CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF TRANSPORTATION SCIENCES

BUSINESS AVIATION AND ITS CONNECTIVITY IN EUROPE

Bachelor's thesis

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

(PROJEKTU, UMĚLECKÉHO DÍLA, UMĚLECKÉHO VÝKONU)

Jméno a příjmení studenta (včetně titulů):

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Studijní program (obor/specializace) studenta:

bakalářský – LED – Letecká doprava

Název tématu (česky): **Byznys letectví a jeho konektivita v Evropě**

Název tématu (anglicky): Business Aviation and its connectivity in Europe

Zásady pro vypracování

Při zpracování bakalářské práce se řiďte následujícími pokyny:

- Cílem práce je zmapovat a vyhodnotit provoz byznys letectví v Evropě, určit páteřní síť byznys letectví a vyhodnotit konektivitu významných letišť za časová období 2019–2021
- Představte byznys letectví v Evropě, jeho charakteristiky a principy fungování letadel v rámci sítě letišť z provozního i teoretického pohledu
- Vytvořte přehled datových zdrojů pro analýzu a metodiku jejich sběru a zpracování
- Proveďte analýzu konektivity a dalších ukazatelů propojení jednotlivých letišť Evropy
- Výsledky analýzy interpretujte a diskutujte
- Proveďte závěr a validaci metodického postupu

Rozsah grafických prací: dle pokynů vedoucího práce

Rozsah průvodní zprávy: minimálně 35 stran textu (včetně obrázků, grafů a tabulek, které jsou součástí průvodní zprávy)

Seznam odborné literatury: Allroggen, F., et. al - How Air Transport Connect the World: New Metrics of Air Connectivity and its Evolution (2015)
OECD - Defining, Measuring and Improving Air Connectivity (2018)
ACI - Airport Industry Connectivity Report (2021)

Vedoucí bakalářské práce: **doc. Ing. Peter Vittek, Ph.D.**

Ing. Tereza Dvořáková

Datum zadání bakalářské práce: **8. října 2021**
(datum prvního zadání této práce, které musí být nejpozději 10 měsíců před datem prvního předpokládaného odevzdání této práce vyplývajícího ze standardní doby studia)

Datum odevzdání bakalářské práce: **8. srpna 2022**
a) datum prvního předpokládaného odevzdání práce vyplývající ze standardní doby studia a z doporučeného časového plánu studia
b) v případě odkladu odevzdání práce následující datum odevzdání práce vyplývající z doporučeného časového plánu studia

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Potvrzuji převzetí zadání bakalářské práce.

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V Praze dne .... 10. března 2022

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BACHELOR'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Kamila Rybenská

Study programme (field/specialization) of the student:

bachelor's degree – LED – Air Transport

Theme title (in Czech): **Byznys letectví a jeho konektivita v Evropě**

Theme title (in English): **Business Aviation and its connectivity in Europe**

Guidelines for elaboration

During the elaboration of the bachelor's thesis follow the outline below:

- The aim of the thesis is to map and evaluate business aviation operations in Europe to determine a core network of business aviation and evaluate connectivity of significant airports in the time period 2019 - 2021.
- Introduce business aviation in Europe, its characteristics, and principles of aircraft operations in the network of airports from both theoretical and operational perspective.
- Create an overview of data sources for the analysis and data collection and processing methodology.
- Perform the analysis of connectivity and other interconnection parameters of individual airports in Europe
- Interpret and discuss results of the analysis
- Make a conclusion and methodological process validation

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Graphical work range: according to the instructions of thesis supervisor

Accompanying report length: minimum of 35 text pages (including figures, graphs and sheets which are part of the main text)

Bibliography:

Allroggen, F., et. al - How Air Transport Connect the World: New Metrics of Air Connectivity and its Evolution (2015)

OECD - Defining, Measuring and Improving Air Connectivity (2018)

ACI - Airport Industry Connectivity Report (2021)

Bachelor's thesis supervisor: **doc. Ing. Peter Vittek, Ph.D.**
Ing. Tereza Dvořáková

Date of bachelor's thesis assignment: **October 8, 2021**
(date of the first assignment of this work, that has be minimum of 10 months before the deadline of the theses submission based on the standard duration of the study)

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a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule
b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

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I confirm assumption of bachelor's thesis assignment.

Kamila Rybenská
Student's name and signature

Prague .... March 10, 2022

Declaration

I hereby declare that I have prepared the bachelor's thesis entitled Business Aviation and its Connectivity in Europe independently and have used a complete list of citations of the sources used, which are given in the list attached to the bachelor's/diploma thesis.

I do not have a serious reason against the use of this school work within the meaning of §60 of Act No.121/2000 Coll., on Copyright, on Rights Related to Copyright and on Amendments to Certain Acts (Copyright Act).

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Abstract

The subject of the thesis is the European Business Aviation network and its connectivity response to the COVID-19 pandemic. To date, not so much attention was paid to business aviation, compared to other sectors, therefore the thesis also shows the importance of business aviation from both an economic and connectivity perspective. The Flow centrality method is adapted to the sector and its Connectivity Indicator is used for both the determination of the core network and the cluster analysis. The results of this study indicate that airport clusters can be found in the network, and their connectivity values in 2021 were already able to return to their pre-covid characteristics observed in 2019. The thesis also discovered the difference between the number of flights and airport connectivity values, indicating the Flow centrality method could provide important insight into the performance of the business aviation network.

Key words

Business aviation, cluster analysis, connectivity, COVID-19

Abstrakt

Tématem této práce je evropská síť byznys letectví a její reakce na pandemii COVID-19. Doposud nebylo byznys letectví věnováno tolik pozornosti ve srovnání s jinými odvětvími, proto práce také ukazuje význam byznys letectví, a to jak z ekonomického hlediska, tak z hlediska konektivity. Metoda Flow centrality byla adaptována pro toto odvětví a její Connectivity Indicator byl použit jak pro určení páteřní sítě, tak pro shlukovou analýzu. Výsledky této studie naznačují, že v síti lze nalézt shluky letišť, a že jejich hodnoty konektivity se již v roce 2021 dokázaly vrátit k předcovidovým charakteristikám roku 2019. Práce rovněž odhalila rozdíl mezi počtem letů a hodnotami konektivity letišť, což naznačuje, že metoda Flow centrality může poskytnout důležitý vhled do výkonnosti sítě byznys letectví.

Klíčová slova

Byznys letectví, cluster analýza, konektivita, COVID-19

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Table of Contents

List of abbreviations

ADS-B	Automatic Dependent Surveillance–Broadcast
AOC	Air Operator’s Certificate
CEO	Chief Executive Officer
EBAA	European Business Aviation Association
E-STAT	EBAA Statistics, Tables and Analytics Tools
GVA	Gross Value Added
IATA	International Air Transport Association
IBAC	International Business Aviation Council
ICAO	International Civil Aviation Organisation
IQR	Interquartile range
OECD	Organization for Economic Co-operation and Development
PCA	Principal Component Analysis
S&P 500	Standard and Poor's 500

Introduction

The main purpose of this thesis is to map and analyse operation of business aviation sector in Europe, determine its core network and analyse connectivity of its important airports during 2019 - 2021. Although it is a very important part of aviation, it is considered as the consequence of the development and global extension of traditional aviation among the general public, and, as Oxford Economics [1] and Booz et al. [2] show in their studies, has a great impact on the economy, connectivity and many other aspects, Fichert et al. [3] and Budd and Graham [4] conclude that this field seems to be overlooked by the academic community and only a small amount of scientific work has been done in this sector of aviation.

Business aviation cannot be treated as a traditional one due to its completely different operating principles, resulting in the impossibility of applying the commonly used methods for analysis and economical evaluation and prediction. The main differences are, for example, the on-demand operations, deliberate use of connecting flights and unimportance of the load factor of the flight. These differences result in the irrelevance of, very commonly taken into account, indirect connections and other indicators used in different methodologies like for example very popular NetScan and IATA connectivity index [5].

The aim of this thesis is to present a possible method for evaluating the connectivity of business aviation, taking into account its nature, and thereby to propose a way to describe the properties of both business and commercial aviation in a comparable way. This will give opportunity to investigate a possible correlation between the two sectors and also a tool for deeper understanding of its properties. This could be used as a starting point for further analytical description of this business aviation sector, leading to its more effective utilization, for example, how to operate the aircraft fleet more efficiently, therefore, more profitably.

As already mentioned, the next objective is to analyse a response of business aviation connectivity to the COVID-19 pandemic, which massively struck the global aviation industry, starting in the spring of 2020 and continually causing huge consequences in the following years. EBAA [6] shows, the business aviation, unlike airlines experienced a speedy recovery. Moreover, many companies, like Eclair Aviation [7], reported operating more flights, compared to previous years, which may indicate a shift of airline passengers to this sector, when there were strongly limited or no scheduled flight connections. When the airlines were grounding a major part of their fleet or flying empty planes to keep their slots, business aviation companies experienced a boom. For example, a Czech business aviation charter company, Time Air, in fact expanded their fleet during this pandemic [8] and many operators, like Éclair Aviation [7], also agreed, there was a high percentage of new clients using their aircraft.

For these purposes, a two-dimensional airport classification methodology of flow centrality, introduced by Déniz et al. [9] was used. This method differs in its applicability on demand-based operations, where the only assessed parameter is the number of flights. Subsequently, a cluster analysis was used for a more detailed view of airport behaviour based on their connectivity during the pandemic, compared to the year 2019.

The data used were provided by EBAA (European Business Aviation Association) and contain information about all active city pairs, and number of flights between them in the analysed period. The time range is January 2019 – December 2021. This period should give sufficient information on connectivity of both ordinary and Covid-affected networks.

1 Business aviation

1.1 Definition

Business aviation is officially defined sector of aviation by the International Business Aviation Council (IBAC), an organization cooperating and participating in various ICAO bodies whose work affects the sector. The IBAC advocates through ICAO worldwide on behalf of the business aviation community.

Business aviation is defined by IBAC [10] as: *“That sector of aviation which concerns the operation or use of aircraft by companies for the carriage of passengers or goods as an aid to the conduct of their business, flown for purposes generally considered not for public hire and piloted by individuals having, at the minimum, a valid commercial pilot license with an instrument rating.*

Definition Sub-divisions:

a) Commercial - the commercial operation or use of aircraft by companies for the carriage of passengers or goods as an aid to the conduct of their business and the availability of the aircraft for whole aircraft charter, flown by a professional pilot(s) employed to fly the aircraft.
b) Corporate - the non-commercial operation or use of aircraft by a company for the carriage of passengers or goods as an aid to the conduct of company business, flown by a professional pilot(s) employed to fly the aircraft.
c) Owner operated - the non-commercial operation or use of an aircraft by an individual for the carriage of passengers or goods as an aid to the conduct of his/her business.”

The next definitions, further specifying the sector, are by FAA and ICAO, who define it as a part of general aviation, meaning the flights are not conducted by commercial air carriers (including commuter/ regional airlines) and military.

This work is mainly focused on the commercial section of business aviation, where companies own general aviation aircraft to conduct their business. The aircraft is used as a charter, which means it operates on-demand, non-scheduled flights.

1.2 History

At first, commercial aviation was highly regulated both nationally and internationally, restricting the competition between airlines. These included control on market access, on offered capacity, frequency of flights, and pricing. According to Doganis [11], the first considerable economic and political arguments in favour of deregulation of the airline industry arose in the USA in the mid-1970s, proclaiming that it prevents the travelling public from enjoying the options of air travel. The causes were, for example, a limited range of choice of the airline. The airlines served only limited number of cities and owned high-cost and inefficient airplanes resulting in high fares.

Many previous studies on aviation history, such as Budd and Graham [4], show that the liberalization of the market led to competition for price, capacity, frequency, and route between airlines. Many airlines were privatized and their networks were reorganized around their key hub airports, they focused on reducing the operating costs but also on developing new marketing tools and operating practises. Carriers have entered code sharing and alliance agreements to better meet demand. Since the mid-1980s, the number of airline passengers has been scaling up to the point where the airline industry became the victim of its own success. The limited capacities of both airports and airways started causing delays, creating large-scale costs for the entire industry and the global economy through the lost productivity. Schummer and Maloney [12] claim, that delays or cancellations cost both airlines and passengers a billion dollars per year. Passengers' costs include missed connecting flights, therefore, lost productivity through missed meetings, reduced vacation time, or hotel bookings cancellations.

As Budd and Graham [4] concluded in their research, the dissatisfaction of passengers, especially business and first-class travellers, began to slowly form the business aviation market. Airlines also started to offer business jets to provide connections for their premium passengers.

