aerospace technological capabilities may not be easily collectivized. Therefore, aviation needs to pursue a dual policy of promoting excellence in the different aerospace subfields while also aggregating their information. On one side, research policy should support every cluster's continued excellence in different subfields. On the other side, research policy must facilitate the aggregation of the diverse experience and knowledge in each subfield into a shared platform for the aviation industry. It has to be considered that although national technological capabilities of aerospace engineering may not be collectivized, information and experience may differ in this regard. Therefore, innovation creation policy should reinforce the spread of knowledge while maintaining its mission orientation. Implementation of multi-objective innovation measures, both diffusion-oriented and mission-oriented, will be more suitable for maintaining excellence in aviation than single-objective policies.

The analysis of representative countries in the European clusters is also important, particularly with respect to EU-13 (Group of 13 EU countries: Bulgaria (BG), Croatia (HR), Cyprus (CY), Czech Republic (CZ), Estonia (EE), Hungary (HU), Latvia (LV), Lithuania (LT), Malta (MT), Poland (PL), Romania (RO), Slovakia (SK) and Slovenia (SI)) countries, which, with the exception of Poland, are practically absent from the international collaboration network. This result is coherent with the level of participation of EU-13 countries in European Research funded initiatives. In 2007, ACARE published a high-level report on the aeronautical research capabilities of the 12 most recent members of the European Union. The report included recommendations for successfully integrating the new Member States' aeronautical research organizations and companies with research capabilities into the relatively well-developed research network of the "older" Member States [38]. As pointed out by a recent report of the European Union about research in the EU-13 countries, despite the efforts made by politics, institutions, and industry, the participation of individual EU-13 countries in European research initiatives is very heterogeneous, but overall, they are underperforming [39]. The results obtained in this paper corroborate that, regardless of the efforts made, there is still a great gap to close for the effective integration of the aeronautical potential research capabilities of the EU-13 countries into the European scheme.

Additionally, the figure not only illustrates higher publication frequencies in both China (Weighted Degree-WD = 1287) and the USA (WD = 3217), but also a high level of correlation between their research topics. On the other hand, European countries have very weak connections with the research carried out in China and other Asian economies. Research in the USA plays a pivotal role in the research infrastructure connecting the major players. The elevated number of publications in the USA and China, as well as the highly correlated topics between the two research networks, suggests the need for further analysis of the details of both research networks. Particularly, due to the weak connections between European clusters and Chinese publications, the specific analysis of China's research may provide the insight necessary to develop a competitive EU aerospace innovation policy.

3.1.2. Collaboration Network of Institutions

A second visualization is prepared to illustrate the institutional collaboration network worldwide. There are many universities and research centers located as illustrated in Figure 6. The European cluster can be identified as the blue group. The figure shows strong links between some Korean universities around the Korea Advanced Institute of Science and Technology, that with a WD of 205 is acting as a research enhancer; and some strong links in several USA universities.

Those strong links evidence compact areas of collaboration and integration among these institutions. In particular, it can be observed that universities and research centers in the USA are organized into two distinct clusters. One of them is dominated by NASA (WD = 826) and MIT (WD = 196), and the other one is shared among NASA, some universities, and the United States Air Force (WT=179). Xiuxiu obtained similar results [24].

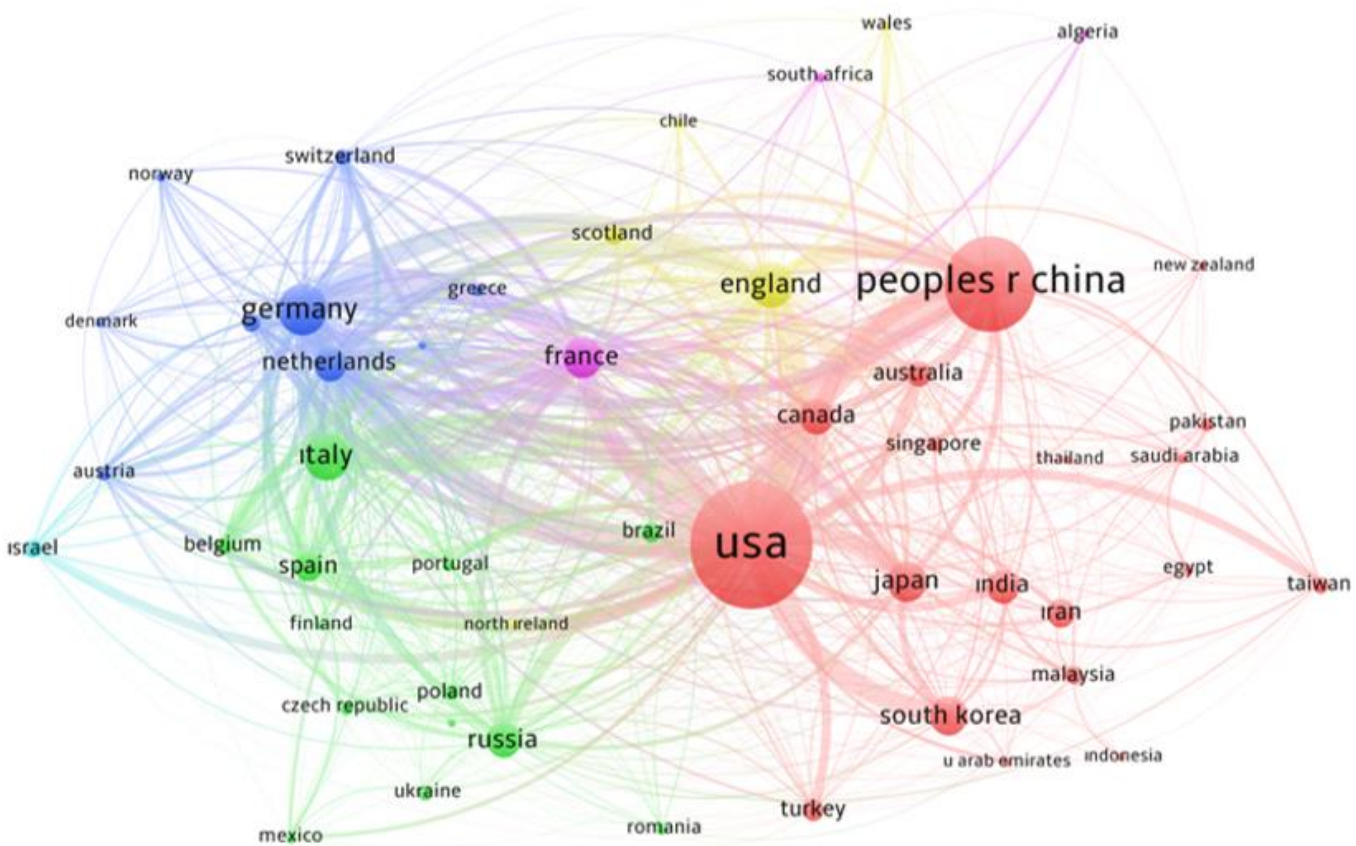

Figure 5. International Collaboration Networks with Document Frequency.

The main research directions of the two USA groups are the space station, target tracking, and monitoring of aircraft feedback. USA universities with the highest weighted degree are Caltech (WD = 485), Georgia Institute of Technology (WD = 217), University of Michigan (WD = 217), Massachuset Institute of Technology—MIT (WD = 196) and the University of Colorado (WD = 184). Among the 10 top institutions, we can also find the Japan Aerospace Exploratory Agency (WD = 203), the Korea Advanced Institute of Science and Technology (WD = 205) and the Beihang University (WD = 150). The three of them play a pivotal role agglutinating and connecting research initiatives in their respective countries.