Nowadays, a well-established concept of the business aviation market originated in the United States after World War One. However, the typical genre of private business aviation developed in the mid-1930s, when American manufactures, such as Cessna, Beech, and Piper, began to produce light aircraft for private flights. The second World War innovations in aircraft design enabled manufacturers to produce the first jet-powered aircraft for private flights and, according to Jacbs and Goebel [13], their deliveries began in 1960s. The best-known example is William Lear's Learjet. According to BBC [14], Seaton [15] and the book Jet Set [16], Frank Sinatra was then one of the first celebrities purchasing a business jet (Learjet 24) for his own traveling. This trend achieved great success and quickly became the preferred method of travel for many rich and famous celebrities, sportsmen etc. However, high acquisition, maintenance, and operating costs caused business aviation remained perceived for a long time as a luxury obtainable by a few.

1.3 Advantages over Commercial Aviation

As mentioned above, Budd and Graham [4] state that the progressively more 'stressful', ineffective, impersonal nature of modern air travel was increasingly being articulated. Airline passengers may encounter a lot of unpleasant situations, such as lost luggage, delays, overcrowding, cancellations, etc. Among a certain group, this has created a demand for travelling differently.

Business aviation offers comfortable and pleasant travel, according to client's schedule and preferences. It includes improved time and cost efficiency, enhanced personal safety, reduced opportunities for industrial espionage, access to a wider range of airports and, as Budd and Graham [4], Andersen [17] and Oxford Economics [1] agree, increased employee productivity.

According to surveys previously presented by Hankovská [18] and Oxford Economics [1], the main reason customers prefer business aviation is to save time. Passengers do not have to be at the airport several hours prior to their flight and wait for it. In this sector, it is the flight that waits for the passengers, and taking them directly to their desired destination, without the need of transfers.

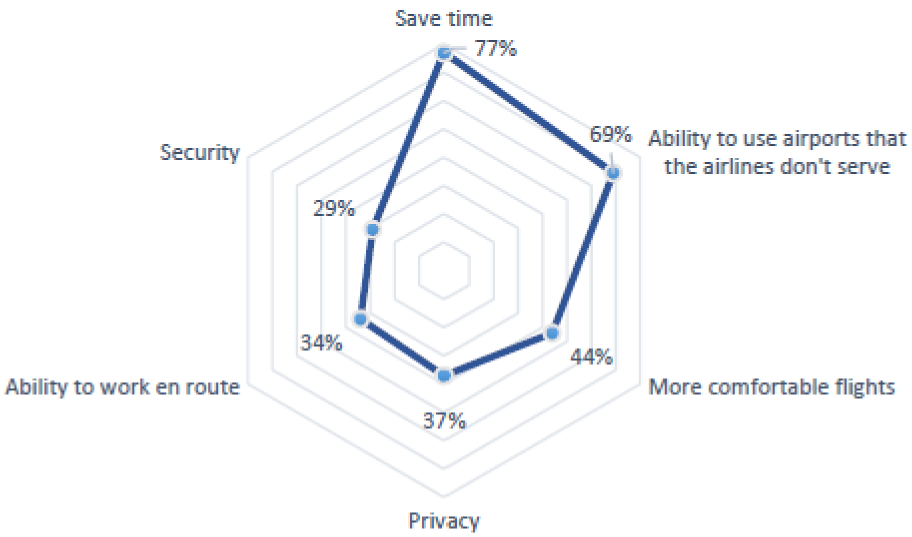


Figure 1 Business aviation customers' preferences [18]

In fact, according to Booz et al. [2], passengers using business aviation can reduce up to 12 minutes per trip compared to the fastest airline connection. With this time saving, the company can save about 1380 man-hours a year. Booz et al. [2] also adds that about 16 000 business aviation trips consisted of more than three flights per day. This could altogether save 75 000 overnight hotel stays, representing approximately 15 million in hotel costs.

Altogether, business aviation can, in fact, become a more effective alternative to commercial airlines with the added value of comfortable cabins, safety, and privacy, which are by Oxford Economics [1] another important reason why business executives choose this type of travel.

1.3.1 Corporate aircraft

Andersen [17] states that according to his previous study on S&P 500 companies in 2001, those who operated aircraft earned 146% more in cumulative returns between 1992 and 1999, in contrast to non-operators. However, he also adds that every company is different and recommends performing an analysis, whether the business aviation is suitable for the particular subject.

The use of business aviation aircraft offers greater mobility to employees, which improves their productivity. This can be applied not only on top managers but also on technicians in case of any urgencies. Increased mobility can therefore lead to reduction of employees. There could be, for example, only one engineering team for a number of facilities around Europe, and thereby reducing wage costs. Alternatively, corporate aircraft can deliver crucial parts when conventional transportation methods fail and avoid the costs of stopped production.

On the contrary, when not used by the staff, the aircraft can be leased to a charter company to increase its utilization and still generate profit. This business method was described by Nigham et al. [19] and Oxford Economics [1] and is called fractional ownership. It is discussed in more detail in Chapter 1.4.1.

Companies often do not see the advantages they can gain, yet they are concerned of public perception of private jets as costly and unnecessary accessories. Andersen [17] gives them a basic understanding of the possibilities and advantages of owning a corporate aircraft and also provides a tool to analyse options for their own business.

1.3.2 Business charter

Companies can use business aircraft without actually owning one. Charter companies can offer a great compromise for those who cannot or do not want to purchase their own plane, but still see the benefits of it.

Certainly, this is not as flexible solution as owning an aircraft because they need to rely on an external company and the availability of their airplanes. On the other hand, these companies still offer better flexibility than commercial airlines and there are several of them in every country to reliably meet the demand. Moreover, the advantages include the possibility of choosing the right airplane size for every particular trip as well as saving money for the aircraft maintenance.

1.4 Charter companies operation

As an on-demand sector, business aviation offers numerous possibilities, with the same underlying principles: the flight is tailor-made to fit passengers needs and preferences.

In the commercial sector of business aviation, most companies operate their airplanes in a point-to-point manner, rather than the hub-and-spoke method, preferred by the airlines. They often have a floating fleet, meaning that the airplanes do not start their flights from the company base, but from a place where the previous flight ended.

1.4.1 Business models

Business aviation companies are usually based on widely used modes of aircraft operation and ownership. The basic division, according to IBAC, is mentioned Chapter 1.1; however, Nigham et al. [19] and Oxford Economics [1] add another, widely spread type: fractional ownership.

Fractional ownership could be considered as both an owner and a commercial operation. The aircraft is owned by a company for a group of owners who hold minimum shares of the aircraft. It normally flies non-commercial flights, but it can conduct a commercial operation in accordance with the company's Air Operator's Certificate (AOC). This is used, for example, by one of the largest business jet companies, NetJets.

Besides that, a survey on 74 business air charter companies from all over the world carried out by Fichert et al. [3] shows that around 43% of companies have some type of cooperation with other business aviation companies, this includes alliances, aircraft leasing, or marketing. 21% have shared fleet with other business aviation companies and some of them even cooperate with airlines.

The operations of this sector also include humanitarian and charitable flights. Due to the fleet flexibility, quick reaction times, and the aircraft capability of flying into smaller, more challenging airports with smaller runways, the business aviation aircraft are often the first to provide help in disaster areas.

Special type of operation are medical and repatriation flights. For example, there were about 70 repatriation flights a day during the COVID-19 pandemic, according to IBAC for Uniting Aviation [20]. Business aviation aircraft can quickly and efficiently transport patients for their treatment, whether by helicopters or turboprop or jet airplanes.

1.4.2 Destinations

Passenger surveys, as presented by Oxford Economics [1], show that another great advantage over airlines is the ability to reach destinations without scheduled flights. In fact, Oxford Economics [1] also claims that 96% of the city pairs served by business aviation in Europe in 2011 had no scheduled connection and that business aviation flies to more than three times the number of airports served by scheduled services.

Business aviation offers the alternative to crowded airplanes and airports, impersonal services, and delays. To provide these, aircraft often operate to smaller airports rather than large international hub airports operated by airliners. This is also confirmed by Oxford Economics [1], who claim that 70% of European business aviation flights serve airports with fewer than 100 departures per day. This also offers privacy for the client, which is often a very important reason for using this aviation sector, accompanied with a more personal approach and more possibilities of tailor-made services.

These airports are often focused primarily on business aviation sector, offering more professional services and options like door-to-door boarding directly from their car with chauffer parking the car and then driving it back to the aircraft upon their arrival.

Using smaller airports can also result in less expensive airport fees, as well as faster security, customs, and immigration process, as well as shorter taxiing time and less delays, or eventually no delays at all. For example, the well-known Biggin Hill Airport is dedicated to business aviation. It is located 24 kilometres southeast of London and advertises its benefits as no runway slots and door-to-door helicopter shuttle to central London with flight time of only 6 minutes [21]. It also offers catering, ground transportation, aircraft cleaning, and maintenance.

1.4.3 Aircraft

The most common aircraft in this sector are private jet airplanes. Their range of operation and flight speed make them the most suitable way to travel around Europe. They can be, according to Spangler [22] and Jetex [23] , divided into 7 categories:

Very light jets – small airplanes for 4-6 passengers, often used for shorter routes. The range of operation is around 2 000 km. On the other hand, it can reach airports with very short runways. Typical and mostly used examples include: Cessna Citation Mustang, Embraer Phenom 100 or Hondajet HA-420.

Light jets – offer more passenger capacity and space. Can seat up to 8 people, but no flight attendant. The range is up to 4 600 km. Unlike most Very light jets, these airplanes can be equipped with a lavatory. The most preferred types are Hawker 400XP, Cessna Citation CJ2, or Pilatus PC 24.

Midsize jets – are optimal for passengers flying longer, even transcontinental routes. The average range is around 4 000 km or a five-hour non-stop flight. It standardly has full standing capacity in the cabin, additional space for luggage and galley. It can transport up to 10 passengers with the services of a flight attendant. Types include Learjet 60, Gulfstream 6150 and the most preferred Cessna Citation Latitude.

Super Midsize jets – can fly up to 7 hours non-stop flights with an average range of 6 500 km. They offer a spacious standing cabin, enclosed lavatory, and service galley. These airplanes often provide quieter operation than smaller ones. The most known are the following: Cessna Citation Sovereign, Bombardier Challenger 350 and Gulfstream G280.

Large jets – first-class seats with more legroom, two flight attendants managing full in-flight catering for 10 or more passengers are included. Cabins can even have dedicated sleeping areas and Wi-fi. The operating range is around 9 hours or 7 500 km. Preferred types are: Dassault Falcon 900, Gulfstream 450 and Bombardier Challenger 605.

Ultra-long-range jets – are referred in some literature. These are large jets dedicated for very long flights. They offer closed areas for dinning, work, entertainment and relaxation, with lie-flat beds. They comfortably seat 14-17 passengers and can fly up to 12 000 km with the speed up to Mach 0.9. The latest models are Gulfstream V, Dassault Falcon 10X and Bombardier Global 6000.

Bizliners – these are modified commercial aircraft models, making them the most expensive and best jets in the market. They can offer private spacious suites, showers, cocktail lounge, spacious dining areas, conference rooms. and full-service galleys manned with flight attendants. These airplanes can handle 10-hour trips to 19 – 50 passengers. The most popular are Boeing BBJs, Airbus ACJ, and Embraer Lineage 1000.

However, for shorter trips are also used turboprop airplanes. The advantages of turboprop aircraft lie in the required runway length, making it a great solution for travelling to smaller airports, cheaper operational costs on short distances, and more payload capacity. For example, according to Gollan [24] and Robb Report [25], Kenny Dichter, CEO and co-founder of business aviation charter company Wheels up, having a majority of King Airs 350i in their fleet, 80% of all private jet flights are less than 2 hours in the US, where the benefits of turboprops would outweigh those of jet airplanes. Mr. Dichter adds that there is a strong increase of customer interest in the turboprop travelling with clients starting to realize that.

1.5 Economic contribution of the business aviation market and industry in Europe

Business aviation plays an important role in the European economy. In addition to aircraft operators, this sector consists of aircraft manufacturers and maintenance companies. Their economic output consists of employment, GVA, and wages.

By EBAA’s Yearbook for 2021 [26], business aviation provided 294 650 direct or indirect jobs in Europe and created an economic output of €62,7 billion. Although global aviation was affected by the pandemic, business aviation almost doubled its market share compared to 2019. The impacts of the pandemic are further discussed in the thesis in Chapter 1.6.

The majority of the economic impact is visible in western Europe. According to Booz et al. [2], 63% of the GVA is produced in Germany, France and the UK and next 17% in Italy, Switzerland and Spain.

For example, the above mentioned Biggin Hill Airport offers employment to more than 1 000 people in 65 companies located in the airport. These span from air charter, catering, and aircraft maintenance and cleaning to flight schools and even now built hotel. Oxford Economics [1] also mentions Farnborough Airport, which also employs around 1 000 people and an additional 4 000 jobs in the local area through the wider supply chain.