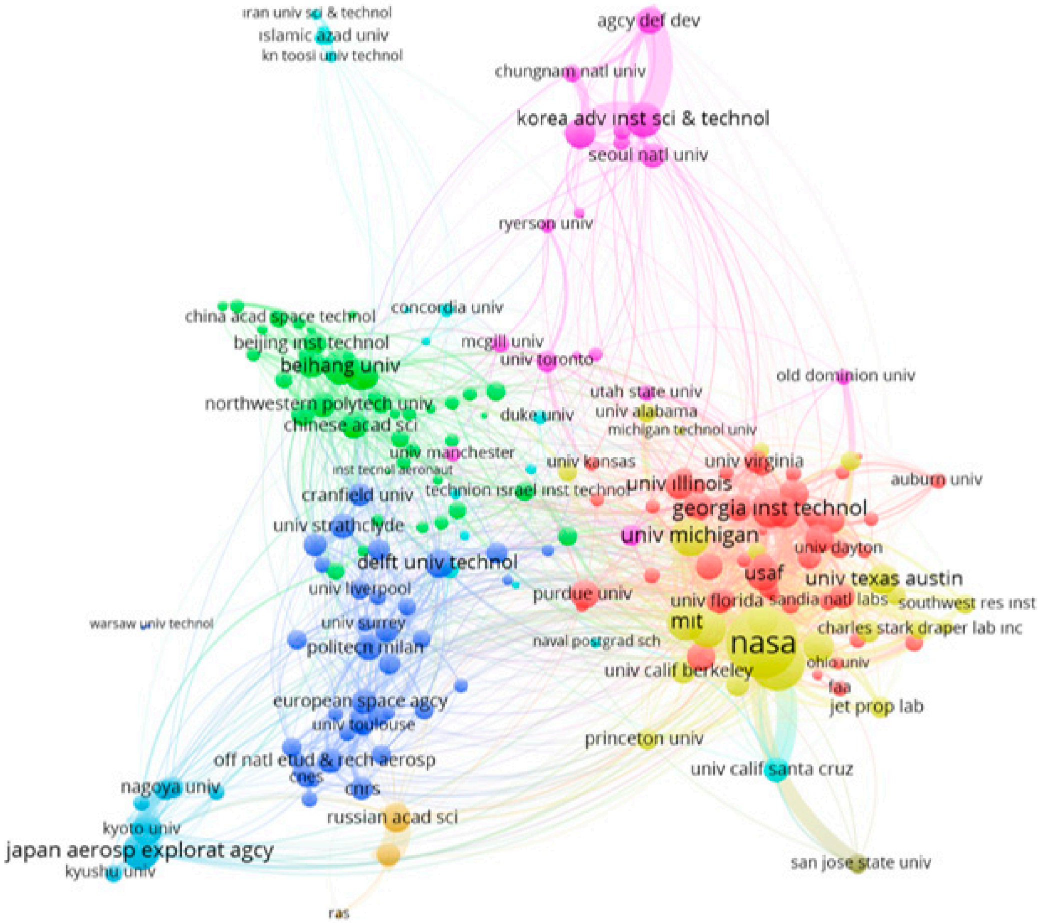

Figure 6. Institutional Collaboration Network.

3.1.3. Collaboration Networks in Aerospace Engineering Subfields

Finally, the last visual is prepared for demonstrating the research space of aerospace engineering by using the co-occurrences of different Web of Science categories. The prepared visual is shown in Figure 7. Naturally, aerospace engineering (WD = 40419) is the central node of the network because it was the main Web of Science category selected. Additionally, five main clusters, grouped in the figure with different colors, are identified that cover the following fields:

1. Mechanical engineering (WD = 10173), including biomedical engineering (WD = 292), robotics (WD = 46), and manufacturing (WD = 886);
2. Physics (WD = 187), automation (WD = 2020), telecommunications (WD = 6798), electric-electronic, and computer science (WD = 13218);
3. Materials science optics (WD = 7937), nano-science and remote sensing (WD = 3409);
4. Energy (WD = 1644) and polymer science (WD = 263);

5. Acoustics (WD = 734), thermodynamics (WD = 1106), environmental studies (WD = 54) and geology (WD = 54).

The co-occurrence network graph in Figure 7 illustrates the connectivity among various research topics in the aerospace literature. The size of the nodes reflects the frequency of keywords: The higher the frequency of the keyword, the larger the size of the node. The size of the node indicates also weighted degrees of the topic. The thickness of the line is proportional to the nearness of keyword connections; the closer the relationship between the two nodes, the thicker the line.

Nodes without connections signify research fields lacking substantial cooperation with other research areas in the aerospace literature; they may be considered emerging or nascent topics that are sometimes in the margin of a research field, or they can be identified as areas in which mutual collaboration is lacking.

Mechanical engineering (WD = 10713), telecommunications (WD = 6798), electrical and electronics engineering (WD = 13218), instrumentations (WD = 5450), astronomy and astrophysics (WD = 4028), optics (WD = 7937), and mechanics (WD = 3864) had the highest frequency of co-occurrence in the literature with aerospace engineering; evidencing the areas where aerospace engineering publications are concentrated.

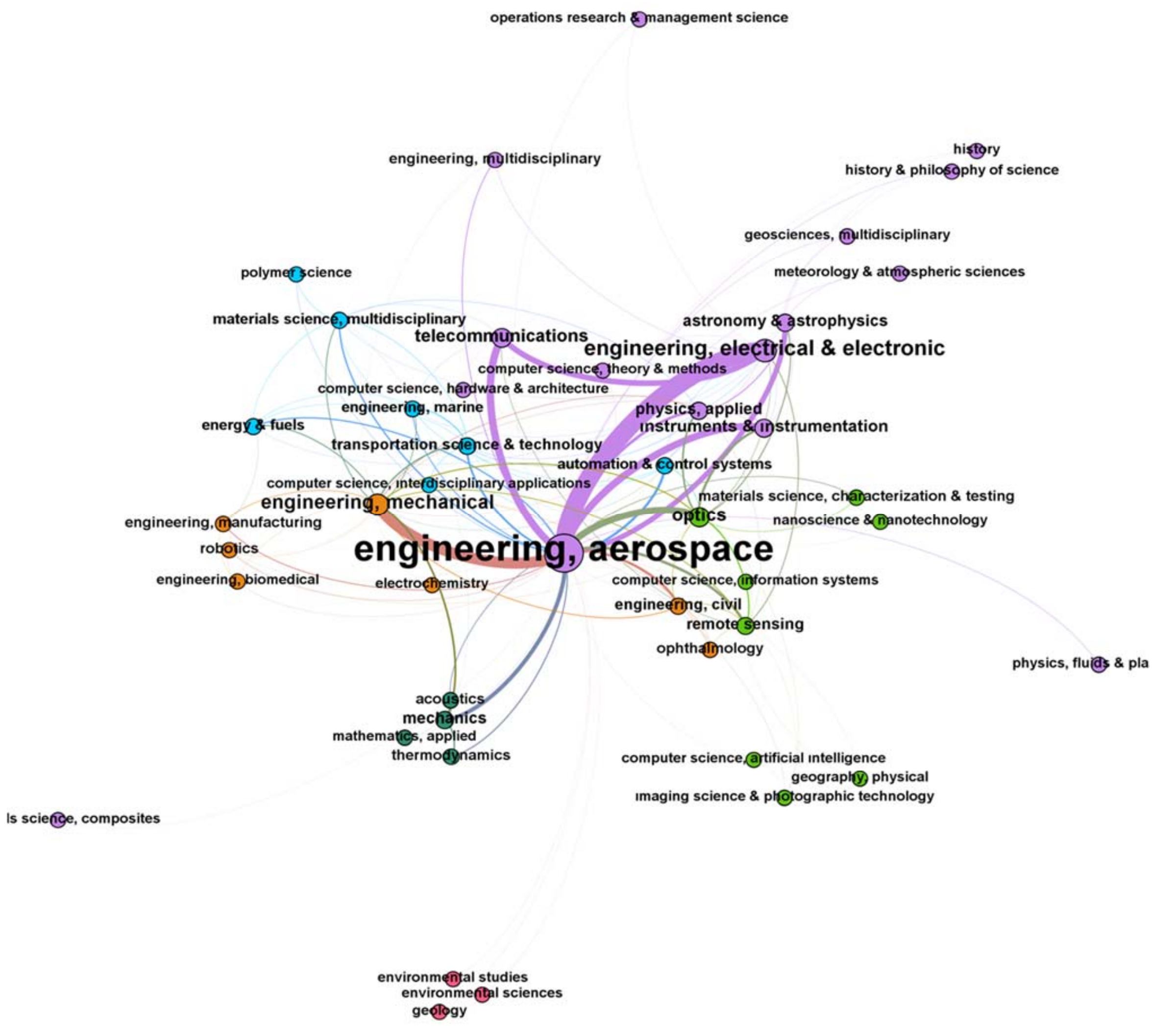

Figure 7. Collaboration Networks Based on Web of Science Categories.