1.5.1 Role of business aviation in the Czech Republic

According to Booz et al. [2], there were approximately 2700 direct employees in the Czech business aviation sector in 2014. Employees are distributed into aircraft operations by 31,5%, aircraft manufacturing and maintenance by 67,1% and fixed-based operators by 1,4%. Manufacturing is therefore the primary driver of the sector in the country and is mainly located at the Honeywell company. EBAA's Yearbook [27] says that in year 2021 business aviation provided around 12 300 directly or indirectly connected jobs.

EBAA in Yearbook for 2021 [27] also states, the Czech Republic has 112 based aircraft and 40 active airports in this segment with almost 19 500 total business aviation movements connecting over 1 922 unique airport pairs. Almost 80,8% of these flights are within Europe, 17,3% are domestic, and the remaining 2% are extra-Europe.

The main airport is Prague airport, which ranks among the top 30 European business aviation airports. Before the pandemic, it served almost 11 000 business aviation movements a year. Its Terminal 3 is dedicated to business aviation and offers VIP services and privacy. The airport is a base for many Czech business aviation companies such as ABS Jets, Eclair Aviation, Time Air, etc. It also offers aircraft maintenance, VIP catering, and other services.

1.6 COVID-19 pandemic affecting business aviation

During the beginning of 2020, the COVID-19 pandemic and its related restrictions struck global aviation, when most European countries restricted or even prohibited entry into the country. The European Union did not lift their internal restrictions until Mid-June 2020, according to EBAA [28]. The second wave of the pandemic followed in September 2020 with further ones in 2021.

Due to the significant reduction in travel demand, airlines were no longer capable of keeping their flights profitable. This led to countless flight reductions and cancellations. Most of their aircraft were grounded for several months or used only as cargo carriers.

However, some people still needed to travel, whether it was related to business or leisure, so they searched for other alternatives and were willing to pay more to travel. Business aviation was a great option. By the time commercial airlines were still at their lowest, business aviation was experiencing its peak again.

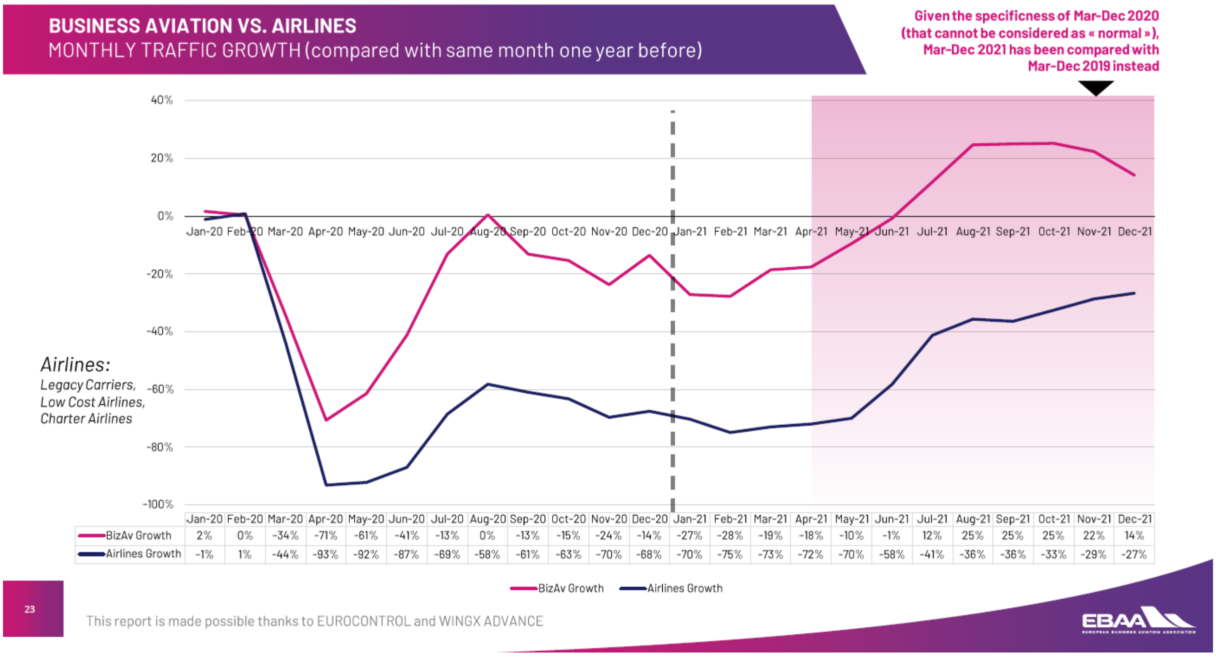


Figure 2 Comparison of airline and business aviation during COVID-19 [6]

Figure 2 compares the growth of European traffic from airlines and business aviation during the years 2020 and 2021 compared to the previous year 2019. Both sectors have experienced a plummet since February 2020 with the lowest low in April 2020. However, business aviation dropped only by 70% compared to 90% of airlines. The EBAA [29] comments: "*With airlines operating at only 10% of their regular activity, Business aviation accounts now for 1 out of 4 airplanes flying in Europe (the largest market share ever recorded for Business aviation).*"

EBAA [30] in their report also describes a slight initial increase in business aviation traffic at the beginning of March 2020 due to the number of medical and repatriation missions. During the pandemic, the sector still plays a crucial role in providing medical help and supplies.

Furthermore, unlike airlines, business aviation was able to get back to its pre-covid traffic already in August 2020 and reach even better values in 2021 than in 2019. Whereas airlines were not able to meet its pre-covid number not even until the end of the year 2021.

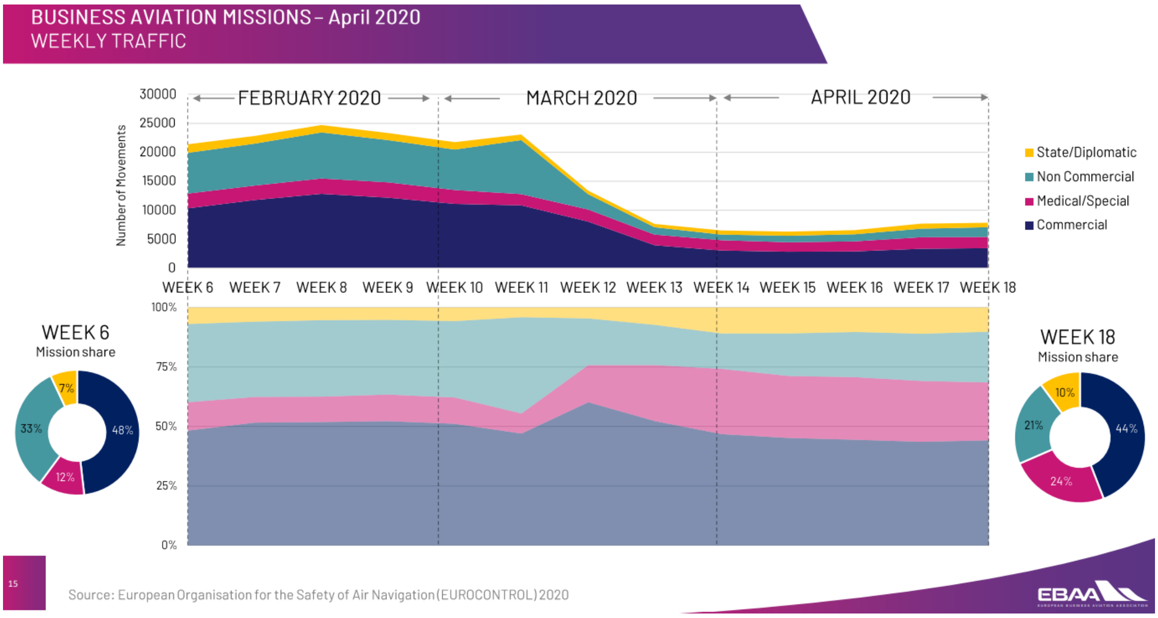


Figure 3 Business aviation missions [29]

Figure 3 above presents the type of missions flown in business aviation during week 6 to week 18. There is an evident doubling of medical and special type of flights since week 12, compared to the beginning of the year, as well as reduction of commercial and non-commercial flights.

The following months brought an increase in commercial flights, especially during summer, when the European restrictions were lifted. With its small airplanes, business aviation also offered a safer alternative to airliners filled with hundreds of potentially ill people. Some companies even claim to expand their fleet to accommodate the increased demand and reported extremely high frequency of flights. Michal Laboutka, CEO of Eclair Aviation [7], states a large percentage of their passengers were new clients and number of 2021 suggests the clients continue using this sector in 2021 increasing the traffic volume, compared to pre-covid year 2019.

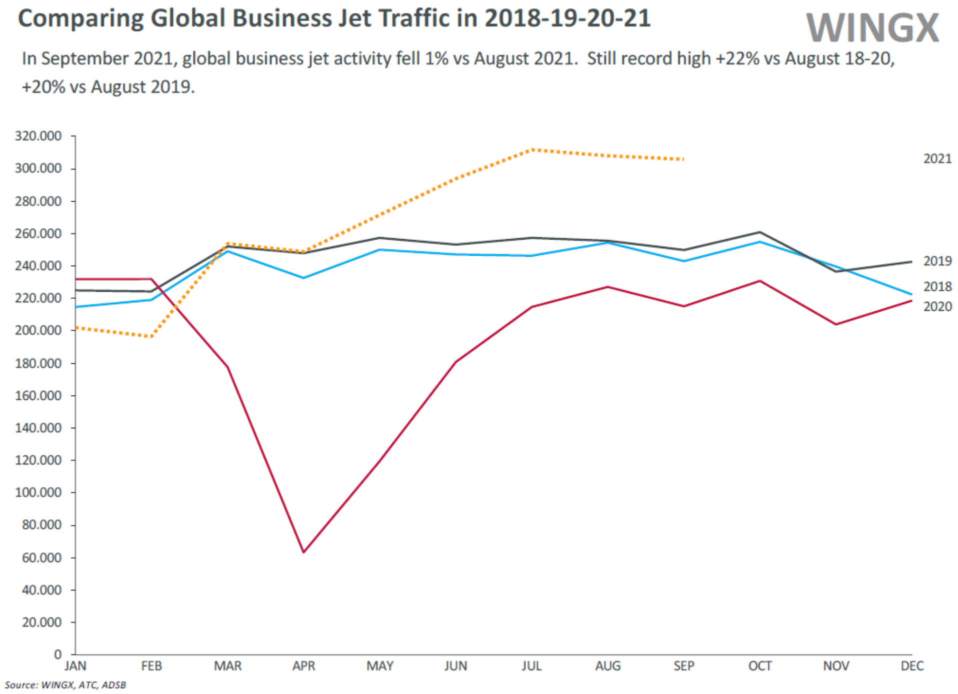


Figure 4 Business jet traffic in 2018-2021 [31]

The global business jet traffic from January 2018 to September 2021 is presented in Figure 4. The first two pre-covid years show similar traffic volume trend, whereas 2020 shows the significant decline and return in the first half of the year. The year 2021 suggests a trend of increase in traffic volume, even compared to normal, pre-covid years 2018 and 2019.

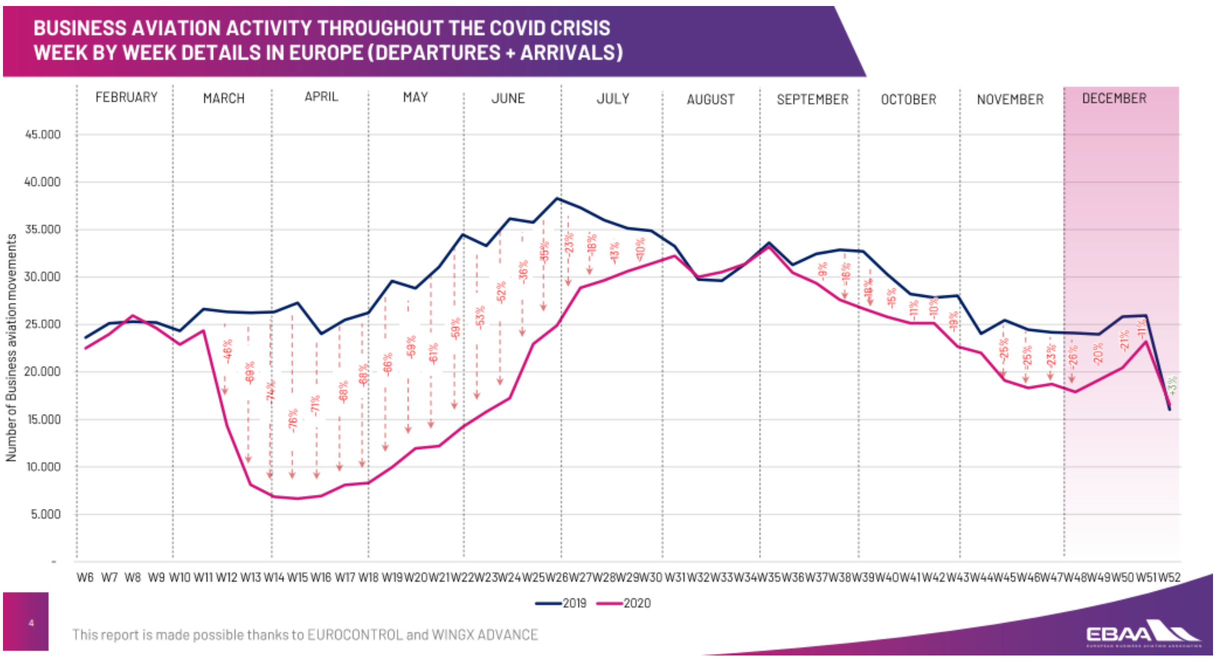


Figure 5 Business aviation activity during 2020 compared to 2019 [6]

Figure 5 shows in detail the decrease in traffic movement decline in business aviation in 2020, compared to 2019. It identifies the steady increase up to the normal values in August in more detail. There is also a very noticeable second wave of the pandemic beginning in September and followed by the second, less significant decrease in activity.