3.2. Assessment of the European Aerospace Innovation Capacity on the Basis of Mapping Patents in Aviation Technologies

The patent analysis performed in this study covers the following topics:

I. Analysis of the trends of patents in aviation through the annual distribution analysis;
II. Regional distribution analysis of the patents, including assignee analysis;
III. Analysis of the patent structure detailing the technical fields in which patents are produced.

It is worth comparing the topics in Figure 7 with the 11 areas previously identified (see Section 2.1) as key scientific disciplines involved in aircraft development. It can be observed that all of these areas are present in Figure 2 with a relatively high number of publications. However, these areas are not highly interconnected, evidenced by the lack of common research, and are thus losing potential synergies that could foster innovation. According to Figure 7, this lack of common research is particularly notable between physics (WD = 187), computer science (WD = 174), and materials engineering (WD = 520)—three fields among which collaboration is required to boost aviation innovation. To close this gap, it will be necessary to promote collaborative studies between these areas as part of the aerospace innovation funding policy.

3.2.1. Trends of Patents on Aviation

Figure 8 presents the yearly evolution of the number of patents in aviation in the last 40 years. It can be observed that the number of patents has grown exponentially in the last decade. Figure 9 shows the breakdown of this evolution into the main Derwent categories. It can be observed that the greatest patent growth has taken place in the categories of operations and physics. Operations and physics are named macro-classes. Second in growth, named medium classes, are electricity, mechanical engineering, and chemistry. In contrast, the area of human factors has experienced very low growth, and the area of textiles has experienced practically no growth. Human factors and textiles are grouped in the micro-classes. Figures 10–12 provide a zoomed view into the evolution of macro-classes, medium classes, and micro-classes.

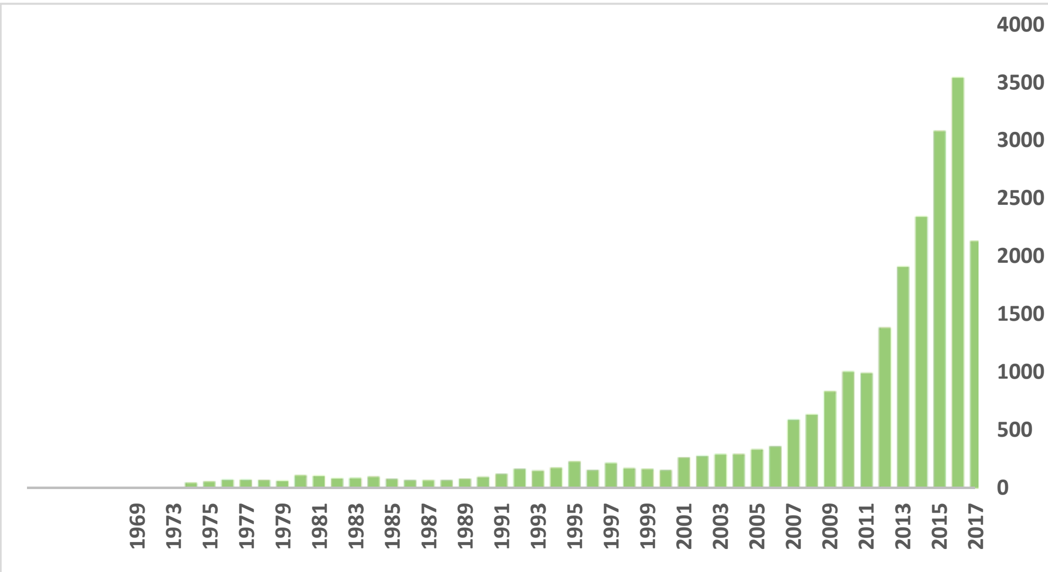

Figure 8. Number of patents in aviation per year.

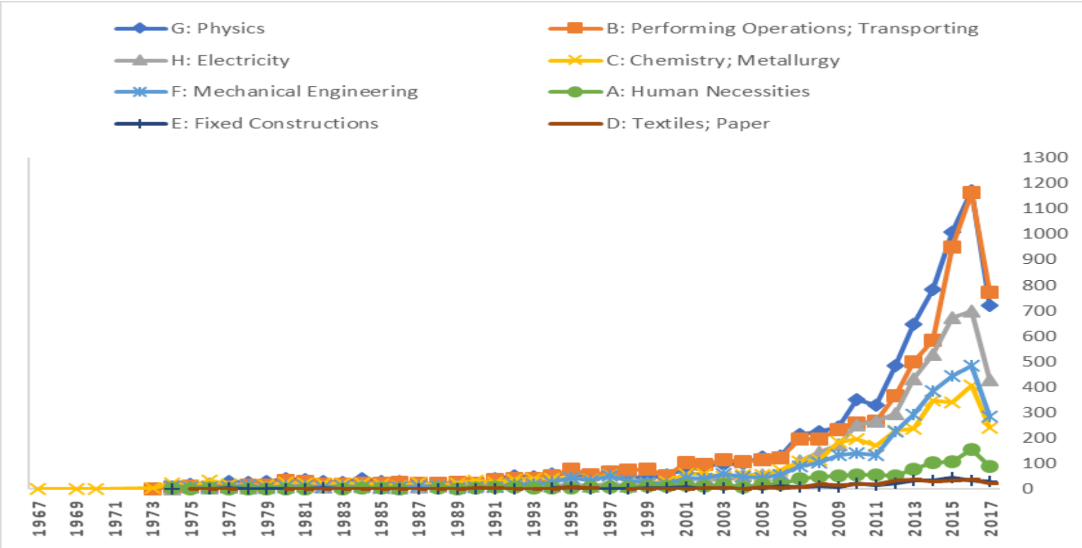

Figure 9. Chart of subclasses per year.

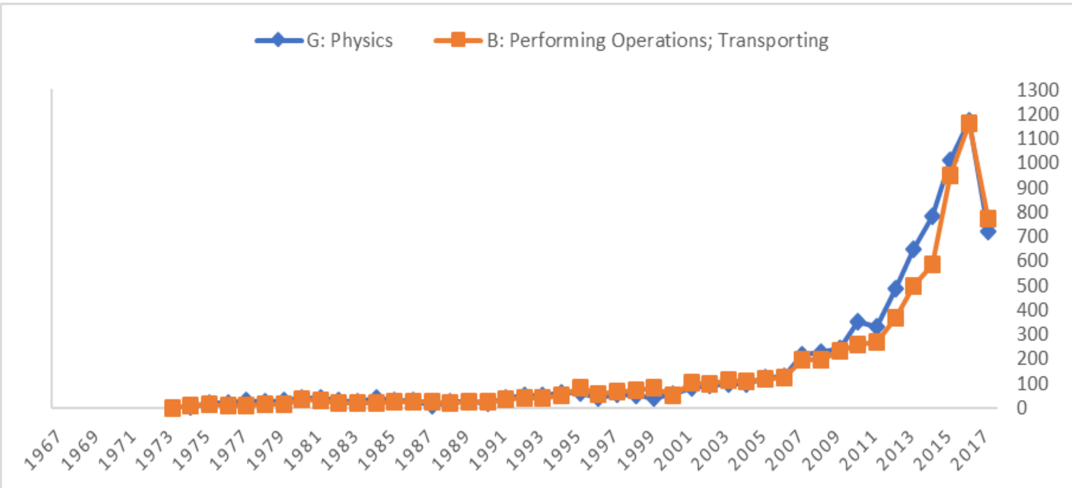

Figure 10. Macro-classes.

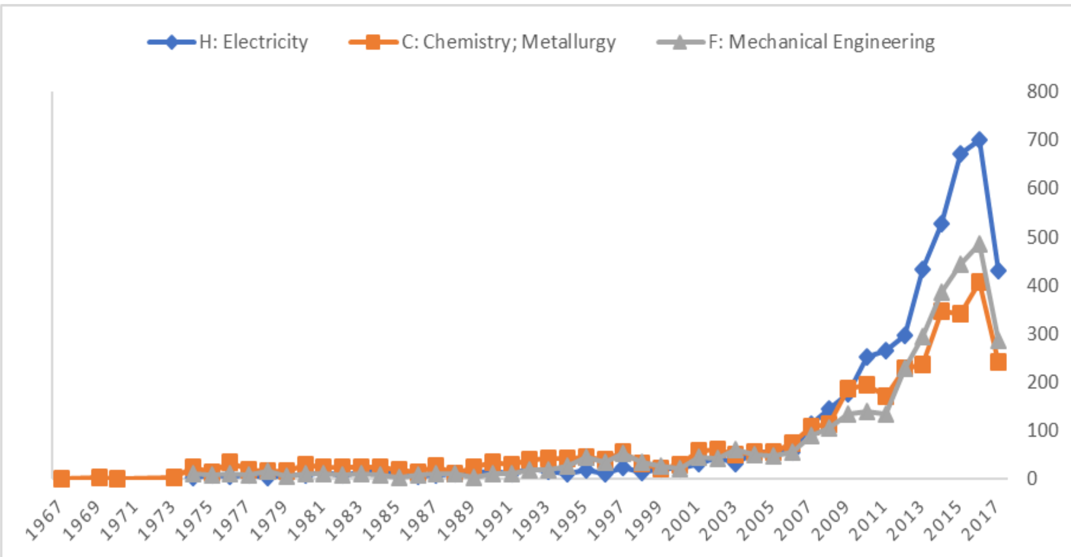

Figure 11. Medium classes.

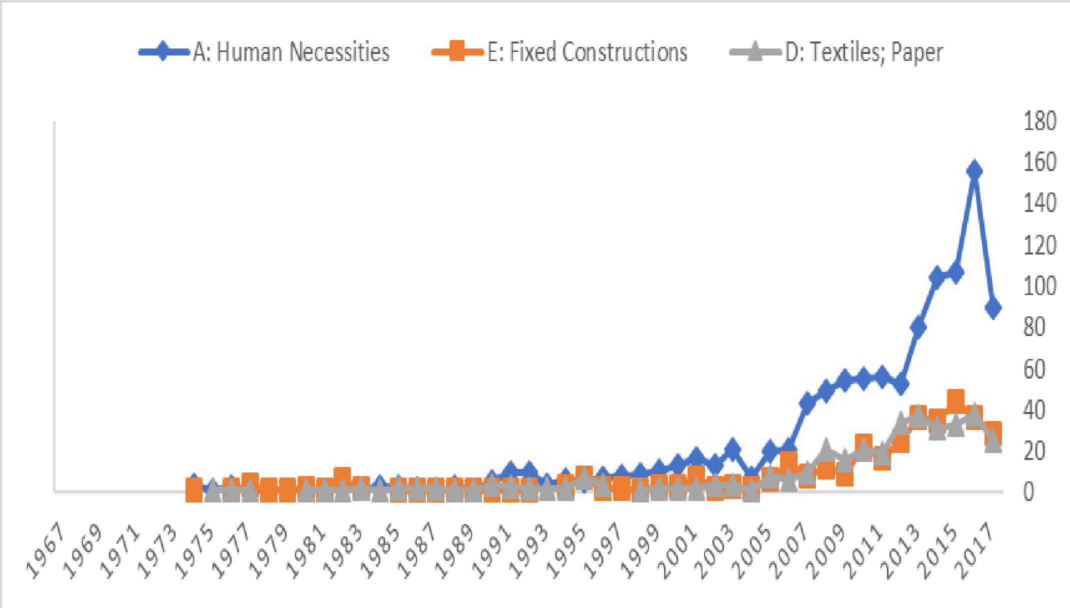

Figure 12. Micro-classes.

3.2.2. Geographical Analysis

Table 1 summarizes the accumulated number of patents per country. Figure 13 presents the annual evolution of patents for the top 10 countries, and Figure 14 shows the distribution of the patents according to class for these top 10 countries.

Table 1. Number of patents per country.

Basic Patent Country	Patent Number
China	11876
United States of America	3249
Russian Federation	2140
Soviet Union (USSR)	1393
World Intellectual Property Organization (WIPO)	1327
Korea (South)	1308
European Patent Office	637
Germany	369
France	305
Japan	254
United Kingdom	191
India	98
Canada	56
Brazil	37
Australia	28
Belgium	28
Taiwan	26
Romania	19
Spain	15
Poland	14

China is observed to be the country with the most patents in aviation, showing a strong dynamic in the field of patenting. There is a sharp increase in the volume of patents filed in China: The number has quadrupled in the last 5 years. The data reflects how Chinese agents protect their intellectual property through patents, regardless of whether it was received through technology transfers or generated autonomously. Some authors have regarded this situation as replicating the strategy applied by the government and the Chinese industry in the railway sector; that is, the progressive development of barriers that are put in place to reduce the ability of non-Chinese agents to access the domestic market [40].

The high attrition rate should not be considered in isolation, as sometimes it is a consequence of governmental policies and effectively decreases when incentives are no longer applicable. Most authors recommend studying the patent lifecycle and its utility by periodically reviewing the number of patents discarded after a 5- or 10-year period [40], the number of international citations [41], or the citation lag [42].

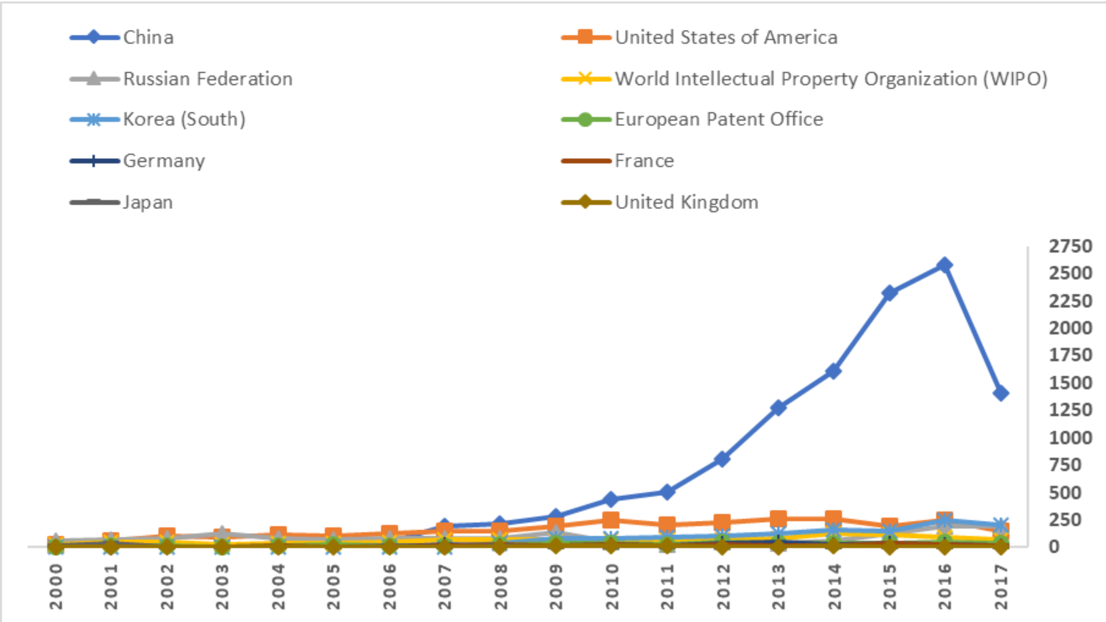

Figure 13. Evolution of the number of patents.