The year 2021 divided Europe into three sectors according to their typical behaviour: Eastern Europe had positive numbers at the beginning of the year, while Western Europe, typically the largest business aviation market, remained strongly impacted by the pandemic and northern Europe tend to be relatively stable, according to EBAA [32]. By June 2021, business aviation is above the numbers of 2019 and this trend stays until the end of the year. Figure 6 presents this in the number of business aviation flights compared to years 2020 and 2019.

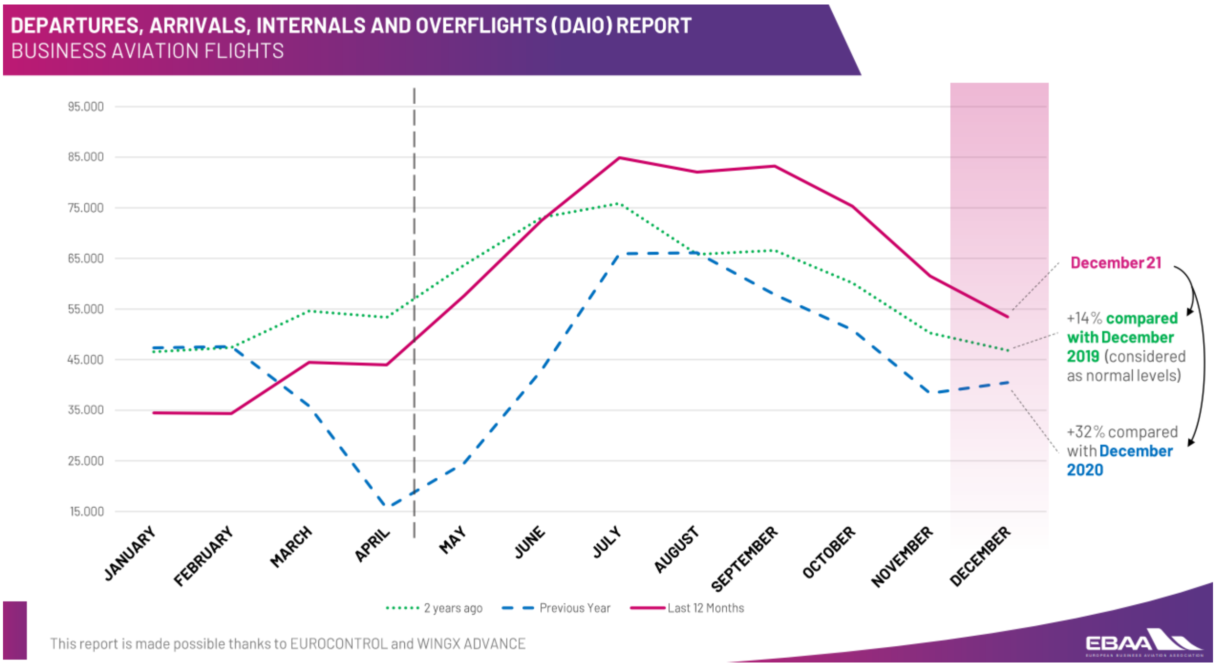


Figure 6 Business aviation flights in 2021, compared to 2019 and 2020 [33]

In general, the year 2020 was, according to EBAA [34], the worst year for civil aviation. On the other hand, it brought new clients to charter companies and showed the importance of business aviation for medical and repatriation flights. During 2021, new records of business aviation traffic were recorded, indicating that new clients, who came to business aviation during 2020, remained in this sector.

2 Aviation network

The aviation network consists of airports and flight connections between them. Airlines and business aviation operators create this network by their flight activities. In terms of airlines, we speak mainly about their scheduled flights. In business aviation, these are demand-driven flight connections.

The operating networks of both airline and business aviation operators are based on commonly known models. The used model determines the basic operating strategy of each company.

The models can be divided into two main types:

- Hub-and spoke
- Point-to-point

2.1 Hub-and-spoke

This model became very popular among airlines after the deregulation of the aviation market. Airlines created their bases - hubs in metropoles, from which they operated other big cities with direct flights back and forth. This helped them maximize the number of connected city pairs with a certain number of flights and also ensured better load factors, therefore bigger revenues. This trend also created demand for large airplanes, such as the B-747 and A380. Figure 7 shows the formation of hub-and-spoke networks after deregulation.

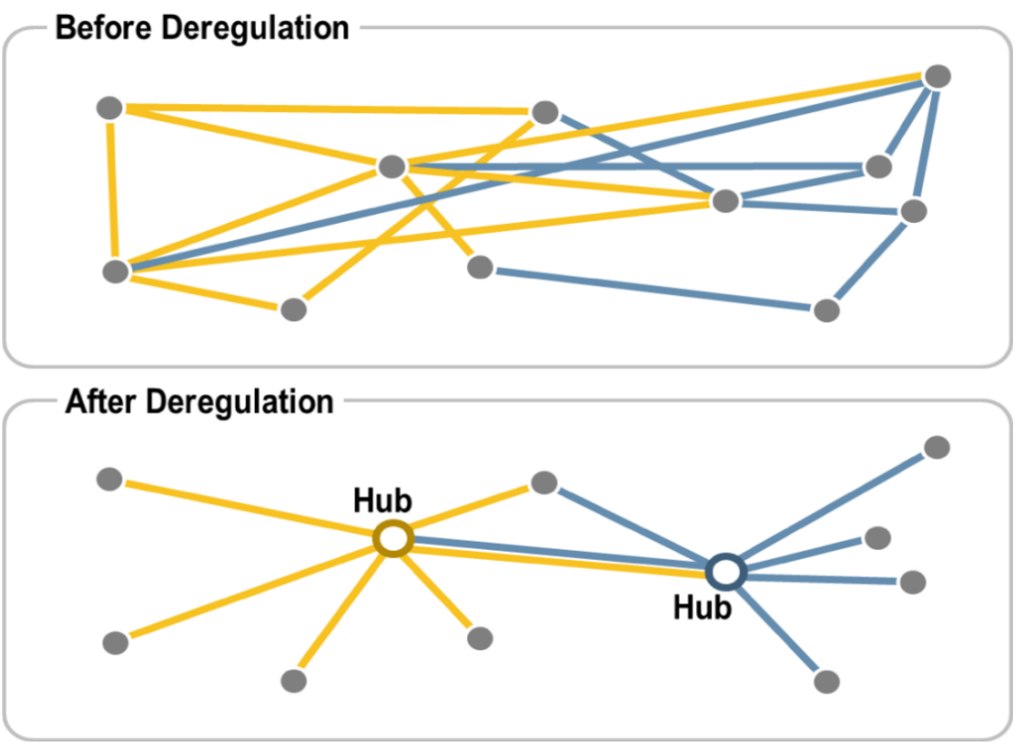


Figure 7 Forming of a Hub-and-spoke network [35]

The widespread use of this network model created the first analyses of airport and airlines' positions in the competition, say Burghouwt and Redondi [36]. Indicators such as number of passenger enplanements, aircraft movements, or tonnes of cargo became insufficient because they did not give information on the competitive position of the airline's network or level of accessibility of the airport. Airlines competed through both direct routes and indirect routes, with transfer at their hubs. This derived the first connectivity performance measures taking into account the indirect connections. The connectivity measures are discussed in more detail in Chapter 2.4.2.

Today, the hub-and-spoke model is still widely used by traditional airlines, like Air France, KLM, or British Airways and air freight companies.

2.2 Point-to-point

This model is mostly known to be the domain of low-cost carriers, where one aircraft connects different destinations, rather than flying back to its hub airport. The model is presented in Figure 8.

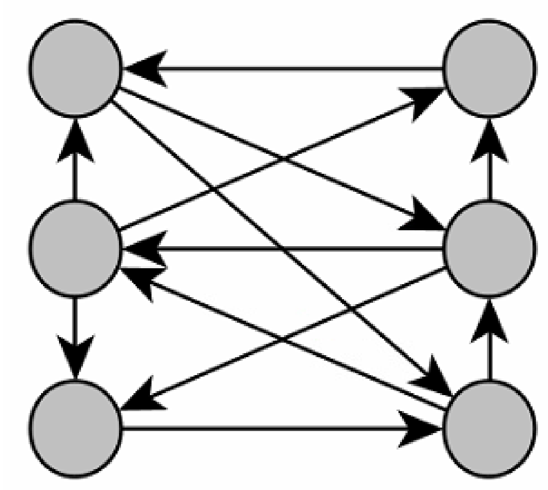


Figure 8 Point to point network

This shortens travel time and can reduce the need for transfers for passengers if the direct connection between airports is operated. However, for the operator, it requires more flights to connect the same number of destinations and lower frequency of flights for passengers, in contrast to the hub-and-spoke model.

Business aviation charter companies also use this model, but in a different manner, since their flights are driven by demand. Operators choose flights to destinations where is the highest probability of having connecting flight to maximize the cost-efficiency of their operation and minimize the number of profitless empty flights.

2.3 Business Aviation network properties

As mentioned above, business aviation is strongly based on requested flight connections. This also shapes the aircraft operation in this sector.

Business aviation charter companies have one or more bases, but operate their aircraft point-to-point between different destinations according to requested connections. Their returns to the base are very irregular, mainly influenced by crew duty regulations or aircraft maintenance.

Most operators use an Avinode marketplace, in addition to their websites, to increase the number of flight requests. On this platform, brokers upload flight requests from their clients and charter companies accept or decline these requests according to their already arranged schedule. In doing so, they plan the schedule of every plane only days or weeks ahead with unique flight patterns.

Each charter company's sales department has to take into account the revenue of the flight as well as its cost efficiency, very influenced by the possible continuity of other requested flights. To evaluate that, they have to know the average demand of flights from each airport, its connectivity.

2.4 Connectivity

The expansion of the airline market has created many different connectivity measures to evaluate airport connectivity. According to the OECD [37] both airports and aviation companies plan their commercial strategies based on the connectivity. Governments also understand that connectivity plays a crucial role in economic growth through tourism and air transportation.

2.4.1 Graph theory

The graph theory describes connectivity as the degree to which nodes are connected to each other in a network. The basic connectivity measure is a measure of degree and weighted degree. Degree represents the number of connections (edges) each airport (node) has, weighted degree adds weight to each edge, for example, the number of flights, the travel distance or flight time, and represents the number of connections multiplied by the weight of each connection. Figure 9 below shows the difference between degree and weighted degree. The nodes in the left diagram contain the value of their degree, and the nodes in the right diagram contain the value of their weighted degree.

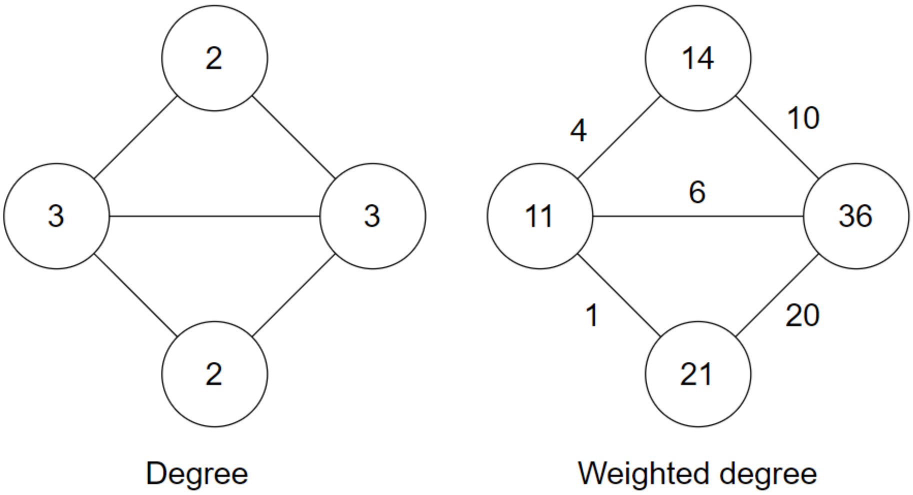


Figure 9 Degree and weighted degree

Also, two types of graphs are distinguished in graph theory: undirected and directed. The directed graph determines the direction of each edge, meanwhile the undirected one only shows if there is an edge or not. Figure below shows the difference of these two graph types.