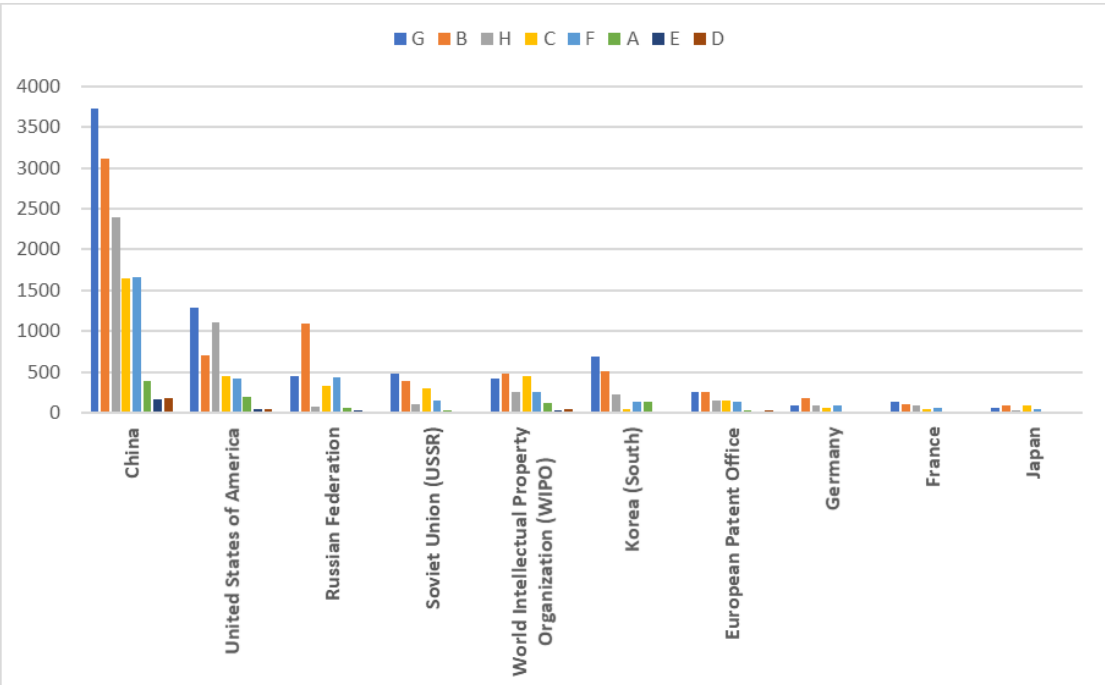

Figure 14. Aviation patents per country and class (A: Human necessities; B: Performing operations and Transporting; C: Chemistry and Metallurgy; D: Textiles and Paper; E: Fixed constructions; F: Mechanical Engineering, lighting, Heating, Weapons, and Blasting; G: Physics; H: Electricity).

The geographical analysis is complemented with the analysis of patent assignees. Table 2 summarizes the top 20 firms by patent number. Figure 15 illustrates the evolution of the annual number of patents for the 10 top firms, and Figure 16 resents the number of patents per holder according to subclasses.

Table 2. Top 20 Firms by number of patents.

Patent Assignees	Records
Stats Chippac Ltd	369
Honeywell Int Inc	233
Shenyang Liming Aero Engine Group Corp	222
General Electric Co	193
Univ Beijing Aeronautics & Astronautics	189
Univ Nanjing Aeronautics & Astronautics	165
Boeing Co	151
Harbin Inst Technology	145
State Grid Corp China	142
Rockwell Collins Inc	123
Univ Beihang	106
Avic Comml Aircraft Engine Co Ltd.	103
Aviation Ind Corp China Shenyang Engine	99
Stats Chippac Pte Ltd.	94
Univ Northwestern Polytechnical	90
Aviation Materials Res Inst	88
Univ China Civil Aviation	83
Thales	75
Avic Shenyang Engine Design Inst	71
United Technologies Corp	71

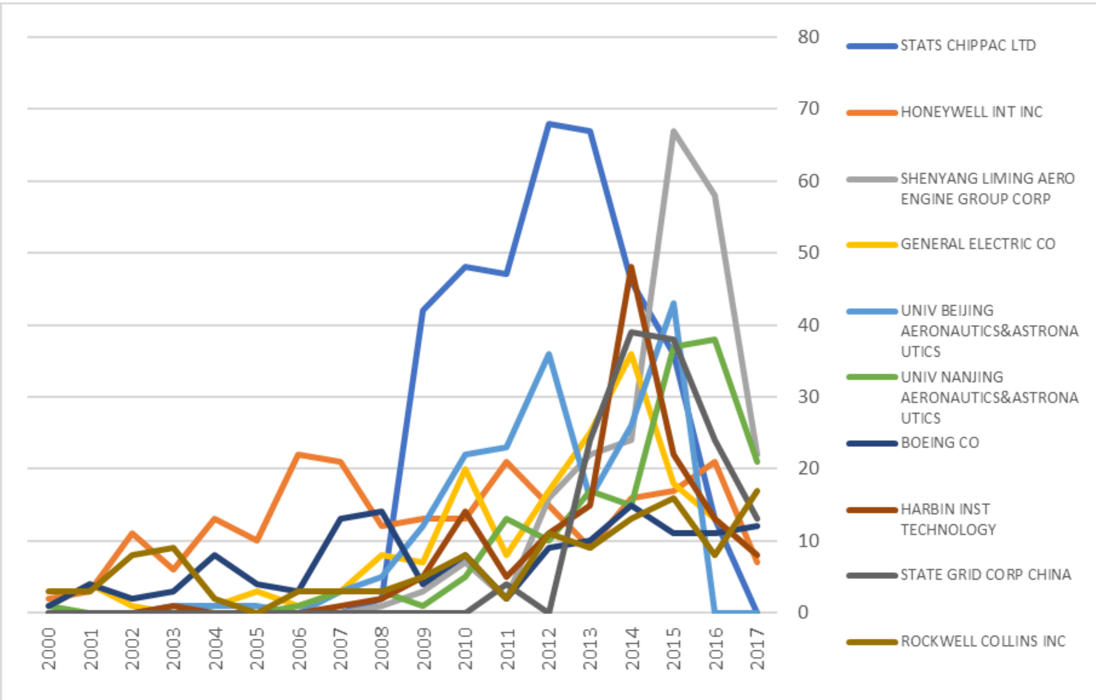

Figure 15. Top 10 Firms by number of patents.

The above results show that although there was significant dominance by universities and research centers worldwide in the publication network (see Section 3.1.2), there are only a few universities among the top 20 firms by number of patents, and all of them are Chinese universities. This highlights the lack of capacity of universities in Europe, as well as the USA, to translate basic research into products and industrial innovation. Future innovation and research policies should contribute to closing the existing research and innovation gap between academia and the aeronautical industry. University spin-offs may be integral to bridging this gap by playing different roles in intermediation, technology diversification, and technology renewal [43]. University spin-offs are start-up companies that are created by academics to exploit technologies and knowledge originating from the university. During the last two decades, spin-offs from universities have attracted increasing interest from research institutions and industry, mainly because these spin-offs have the capacity to bridge the gap between scientific and academic knowledge and their industrial application [44,45]: "Universities need to reinvent themselves as micro environments for innovation and entrepreneurship. A university that will not demonstrate its impact on industry and the marketplace will become less relevant in the future" [46]. Today, Israel is the country with the most efficient policies for transferring innovation from universities and military tech units to industry and production. Policy programs are needed to stimulate entrepreneurial activities of academics in aerospace [44].

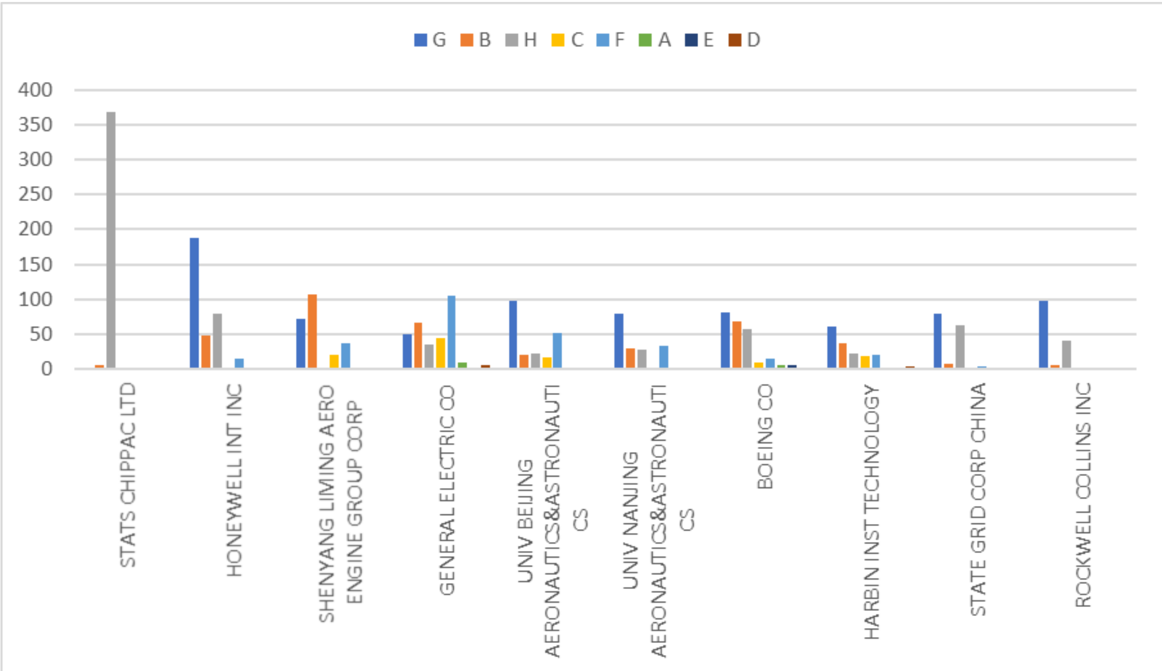

Figure 16. Number of patents per holder.

The last conclusion, which is derived from the above analysis, is regarding the specific geographical differences between aerospace science and technology journals and patent information. Only one among the 20 top firms is European (Thales), and the remaining companies are American or Chinese. It is also remarkable that Airbus Industries is not among the top firms by number of patents.

3.2.3. Patent Structure Analysis

In this section, we examine the technological network derived from the patent technology space. Table 3 represents the percentages of patents for each class, and Tables 4 and 5 present the percentages for each subclass in the categories of physics and operations.

As can be observed in Table 3, among the aviation patents, about 27% belong to the class of Physics, and 25% are in the class of Operations and Transporting. Tables 4 and 5 show the areas with higher concentrations of patents among the subclasses in Operations and Physics. Figure 17 presents a classical sunburst diagram for general macro-classes and their subclasses.

Figure 18 presents a network map of the patent topics relevant to aviation development. Five major clusters are observed in the figure with very limited interconnections. One cluster aggregates classes around power generation topics, including electronics and materials involved in power systems. Another integrates instrumentation, digital computers, optics, printed circuits, and semiconductor materials and processes. The third one pivots around all types of materials used for aviation. The fourth includes electromechanical storage, power distribution, components, converters, and lighting. The last one includes organic compounds, lubricants, etc. It can be seen that, aside from the differences in the names of the classes, there is a high level of correlation between the areas in which patents and publications are produced.

The next step consists of comparing the network structures derived from the analysis of publications (Figure 7) and from the analysis of patents (Figure 18). This figure shows that whereas a high level of cooperation and a mature stage is seen at the level of publication networks, the patent cooperation networks are relatively low and primary.

It can also be seen that there are significant differences in the density between the two networks. The network structure derived from publications presents a lower density exhibiting higher and looser contact, whereas the patent network is denser with less contact between the nodes and a closer structure. Worldwide universities are well represented in the publication networks, while the patent network is dominated by companies, apart from Chinese universities.

It is believed that cooperation should be aimed at the differences to encourage the integration of academic research and applied research so as to promote the development of the subject and the level of aerospace industry.

Table 3. Some patent codes.

Code	%	Definition
G	27.3	Physics
B	24.9	Performing Operations; transporting
H	16.2	Electricity
C	13.1	Chemistry; Metallurgy
F	12.2	Mechanical Engineering; lighting; Heating; Weapons; Blasting
A	3.7	Human Necessities
E	1.3	Fixed Constructions
D	1.3	Textiles; Paper

Table 4. Some patent subcodes.

Code	%	Definition
G01	12.7	Measuring; Testing
B64	9.3	Aircraft; Aviation; Cosmonautics
H01	6.2	Basic Electric Elements
G06	6.2	Computing; Calculating; Counting
H04	4.0	Electric Communication Technique
C08	3.1	Organic Macromolecular Compounds; Their Preparation Or Chemical Working-Up; Compositions Based Thereon
C10	3.1	Petroleum, Gas Or Coke Industries; Technical Gases Containing Carbon Monoxide; Fuels; Lubricants; Peat
F16	2.9	Engineering Elements Or Units; General Measures For Producing And Maintaining Effective Functioning Of Machines Or Installations; Thermal Insulation In General
F02	2.9	Combustion Engines; Hot-Gas Or Combustion-Product Engine Plants
H02	2.8	Generation, Conversion, Or Distribution Of Electric Power
B23	2.6	Machine Tools; Metal-Working Not Otherwise Provided For
G05	2.5	Controlling; Regulating
G08	2.0	Signaling
G09	1.9	Educating; Cryptography; Display; Advertising; Seals
C22	1.7	Metallurgy; Ferrous Or Non-Ferrous Alloys; Treatment Of Alloys Or Non-Ferrous Metals

Table 5. Some patent sub-subcodes.

Code	%	Definition
B64C	4.1	Aeroplanes; Helicopters
B64D	3.7	Equipment For Fitting In Or To Aircraft; Flying Suits; Parachutes; Arrangements Or Mounting Of Power Plants Or Propulsion Transmissions
G06F	3.7	Electric Digital Data Processing
G01N	2.2	Investigating Or Analysing Materials By Determining Their Chemical Or Physical Properties
G01C	1.9	Measuring Distances, Levels Or Bearings; Surveying; Navigation; Gyroscopic Instruments; Photogrammetry Or Videogrammetry
G01M	1.8	Testing Static Or Dynamic Balance Of Machines Or Structures; Testing Structures Or Apparatus Not Otherwise Provided For
C08L	1.7	Compositions Of Macromolecular Compounds
H01L	1.7	Semiconductor Devices; Electric Solid State Devices Not Otherwise Provided For
G01R	1.4	Measuring Electric Variables; Measuring Magnetic Variables
B32B	1.4	Layered Products, I.E. Products Built-Up Of Strata Of Flat Or Non-Flat, E.G. Cellular Or Honeycomb, Form

Figure 17. Sunburst diagram for general Macro-classes and subclasses.

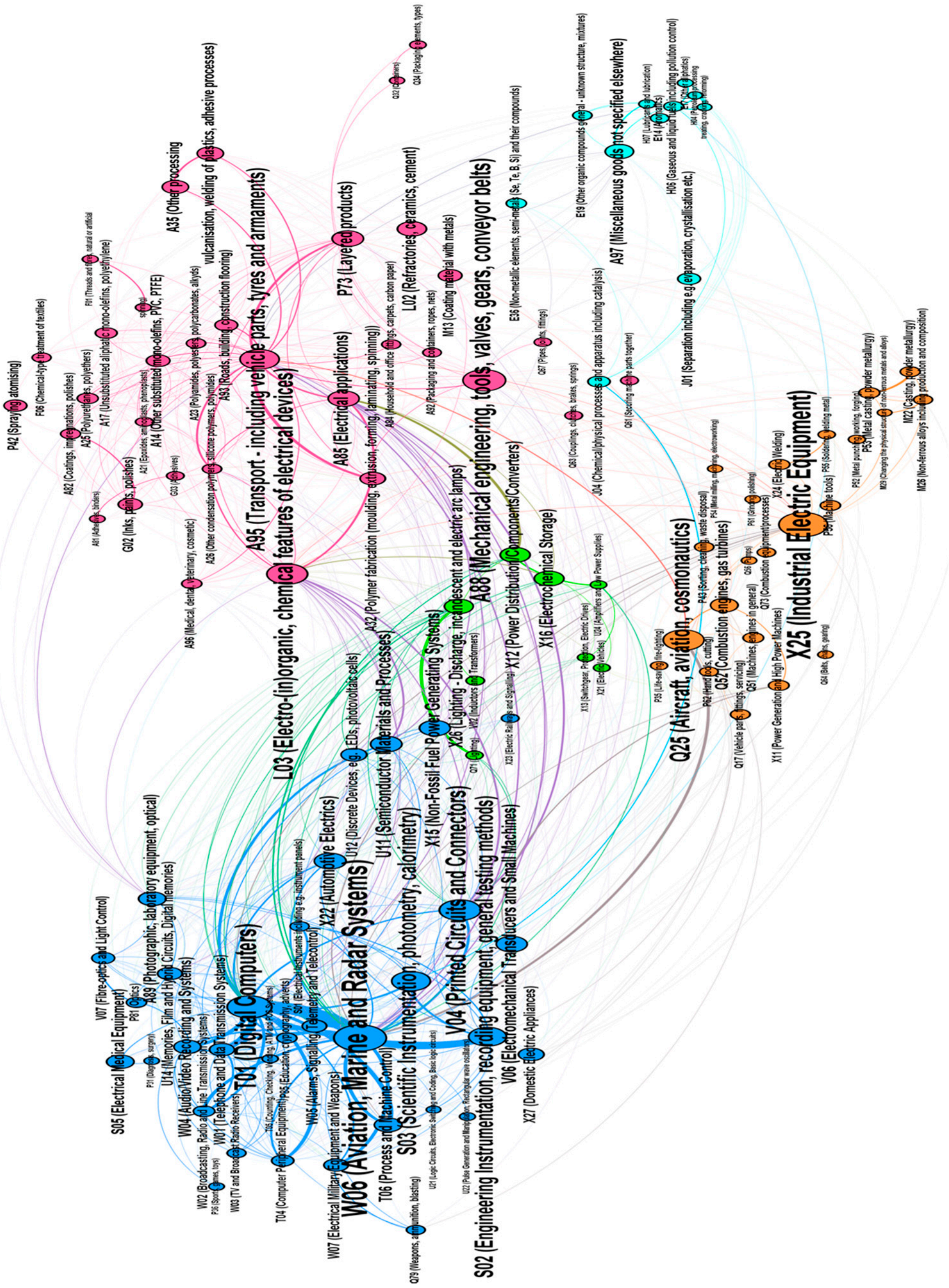

Figure 18. Patents in areas relevant to aeronautics.