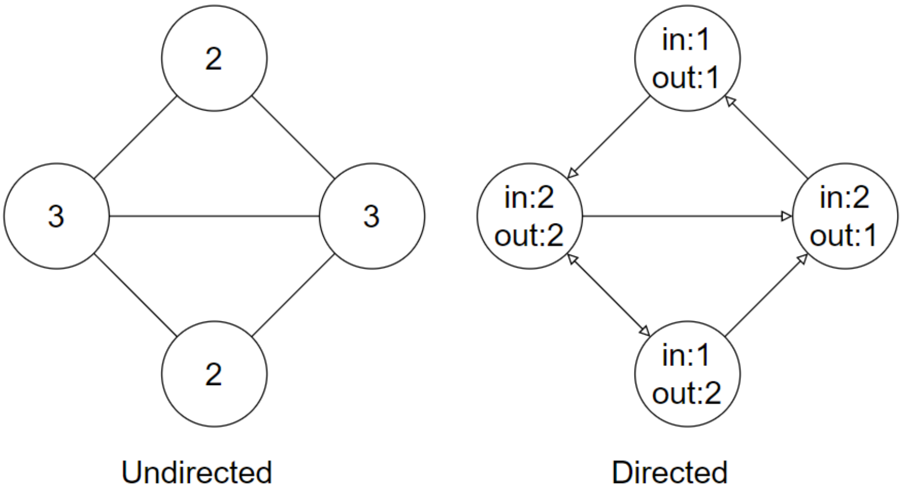


Figure 10 Undirected and directed graphs

Graph orientation also brings a new dimension to the degree measures. By the orientation of edges, indegree and outdegree, as well as weighted indegree and weighted outdegree, are distinguished. As their names suggest, these values indicate how many edges, eventually with what weight, enter or exit the particular node. The difference between the degree and the weighted degree parameter is shown in the Figure 11.

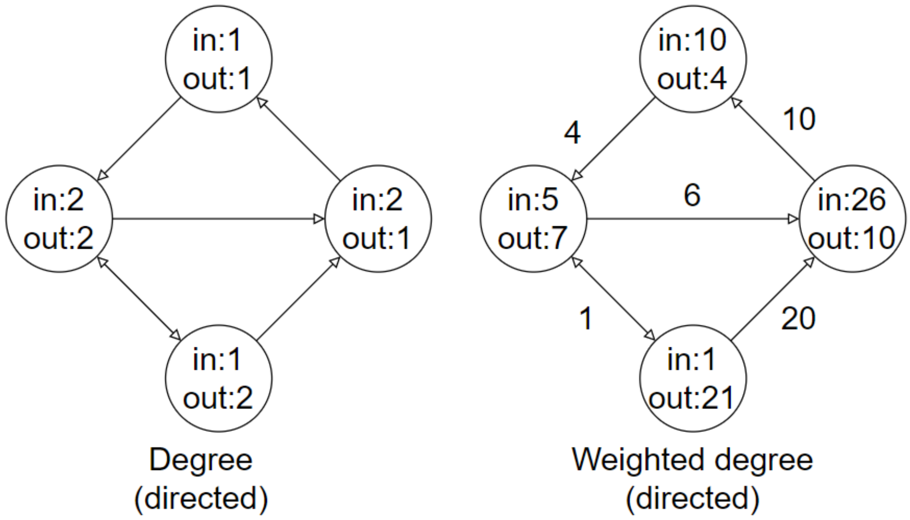


Figure 11 Degree and weighted degree in directed graph

2.4.2 Connectivity measures

Most connectivity measures complement the graph theory by adding weight to various parameters for either flight connection or airport, depending on the purpose of measuring connectivity and creating number of other connectivity definitions.

The most famous models, like the NetScan Connectivity Model, also take into account direct, indirect, or hub connections [5], because airlines compete in both domains [38]. Different types of connection are represented in Figure 12.

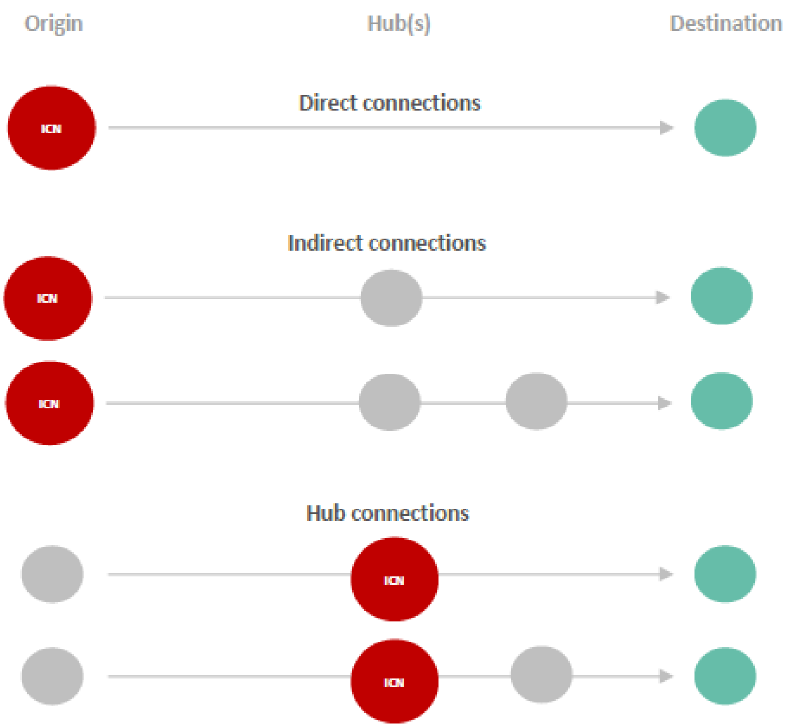


Figure 12 Types of connections, assessed airport: ICN [37]

As their names suggest, direct connections are only between the origin and destination, the indirect involve stop or transfer in the third airport and the hub connections involve stop or transfer at the airline's hub airport or a currently assessed airport. These measures can identify airports which play a crucial role as a connecting point and compare them with other hubs. This approach can also be classified as centrality based, because it is focused on the airports and their transfer opportunities.

Another famous model, the IATA air connectivity index, takes into account available seats. IATA states that this model measures how connections support country's economic development in the country and is designed primarily for governments [5].

Other perspectives bring a number of different approaches. From the passenger perspective, connectivity is the ability to travel between destinations in the shortest time. Cargo companies are focused on finding the fastest and most profitable routes, and airports measure their connectivity to evaluate the benefits of each airline route. The OECD [37] assessment of connectivity models mentions other measures based on the connecting time, airport capacity, the fastest route, travel cost, number of connections, etc. Table 1 shows some other connectivity measures and their definitions.

Table 1 Connectivity measures [38]

Model	Short definition	Main references
Hub potential	Incoming * outgoing frequency	Dennis (1998)
'Doganis & Dennis' connectivity	Number of connections. Indirect connections meet conditions of minimum & maximum connecting time and routing factor	Dennis & Doganis (1989); Dennis (1994a&b)
'Bootsma' connectivity	Number of connections. Indirect connections meet conditions of minimum & maximum connecting time and are classified as 'excellent', 'good' and 'poor'	Bootsma (1997)
WNX (weighted number of connections)	Number of direct and indirect connections weighed by their quality in terms of transfer and detour time	Burghouwt & De Wit (2004); Burghouwt (2007)
Netscan connectivity units	Number of direct and indirect connections weighed by their quality in terms of transfer and detour time relative to a theoretical direct flight	Veldhuis (1997); IATA (2000); Burghouwt & Veldhuis (2006); Matsumoto et al. (2008); Veldhuis & Kroes (2002)
WCn (Weighted Connectivity Number)	Number of direct and indirect connections weighed by their quality in terms of transfer and detour time	Danesi (2006)
Shortest Path Length centrality	Number of connections lying of O-D shortest paths. The shortest path is the path involving the minimum number of steps from O to D	Cronrath et al. (2008); Malighetti et al. (2008); Shaw (1993), Shaw & Ivy (1994)
Shortest Path Length accessibility	Average number of steps to reach any other airport in the network	Cronrath et al. (2008); Malighetti et al. (2008); Shaw (1993), Shaw & Ivy (1994)
Quickest Path Length centrality	Number of connections lying of O-D quickest paths. The quickest path is the path involving the lower travel time from O to D	Malighetti et al. (2008); Paleari et al. (2008)
Quickest Path Length accessibility	Average travel time to reach any other airport in the network	Malighetti et al. (2008); Paleari et al. (2008)
Gross vertex connectivity	Sum of all possible paths (of any number of steps) to other airports weighted by a scalar value that lessen the importance of indirect connections	Ivy (1993); Ivy et al. (1995)
Number of connection patterns	Number of statistical significant patterns of incoming and outgoing flights	Budde et al. (2008)

2.4.3 Approaches

As discussed above, Malighetti [39] and other authors divide connectivity into two approaches:

- Accessibility
- Centrality

Burghouwt et al. [38] state that accessibility is defined as the number and quality of direct and indirect connections at a certain airport.

While the centrality is focused on the number of transfer opportunities at the given airport and measures the performance of airlines' hubs or hubbing potential of each airport.

2.5 Suitability of connectivity measures on business aviation

As mentioned above, most measures are tailored to the airlines' hub-and-spoke operation network and consist of parameters that are not relevant to business aviation.

For example, the often taken into account, indirect connections have no value for business aviation passengers, since they demand direct flights between destinations to avoid time-consuming transfers. This fact also eliminates parameters like minimum connecting time, the fastest path, etc. Also, the number of available seat capacity or number of passengers is not very relevant, because clients pay for the whole plane, regardless of the number of occupied seats. These principles make most of the measures inapplicable to business aviation.

For purposes of the thesis, I tried to find a connectivity measure from the perspective of a business aviation charter company, trying to assess the most sought-after airports. This means that the most important parameter will be the number of flights from the airport or the continuity between inbound and outbound flights at the particular airport. Therefore, it should be a centrality-based model without any inapplicable parameters that distort the results, so I can analyse the importance of each node in the network and hereby determine the core network of business aviation airports in Europe.

3 Methodology

Figure 13 presents the whole process of methodology determining, as well as data processing. Individual steps are well described throughout the thesis. The figure shows all steps with their inputs.

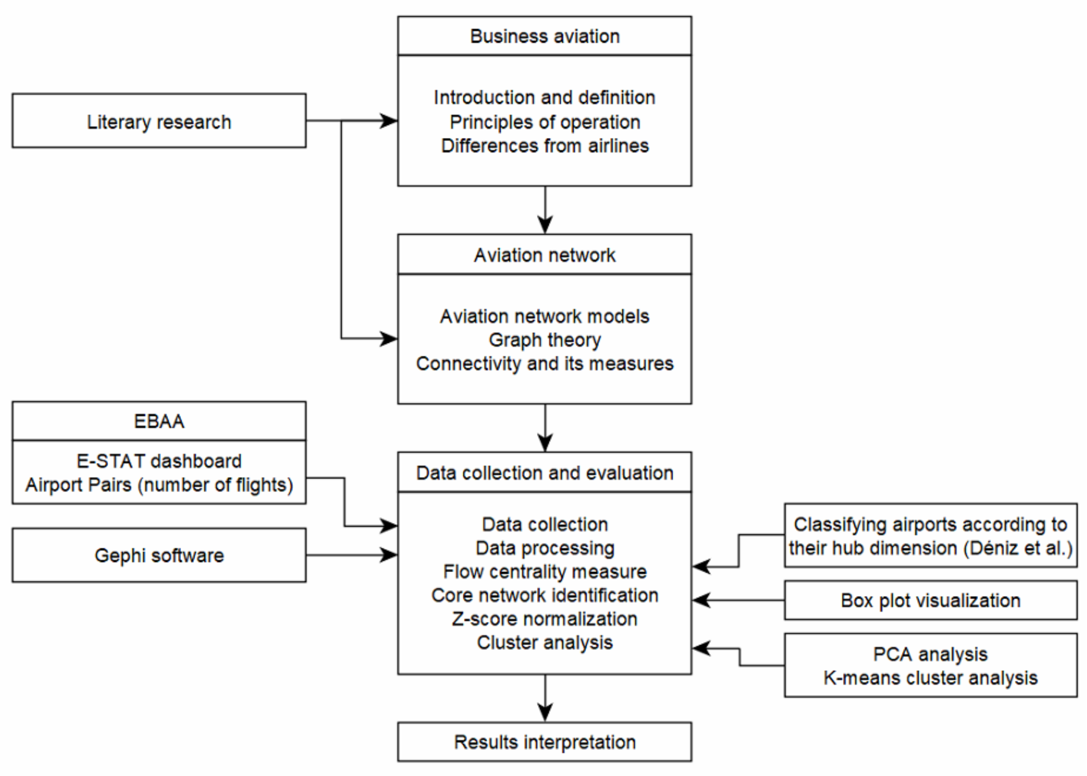


Figure 13 Methodology determining and data processing

3.1 Available data

Generally speaking, acquisition of business aviation data is not an easy task. Due to clients' privacy, charter companies do not share their schedules, so the main source are ADS-B data. However, common free sources, such as Flighradar24, have very limited data history, usually containing often only data of the current year and a great number of missing flights.

The data used for the purposes of my work were provided by the European Business Aviation Association (EBAA), which is the largest European organisation that represents more than 700 members of the European business aviation sector. The organization helps companies with their development, providing various types of data insights, as well as useful information about taxes, regulations and sustainability, and participates in the implementation of international Business Aviation Council (IBAC) Safety Standards for both aircraft operations and aviation handling.

I was given the membership with the access to various information sources including Traffic and Fleet Trackers, monthly updated reports of business aviation fleet structures, year-on-year and month-on-month comparison of aircraft movements, busiest routes and airports, aircraft types and classes, etc, and the Yearbooks comparing the Top 50 Airports, Countries, and Aircraft Types of each year.

However, the main data source was the E-STAT Dashboard, the interface with the possibility to filter data by month, country, airport, and aircraft. The Dashboard is split up to arrivals and departures and shows different statistics for the given filter such as tables of: Top Airports, Top Country Flows, Top Airport Pairs, Aircraft Type Performance; and graphs of: Number of Departures/ Arrivals to Regions, Departures/ Arrivals by Flight Mission, Departures/ Arrivals by Aircraft Segment and it is possible to export every feature into xlsx. or csv. file.

The Figure 14 and Figure 15 show the Departure Dashboard. Filters can be selected in the bar on the right side, and the Dashboard reloads its values accordingly.

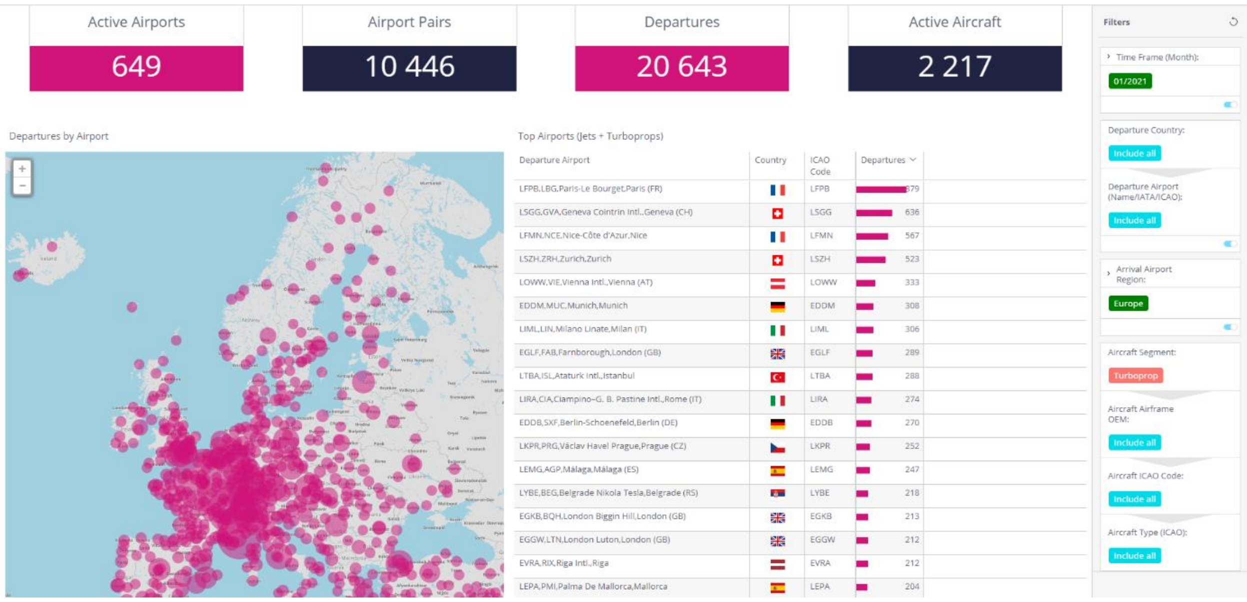


Figure 14 EBAA Departure Dashboard (upper part)

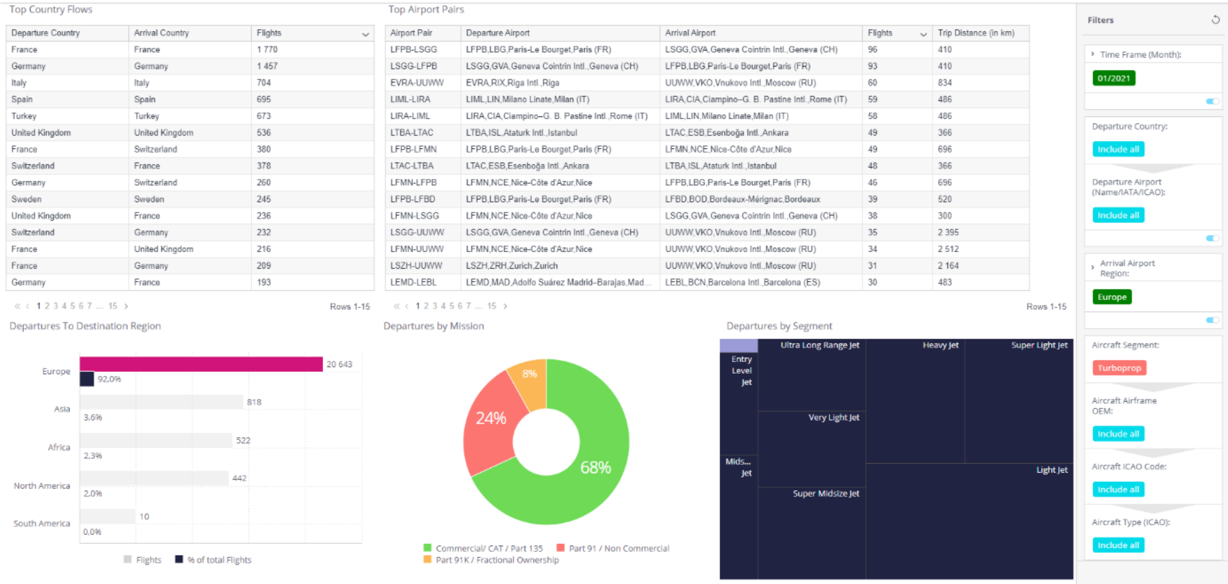


Figure 15 EBAA Departure Dashboard (bottom part)

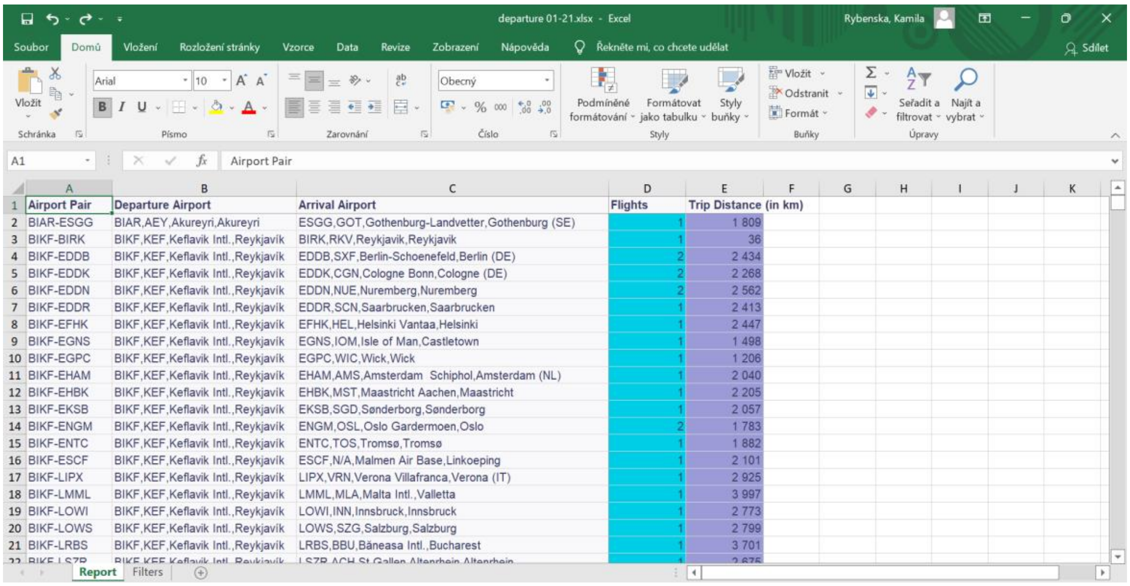
The best source of data for my purposes were the Top Airport Pairs, giving the information about the number of flights between every pair of airports in the given time interval.

The limitation of the data is the minimal filtrable time interval, which is one month. To get the most accurate values as possible, this interval was selected. Also, to get only flights within Europe, only departures and arrivals to / from Europe were selected.

During data processing, data inconsistency was discovered. For some airports the numbers of arrivals and departures were too different to correspond with real numbers. In some cases, the difference was in hundreds of flights, meaning hundreds of airplanes would stay at the airport. This issue was consulted with the data provider, and the solution was to remove turboprop aircraft from the filter because of the possible flight coverage errors.

3.2 Data preparation

Data were exported for every month from January 2019 to December 2021 for both Arrival and Departure Dashboards. Figure 16 shows the form of the exported data for one month and one Dashboard.



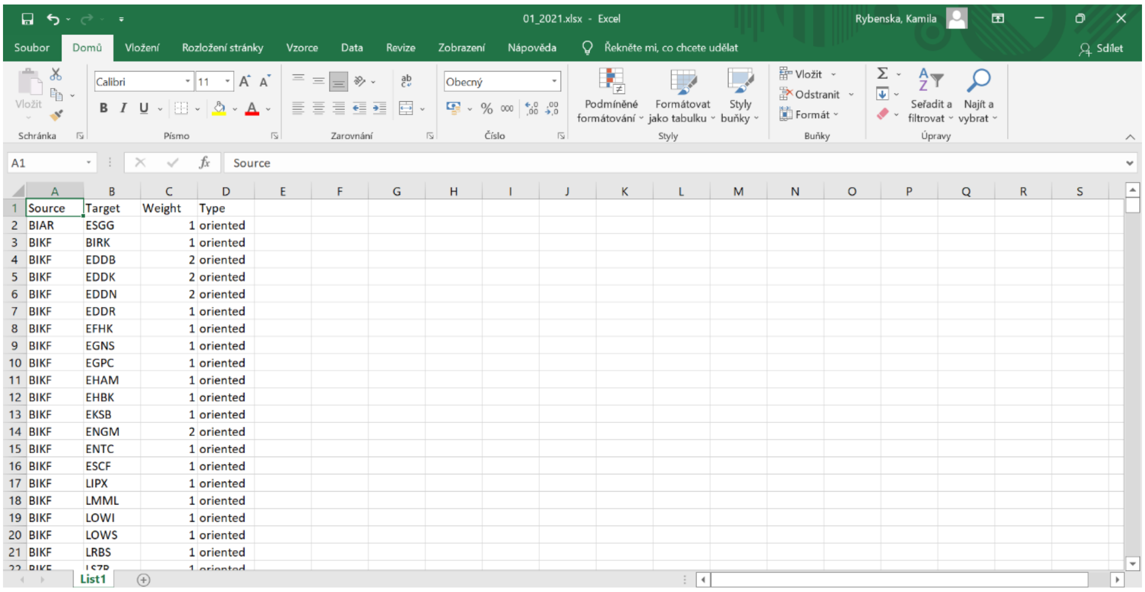
Airport Pair	Departure Airport	Arrival Airport	Flights	Trip Distance (in km)
BIAR-ESGG	BIAR,AEY,Akureyri,Akureyri	ESGG,GOT,Gothenburg-Landvetter,Gothenburg (SE)	1	1 809
BIKF-BIRK	BIKF,KEF,Keflavik Intl.,Reykjavík	BIRK,RKV,Reykjavik,Reykjavik	1	36
BIKF-EDDB	BIKF,KEF,Keflavik Intl.,Reykjavík	EDDB,SXF,Berlin-Schoenefeld,Berlin (DE)	2	2 434
BIKF-EDDK	BIKF,KEF,Keflavik Intl.,Reykjavík	EDDK,CGN,Cologne Bonn,Cologne (DE)	2	2 268
BIKF-EDDN	BIKF,KEF,Keflavik Intl.,Reykjavík	EDDN,NUE,Nuremberg,Nuremberg	2	2 562
BIKF-EDDR	BIKF,KEF,Keflavik Intl.,Reykjavík	EDDR,SCN,Saarbrucken,Saarbrucken	1	2 413
BIKF-EFHK	BIKF,KEF,Keflavik Intl.,Reykjavík	EFHK,HEL,Helsinki Vantaa,Helsinki	1	2 447
BIKF-EGNS	BIKF,KEF,Keflavik Intl.,Reykjavík	EGNS,IOM,Isle of Man,Castletown	1	1 498
BIKF-EGPC	BIKF,KEF,Keflavik Intl.,Reykjavík	EGPC,WIC,Wick,Wick	1	1 206
BIKF-EHAM	BIKF,KEF,Keflavik Intl.,Reykjavík	EHAM,AMS,Amsterdam Schiphol,Amsterdam (NL)	1	2 040
BIKF-EHBK	BIKF,KEF,Keflavik Intl.,Reykjavík	EHBK,MST,Maastricht Aachen,Maastricht	1	2 205
BIKF-EKSB	BIKF,KEF,Keflavik Intl.,Reykjavík	EKSB,SGD,Sønderborg,Sønderborg	1	2 057
BIKF-ENGM	BIKF,KEF,Keflavik Intl.,Reykjavík	ENGM,OSL,Oslo Gardermoen,Oslo	2	1 783
BIKF-ENTC	BIKF,KEF,Keflavik Intl.,Reykjavík	ENTC,TOS,Tromsø,Tromsø	1	1 882
BIKF-ESCF	BIKF,KEF,Keflavik Intl.,Reykjavík	ESCF,N/A,Malmen Air Base,Linkoeping	1	2 101
BIKF-LIPX	BIKF,KEF,Keflavik Intl.,Reykjavík	LIPX,VRN,Verona Villafranca,Verona (IT)	1	2 925
BIKF-LMML	BIKF,KEF,Keflavik Intl.,Reykjavík	LMML,MLA,Malta Intl.,Valletta	1	3 997
BIKF-LOWI	BIKF,KEF,Keflavik Intl.,Reykjavík	LOWI,INN,Innsbruck,Innsbruck	1	2 773
BIKF-LOWS	BIKF,KEF,Keflavik Intl.,Reykjavík	LOWS,SZG,Salzburg,Salzburg	1	2 799
BIKF-LRBS	BIKF,KEF,Keflavik Intl.,Reykjavík	LRBS,BBU,Băneasa Intl.,Bucharest	1	3 701