4. Conclusions and Recommendations

To cope with the challenges and opportunities that populate the 2050 horizon, the aviation industry needs to maintain its technological innovation capability. To achieve the required level of innovation across the full range of aeronautical products, it will be necessary to (a) master leading-edge technologies in all sectors that contribute to the design of aeronautical vehicles; and (b) collaborate to integrate all of these cutting-edge technologies into efficient aircraft production, certification, and service-support programs.

In this paper, we present the research accomplished by the PARE project to assess the potential for future long-term technological innovation. This assessment was performed through the characterization of a map of the Aviation Technology Space and provides hindsight into two complementary issues: (a) the capacity of the industry to master key technological areas and to innovate within them; and (b) the aerospace collaboration structures and their ability to cooperate effectively and aggregate knowledge and efforts into the innovation path.

On one side, on the basis of the keyword co-occurrence analysis method, we performed a bibliometric network analysis of more than 58,000 aviation research scientific publications available from Web of Science to map the aerospace collaboration structures. Complementarily, we performed an analysis of more than 23,000 aviation patents to evaluate the innovation capacity of the industry in the cutting-edge technologies previously identified.

The analysis demonstrates and identifies the existence of international scientific collaboration networks. Its structure of clusters highlights how the technological capabilities in aerospace engineering are spread or concentrated. The study highlighted not only higher publication frequencies in both China and the USA, but also a high level of correlation between their research topics. It can be observed that in Europe, research capabilities and knowledge are homogeneously spread with a clear geographical correlation into four highly specialized clusters. Additionally, the results presented in this paper corroborate that, regardless of the efforts made, there is still a great gap to close for the effective integration of the EU-13 (The group of 13 EU countries includes: Bulgaria (BG), Croatia (HR), Cyprus (CY), Czech Republic (CZ), Estonia (EE), Hungary (HU), Latvia (LV), Lithuania (LT), Malta (MT), Poland (PL), Romania (RO), Slovakia (SK) and Slovenia (SI)) countries' aeronautical potential research capabilities into the European scheme.

To foster innovation, aviation research policy should support a view that every cluster can continue gaining excellence in different subfields. At the same time, research policy must facilitate the aggregation of the dispersed experience and knowledge in each subfield into a shared platform for the aviation industry. Particularly, in light of the weak connections between European clusters, the United States clusters, and China's publications, a specific analysis of China's research may provide the insight needed to develop a competitive aerospace innovation policy in other regions.

The analysis also allows for identifying the current main aerospace subfields of research within this international scientific collaboration network. By using the co-occurrences of different Web of Science categories, five main clusters are identified covering the following fields:

1. Mechanical engineering, including biomedical engineering, robotics, and manufacturing;
2. Physics, automation, telecommunications, electric-electronics, and computer science;
3. Materials science optics, nanoscience, and remote sensing;
4. Energy and polymer science;
5. Acoustics, thermodynamics, environmental studies, and geology.

Mechanical engineering, telecommunications, electrical and electronics engineering, instrumentations, astronomy and astrophysics, optics, and mechanics have the highest frequency of co-occurrence with aerospace engineering in the literature, evidencing the areas in which aerospace engineering publications are concentrated. However, these areas are not highly interconnected, evidencing a lack of common research, thus losing potential synergies that could foster innovation. This lack of common research is particularly evident between physics, computer science, and material engineering. These are three fields in which collaboration is required to boost aviation innovation. To fill this gap, it will be necessary to promote collaborative studies between these areas as part of the aerospace innovation funding policy.

The greatest patent growth has taken place in the categories of operations and physics. Second in growth, named medium classes, are electricity, mechanical engineering, and chemistry. In contrast, the area of human factors has experienced very low growth, and the area of textiles has experienced practically no growth.

It is clear from the results that China is the country with the highest number of patents in aviation. Another conclusion derived from the above analysis is that specific geographical differences exist between aerospace science and technology journals and patent information. Only one among the

20 top firms is European (Thales), and the remaining companies are American or Chinese. It is also remarkable that Airbus is not among the top firms by number of patents.

A network map of the patent topics relevant to aviation development shows five major clusters with very limited interconnections. Apart from the differences in the names of the classes, there is a high level of correlation between the areas in which patents and publications are produced.

The global institutional collaboration network shows that while there is a significant dominance of universities and research centers worldwide in the publication network, there are only a few universities among the top 20 firms by number of patents, and all of them are Chinese universities. This highlights the lack of capacity of universities in Europe, as well as in the USA, to translate basic research into products and industrial innovation. Future innovation and research policies should contribute to closing the existing research and innovation gap between academia and the aeronautical industry to encourage the integration of academic research and applied research so as to promote the development of the subject and the level of aerospace industry.

This study has some limitations that should be overcome in future studies. A deeper merging of publication data and patents could be achieved by completing this analysis with patent citations, particularly the unification of inventor and author names, as well as patent-to-patent citations. This will allow for the analysis of the quality of the patents. The analysis should be repeated periodically to verify the advancement of research and innovation toward the goals of aviation in 2050. Additionally, further studies should investigate in more detail whether current research and innovation will actually be capable of addressing the challenges of the future. An analysis of the level of maturity of the research reflected in patents and publications, as well a more detailed technological coverage map could be developed to address this last topic.

Author Contributions: Conceptualization, V.F.G.C.; Data curation, S.B.; Formal analysis, R.M.A.V., S.B., V.T., and V.F.G.C.; Investigation, R.M.A.V. and S.B.; Methodology, R.M.A.V. and S.B.; Project administration, V.T.; Resources, L.M.B.d.C.C.; Validation, S.B. and L.M.

Funding: This research was funded by the European Union within the framework of the EU's Horizon 2020 research and innovation program, Grant number 769220, project PARE.

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

References

1. Industry High Level Group (IHLG). *Aviation Benefits 2017*; Industry High Level Group (IHLG); ACI (Airport Council International); CANSO; IATA (International Airlines Transport Association); ICAO (International Civil Aviation Organization): Montreal, QC, Canada, 2013; Available online: https://www.iata.org/policy/documents/aviation-benefits-%20web.pdf (accessed on 6 April 2019).
2. *Boeing Markter Outlook*; Boeing Commercial Airplanes: Seattle, WA, USA, 2018.
3. *Global Market Forecast—Global Networks, Global Citizens, 2018–2037*; Airbus S.A.S.: Blagnac Cedex, France, 2018.
4. PARE Consortium. PARE Project. Available online: www.pareproject.eu (accessed on 12 December 2018).
5. Alstott, J.; Triulzi, G.; Jianxi, B.Y. Mapping Technology Space by Normalizing Patent Networks. *Scientometrics* **2017**, *110*, 443–479. [CrossRef]
6. Silverberg, G.; Verspage, B. Self-organization of R&d search in complex technology spaces. *J. Econ. Interact. Coord.* **2007**, *2*, 211–229.
7. Leydesdorff, L.; Kushnir, D.; Rafols, I. Interactive overlay maps for US patent (USPTO) data based on International Patent Classi_cation (IPC). *Scientometrics* **2014**, *98*, 1583. [CrossRef]
8. Kay, L.; Newman, N.; Youtie, J.; Porter, A. Patent Overlay Mapping: Visualizing Technological Distance. *J. Assoc. Inform. Sci. Technol.* **2014**, *65*, 2432–2443. [CrossRef]
9. Arthur, W.B. *The Nature of Technology: What It Is and How It Evolves*; Simon and Schuster: New York, NY, USA, 2009.

10. Kroes, M.J.; Nolan, M.S. *Aircraft Basic Science*, 8th ed.; McGraw-Hill Education: New York, NY, USA; Chicago, IL, USA; San Francisco, CA, USA; Athens, Greece; London, UK; Madrid, Spain; Mexico City, Mexico; Milan, Italy; New Delhi, India; Singapore, Singapore; Sydney, Australia; Toronto, VA, Canada, 2013.
11. Mongeon, P.; Paul-Hus, A. The Journal Coverage of Web of Science and Scopus: a Comparative Analysis. *Scientometrics* **2015**, *106*, 213–228. [CrossRef]
12. CWTS. Available online: https://www.cwts.nl/ (accessed on 12 December 2018).
13. Ernst, H. Patent information for strategic technology management. *World Pat. Inform.* **2003**, *25*, 233–242. [CrossRef]
14. Kurtossy, J. Innovation indicators derived from patent data. *Period. Polytechn. Ser. Soc. Man. Sci.* **2004**, *12*, 91–101.
15. Watts, R.; Porter, A.; Cunningham, S.; Zhu, D. Vantage point intelligence mining: Analysis of natural language processing and computational linguistics. In *Principles of Data Mining and Knowledge Discovery*; Komorowski, J., Zytkow, J., Eds.; Springer: Heidelberg, Berlin, 1997.
16. Wu, D.; Xie, Y.; Dai, Q.; Li, J. A systematic overview of operations research/management science research in Mainland China: Bibliometric analysis of the period 2001–2013. *Asia-Pacific J. Operat. Res.* **2016**, *33*, 1–26. [CrossRef]
17. Yang, Y.; Wu, M.; Cui, L. Integration of three visualization methods based on co-word analysis. *Scientometrics* **2012**, *90*, 659–673. [CrossRef]
18. An, X.; Wu, Q. Co-word analysis of the trends in stem cells field based on subject heading weighting. *Scientometrics* **2011**, *88*, 133–144. [CrossRef]
19. Dehdarirad, T.; Villarroya, A.; Barrios, M. Research trends in gender differences in higher education and science: A co-word analysis. *Scientometrics* **2014**, *101*, 273–290. [CrossRef]
20. Chena, X.; Chena, J.; Wua, D. Mapping the research trends by co-word analysis based on keywords from funded project. *Procedia Comput. Sci. ITQM* **2016**, *91*, 547–555. [CrossRef]
21. Lee, B.; Jeong, Y. Mapping Korea's national R&D domain of robot technology by using the co-word analysis. *Scientometrics* **2008**, *77*, 3–19.
22. Liu, G.; Hu, J.; Wang, H. A co-word analysis of digital library field in China. *Scientometrics* **2012**, *91*, 203–217. [CrossRef]
23. Lin, J. Analysis of Development and Research Trends of Aerospace Engineering Based on CiteSpaceII. *Adv. Mater. Res.* **2014**, *945–949*, 3400–3405. [CrossRef]
24. Xiuxiu, M.; Ping, Q.; Xiaotao, L. Visualization Analysis on Collaborative Network and Research Hot-Spot for Aerospace Engineering Subject. *Adv. Eng. Res.* **2017**, *118*, 2017.
25. Karki, M. Patent citation analysis: A policy analysis tool. *World Pat. Inform.* **1997**, *19*, 269–272. [CrossRef]
26. Lee, K.; Kim, K.; Cho, Y. A study on the relationship between technology diffusion and new product diffusion. *Technol. Forecast. Soc. Chang.* **2010**, *77*, 796–802. [CrossRef]
27. Chang, S.; Lai, K.; Chang, S. Exploring technology diffusion and classification of business methods: Using the patent citation network. *Technol. Forecast. Soc. Chang.* **2009**, *76*, 107–117. [CrossRef]
28. Cotropia, C.A.; Lemley, M.A.; Sa, B. Do applicant patent citations matter? *Res. Policy* **2013**, *42*, 844–854. [CrossRef]
29. Curran, S.; Leker, J. Patent indicators for monitoring convergence—Examples from NFF and ICT. *Technol. Forecast. Soc. Chang.* **2011**, *78*, 256–273. [CrossRef]
30. Schmookler, J. *Invention and Economic Growth*; Harvard University Press: Cambrige, UK, 1966.
31. Daim, T.U.; Rueda, G.; Martin, H. Forecasting emerging technologies: Use of bibliometrics and patent analysis. *Technol. Forecast. Soc. Chang.* **2006**, *73*, 981–1012. [CrossRef]
32. Nelson, A.J. Measuring Knowledge Spillovers: What Patents, Licenses and Publications Reveal About Innovation Diffusion. *Res. Policy* **2010**, *38*, 994–1005. [CrossRef]
33. Choi, D.; Song, B. Exploring Technological Trends in Logistics: Topic Modeling-Based Patent Analysis. *Sustainability* **2018**, *10*, 2810. [CrossRef]
34. Gress, B. Properties of the USPTO patent citation network: 1963–2002. *World Pat. Inf.* **2010**, *32*, 3–21. [CrossRef]
35. Yoon, B.; Park, Y. A text-mining-based patent network: Analytic tool for high-technology trend. *J. High Technol. Manag. Res.* **2004**, *15*, 37–50. [CrossRef]

36. Nakamura, H.; Suzuki, S.; Sakata, I.; Yuya, K. Knowledge combination modeling: The measurement of knowledge similarity between different technological domains. *Technol. Forecast. Soc. Chang.* **2015**, *94*, 187–201. [CrossRef]
37. Kwon, H.; Lee, C. A study on aviation technology forecast for sustainable (green) aviation using patent analysis. *LNEE* **2012**, *203*, 633–642.
38. Report on the Aeronautical Research Activities and Capabilities of New Member States of the European Union. Advisory Council for Aeronautical Research in Europe (ACARE) Member States Group WT6, 2007. Available online: https://www.airtn.eu/downloads/report-on-the-aeronautical-research-activities.pdf (accessed on 6 April 2019).
39. EPRs (European Parliamentary Research Service); Scientific Foresigth Unit (STOA). Overcoming innovation gaps in the EU-13 Member States. Study. *Sci. Technol. Options Assess.* **2018**. Available online: http://www.europarl.europa.eu/RegData/etudes/STUD/2018/614537/EPRS_STU(2018)614537_EN.pdf (accessed on 7 April 2019).
40. Chen, L.Y. Bloomberg New Economy. Available online: https://www.bloomberg.com/new-economy-forum (accessed on 12 December 2018).
41. Dang, J.; Motohashi, K. Patent statistics: A good indicator for innovation in China? Patent subsidy program impacts on patent quality. *China Econo. Rev.* **2015**, *35*, 137–155. [CrossRef]
42. Fisch, C.; Sandner, P.; Regner, L. The value of Chinese patents: An empirical investigation of citation lags. *China Econ. Rev.* **2017**, *45*, 22–34. [CrossRef]
43. Aaboen, L.; Laage-Hellman, J.; Frida, L. University Spin-Offs and Their Roles in Business Networks. *Ind. Mark. Manag.* **2014**. Available online: https://www.impgroup.org/uploads/papers/8151.pdf (accessed on 7 April 2019).
44. Müller, K. Discussion Paper No. 08-034 University Spin-Off's Transfer Speed—Analyzing the Time from Leaving University to Venture. Available online: https://www.zew.de/en/publikationen/university-spin-offs-transfer-speed-analyzing-the-time-from-leaving-university-to-venture/?cHash=b4d0d68953ab19d1195a6f361d1bc638 (accessed on 7 April 2019).
45. European Commission Directorate-General for Research and Innovation. *Directorate General for Mobility and Transport. Flightpath 2050 Europe's Vision for Aviation Report of the High Level Group on Aviation Research*; Publications Office of the European Union: Luxembourg, 2011; Available online: https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf (accessed on 7 April 2019).
46. Soffer, B. Interviewee: Chairman of Israel Tech Transfer Network and Head of the T3 TEC. 2018. Available online: https://www.israel21c.org/why-israel-rocks-at-commercializing-academic-innovations (accessed on 12 December 2018).