Figure 16 Exported data

For further processing, it was necessary to delete redundant columns, such as trip distance and airport names, and unite the data from Departure and Arrival Dashboards to eliminate the possibility of missing flights in one of the sources.

This was done by comparing the duplicates of the Arrival and Departure datasets for each month and then combining them into one dataset containing all unique values from each set. Data for one month contained approximately 5 - 20 000 unique airport pairs, 8 – 70 000 flights, and there were around 1 200 active airports.

The next step was to prepare the data for Gephi software. The software requires data in an Excel table containing four columns and the form of the data is represented in Figure 17.



Source	Target	Weight	Type
BIAR	ESGG	1	oriented
BIKF	BIRK	1	oriented
BIKF	EDDB	2	oriented
BIKF	EDDK	2	oriented
BIKF	EDDN	2	oriented
BIKF	EDDR	1	oriented
BIKF	EFHK	1	oriented
BIKF	EGNS	1	oriented
BIKF	EGPC	1	oriented
BIKF	EHAM	1	oriented
BIKF	EHBK	1	oriented
BIKF	EKSB	1	oriented
BIKF	ENGM	2	oriented
BIKF	ENTC	1	oriented
BIKF	ESCF	1	oriented
BIKF	LIPX	1	oriented
BIKF	LMML	1	oriented
BIKF	LOWI	1	oriented
BIKF	LOWS	1	oriented
BIKF	LRBS	1	oriented

Figure 17 Data prepared for Gephi software

The first two columns represent the origin and destination of the flight and were obtained by dividing the Airport Pair column into two. Next column – Weight indicates weight of the edges. In my case, it is the number of flights between the two airports. The last column – Type determines if the edges are oriented or not, and therefore if the graph is directed or undirected. In this case, the edges represent flights from one airport to another; therefore, the edges are oriented. The graph theory was discussed in more detail in Chapter 2.4.1.

3.3 Gephi software

The next phase of data processing was to calculate the degree and weighted degree of airports using Gephi software.

Gephi is a free software for network visualisation and calculating network parameters [40]. The workplace is divided into three sections: Overview, Data Laboratory, and Preview. The first section, shown in Figure 18 below, is mainly for network visualisation, it offers various tools, and the created graph is very interactive. The bar on the right side offers the calculation of different network parameters. For my purposes, the calculation of degree and weighted degree was done.

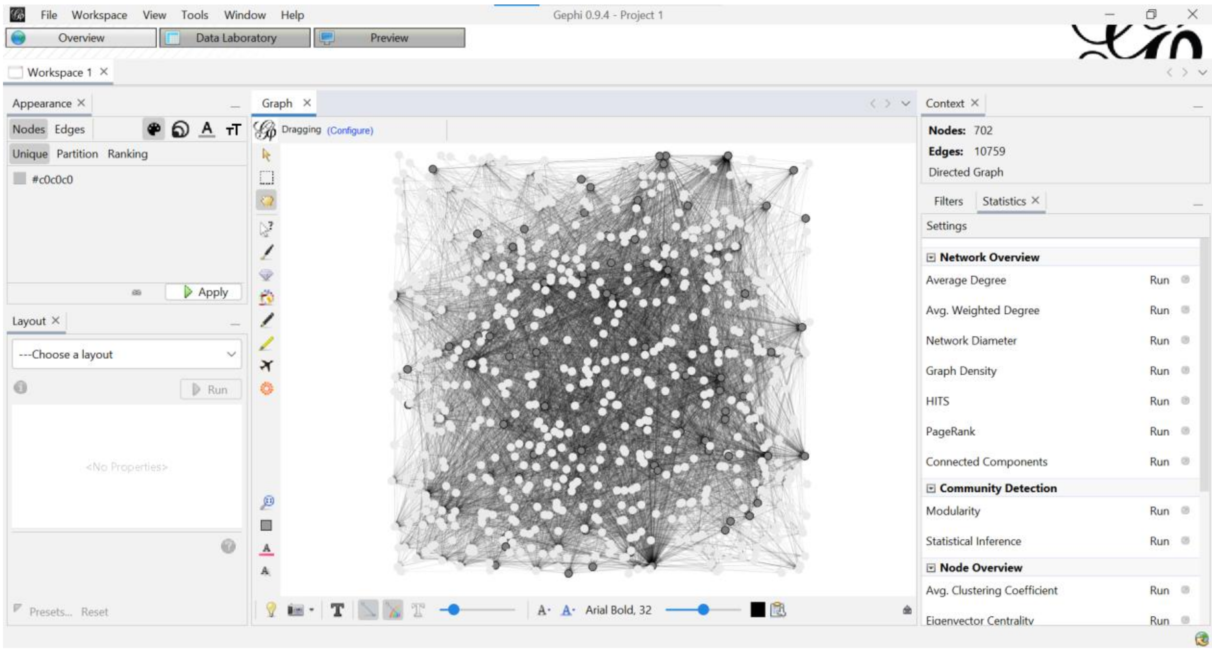


Figure 18 Gephi – Overview

The results of calculations are shown in the next section: Data Laboratory, presented in Figure 19. It is divided into two tables, one for nodes and one for edges. It is not needed to process the data in this software in any other way, so the next step was only to export it to excel table.

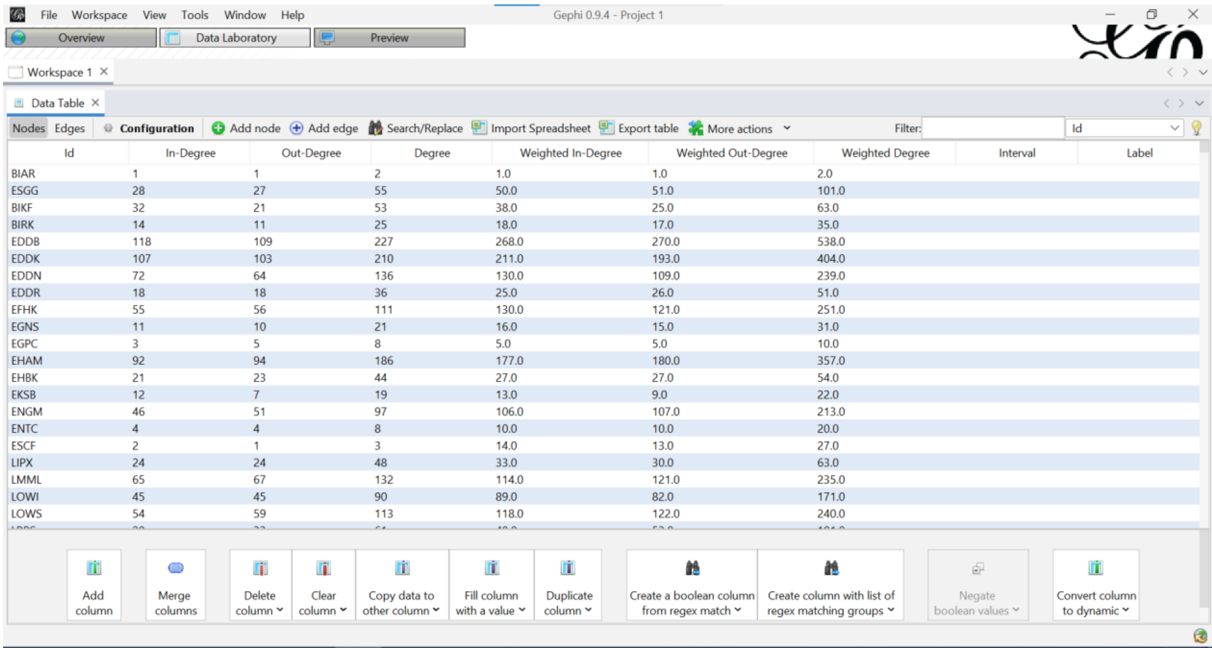


Figure 19 Gephi - Data Laboratory

This process was carried out for every month of the study period, January 2019 to December 2021. The exported data was then processed by dividing into columns and deleting all redundant columns, such as time set and label. Also, columns with degree, indegree and outdegree were not needed for further processing by the method Flow centrality.

3.4 Analysis and selection - Flow centrality

Business aviation is typically determined only by the number of aircraft movements and their changes over time. Airports are classified only by number of flights, and there is hardly any other approach excluding degree and weighted degree based. This thesis is focused on finding a more complex approach of evaluating the performance of business aviation with regard of its properties and principles.

As mentioned above, business aviation charter companies operate on point-to-point manner according to the demand and try to optimise their operations to connect their flights from individual destinations as smooth as possible to minimalize number of empty unprofitable flights. Also positioning an aircraft into the network to get a flight request from its position or nearby as soon as possible is an important task.

Deńiz et al. [9] developed a new measure of airport connectivity based on flow centrality measure [41], which is completely demand based. It is focused on the airports and their role in the network from both traffic generation and connectivity perspective.

Freeman et al. [41] originally developed the measure in context of social network to quantify flow of information. Déniz et al. [9] adapted it to air transport by identifying airports as nodes and passengers as the flow travelling between them from their origin to their destination. They also tested its suitability by testing sensitivity to changes in connectivity during de-hubbing events such as various crisis and threats and compared it to other centrality indicators. Their results showed the flow centrality measure is sensitive enough to react well even to relatively small events like industrial actions, where the traffic is not so affected, and even being more sensitive than other demand-based indicators.

The original indicator presented by Freeman et al. [41] contains the following principles. The flow (m) travels between two nodes, origin (j) and destination (k) through the intermediate node (x_i). For all involved nodes in the transmission, the incoming and outgoing flow must be equal. The total flow, that travels through the node is divided by the total flow between all pairs of nodes where the node is neither a source or destination, so the centrality measures the proportion of the total flow that travel through the particular node and is valued between 0 and 1.

$$C_F(x_i) = \frac{\sum_{j<k}^{n} \sum_{k}^{n} m_{jk}(x_i)}{\sum_{j<k}^{n} \sum_{k}^{n} m_{jk}} \tag{1}$$

Déniz et al. [9] adapted this indicator and defined two separate measures, traffic generation and connectivity, to measure airports' traffic contribution to the network in two-dimensions. *"The traffic generation (OD_i) is the ratio between the passengers that either originate or terminate at the airport I (od_i) and the total network passengers (P). The second measure is the flow centrality indicator (C_i) and measures the airport's importance as a connecting point. It is calculated as the ratio between connecting passengers (c_i) and total network passengers that do not originate or terminate at the airport ($P - od_i$)."* [9].

$$OD_i = \frac{od_i}{P}; \quad C_i = \frac{c_i}{P - od_i} \tag{2}$$

The measures can be easily linked to the FAA indicator, commonly used for airport classification. The indicator represents the share of airport I over the total number of enplanements. For this reason, it was necessary to define the number of enplanements in the network (E) as the sum of all types of traffic across all the airports ($od_i/2 + c_i$).

$$E = \sum_i \left(\frac{od_i}{2} + c_i\right); \qquad FAA_i = \frac{\frac{od_i}{2} + c_i}{E} \tag{3}$$

Then it can be aggregated by following relationship:

$$FAA_i = OD_i \frac{P}{2E} + C_i \frac{(P - od_i)}{E}$$

(4)

$$FAA_i = \frac{od_i}{P} \frac{P}{2(\frac{od_i}{2} + c_i)} + \frac{c_i}{P - od_i} \frac{(P - od_i)}{(\frac{od_i}{2} + c_i)}$$

(5)

$$FAA_i = \frac{od_i}{2(\frac{od_i}{2} + c_i)} + \frac{c_i}{\frac{od_i}{2} + c_i}$$

(6)

$$FAA_i = \frac{od_i + 2c_i}{2(\frac{od_i}{2} + c_i)}$$

(7)

$$FAA_i = \frac{od_i + 2c_i}{2E}$$

(8)

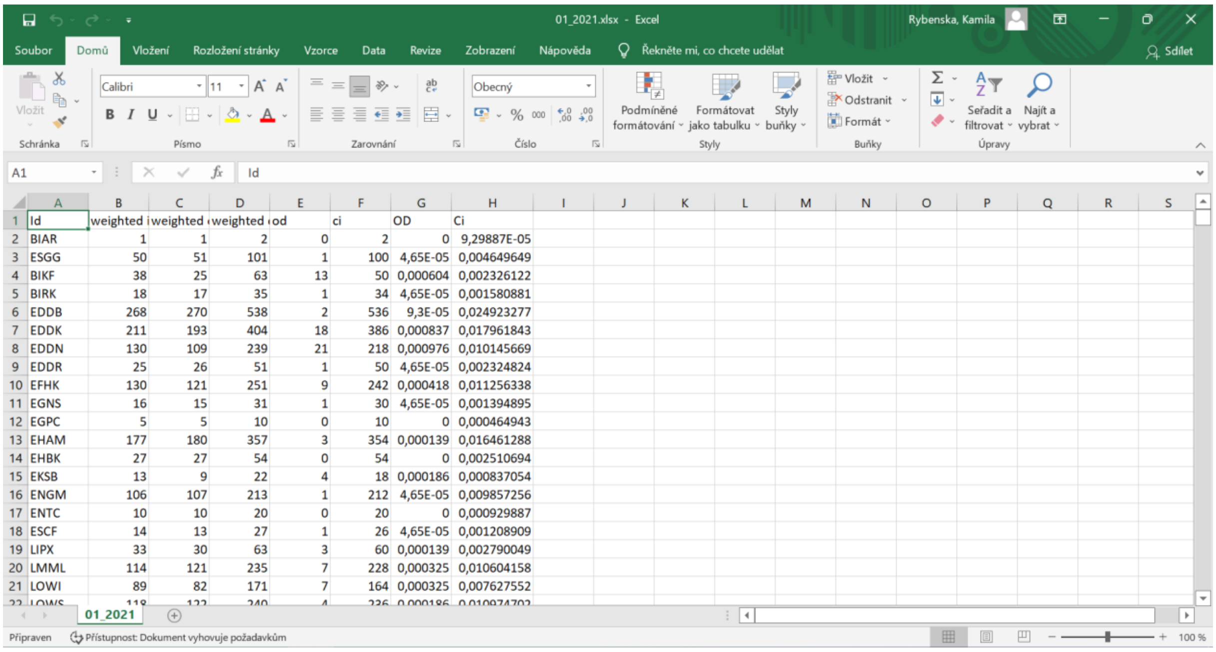
$$FAA_i = \frac{\frac{od_i}{2} + c_i}{E}$$

(9)

Adaptation to the sector of business aviation was done mainly by changing the perspective from which is the connectivity assessed. From charter company's view, connectivity is the ability to get a request for connecting flight from the particular airport. The flow is in my case flights inside the examined network and airports remained being the nodes.

Having two indicators seems to be convenient for business aviation sector too since both traffic generation and connectivity is important for the sector. The Traffic Generation Indicator could indicate airports, where airplanes stayed for longer period time, therefore identify hubs, services or different reasons for longer aircraft parking. Apart from that, Flow Centrality Indicator could indicate airports with the largest amount of connecting flights, therefore airports with the biggest success rate of getting connecting flight.

To be able to reliably determine these airports, it is necessary to have data with the smallest possible time interval, ideally in days or hours, and the possibility to filter only commercial flights without empty legs or other flight missions as required. The data acquired for my thesis are limited by the interval of one month therefore the results do not reflect the situation in such detail as could be possibly achieved. Also, flights could not be filtered to contain only commercial flights without empty legs so all type of flight missions are included. However, it should serve as a sufficient demonstration of the potential of Flow Centrality application on business aviation.



Id	weighted i	weighted (	weighted (	od	ci	OD	Ci
BIAR	1	1	2	0	2	0	9,29887E-05
ESGG	50	51	101	1	100	4,65E-05	0,004649649
BIKF	38	25	63	13	50	0,000604	0,002326122
BIRK	18	17	35	1	34	4,65E-05	0,001580881
EDDB	268	270	538	2	536	9,3E-05	0,024923277
EDDK	211	193	404	18	386	0,000837	0,017961843
EDDN	130	109	239	21	218	0,000976	0,010145669
EDDR	25	26	51	1	50	4,65E-05	0,002324824
EFHK	130	121	251	9	242	0,000418	0,011256338
EGNS	16	15	31	1	30	4,65E-05	0,001394895
EGPC	5	5	10	0	10	0	0,000464943
EHAM	177	180	357	3	354	0,000139	0,016461288
EHBK	27	27	54	0	54	0	0,002510694
EKSB	13	9	22	4	18	0,000186	0,000837054
ENGM	106	107	213	1	212	4,65E-05	0,009857256
ENTC	10	10	20	0	20	0	0,000929887
ESCF	14	13	27	1	26	4,65E-05	0,001208909
LIPX	33	30	63	3	60	0,000139	0,002790049
LMML	114	121	235	7	228	0,000325	0,010604158
LOWI	89	82	171	7	164	0,000325	0,007627552

Figure 20 Flow Centrality indicators calculation

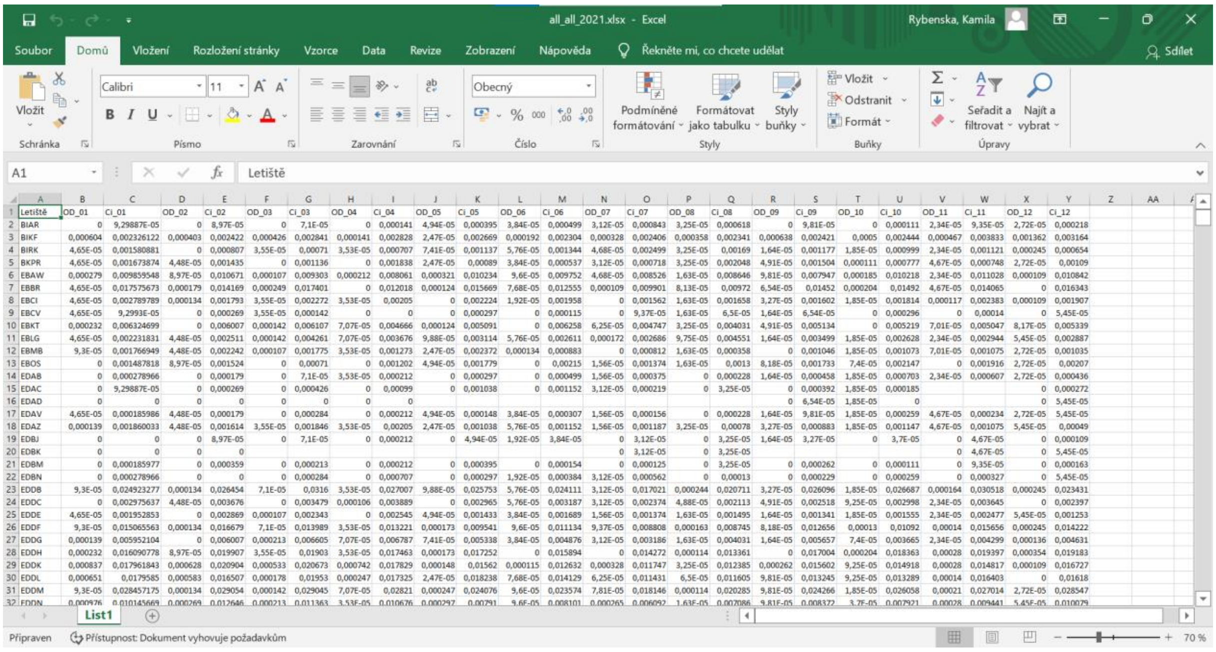
Figure 20 above shows calculation of Traffic generation and Flow centrality indicators based on the formulas above. The actual values used in the calculation are described below.

$$od_i = |weighted\ indegree_i - weighted\ outdegree_i| \tag{10}$$

$$c_i = weighted\ degree_i - |weighted\ indegree_i - weighted\ outdegree_i| = weighted\ degree_i - od_i \tag{11}$$

$$P = \sum all\ flights\ within\ the\ network \tag{12}$$

Since the Traffic Generation Indicator (OD_i) represents the difference between number of inbound and outbound flights divided by all flights within the network, the greater the indicator is, the better the airport is at traffic generation. The Flow Connectivity Indicator (C_i) shows continuity of flights at the airport meaning the greater the indicator is, the better connectivity the particular airport offers.



	Letiště	OD_01	Ci_01	OD_02	Ci_02	OD_03	Ci_03	OD_04	Ci_04	OD_05	Ci_05	OD_06	Ci_06
2	BIAR	0	9,29887E-05	0	8,97E-05	0	7,1E-05	0	0,000141	4,94E-05	0,000395	3,84E-05	0,000499
3	BIKF	0,000604	0,002326122	0,000403	0,002422	0,000426	0,002841	0,000141	0,002828	2,47E-05	0,002669	0,000192	0,002304
4	BIRK	4,65E-05	0,001580881	0	0,000807	3,55E-05	0,00071	3,53E-05	0,000707	7,41E-05	0,001137	5,76E-05	0,001344
5	BKPR	4,65E-05	0,001673874	4,48E-05	0,001435	0	0,001136	0	0,001838	2,47E-05	0,00089	3,84E-05	0,000537
6	EBAW	0,000279	0,009859548	8,97E-05	0,010671	0,000107	0,009303	0,000212	0,008061	0,000321	0,010234	9,6E-05	0,009752
7	EBBR	4,65E-05	0,017575673	0,000179	0,014169	0,000249	0,017401	0	0,012018	0,000124	0,015669	7,68E-05	0,012555
8	EBCI	4,65E-05	0,002789789	0,000134	0,001793	3,55E-05	0,002272	3,53E-05	0,00205	0	0,002224	1,92E-05	0,001958
9	EBCV	4,65E-05	9,2993E-05	0	0,000269	3,55E-05	0,000142	0	0	0	0,000297	0	0,000115
10	EBKT	0,000232	0,006324699	0	0,006007	0,000142	0,006107	7,07E-05	0,004666	0,000124	0,005091	0	0,006258
11	EBLG	4,65E-05	0,002231831	4,48E-05	0,002511	0,000142	0,004261	7,07E-05	0,003676	9,88E-05	0,003114	5,76E-05	0,002611
12	EBMB	9,3E-05	0,001766949	4,48E-05	0,002242	0,000107	0,001775	3,53E-05	0,001273	2,47E-05	0,002372	0,000134	0,000883
13	EBOS	0	0,001487818	8,97E-05	0,001524	0	0,00071	0	0,001202	4,94E-05	0,001779	0	0,00215
14	EDAB	0	0,000278966	0	0,000179	0	7,1E-05	3,53E-05	0,000212	0	0,000297	0	0,000499
15	EDAC	0	9,29887E-05	0	0,000269	0	0,000426	0	0,00099	0	0,001038	0	0,001152
16	EDAD	0	0	0	0	0	0	0	0				
17	EDAV	4,65E-05	0,000185986	4,48E-05	0,000179	0	0,000284	0	0,000212	4,94E-05	0,000148	3,84E-05	0,000307
18	EDAZ	0,000139	0,001860033	4,48E-05	0,001614	3,55E-05	0,001846	3,53E-05	0,00205	2,47E-05	0,001038	5,76E-05	0,001152
19	EDBJ	0	0	0	8,97E-05	0	7,1E-05	0	0,000212	0	4,94E-05	1,92E-05	3,84E-05
20	EDBK	0	0	0	0								
21	EDBM	0	0,000185977	0	0,000359	0	0,000213	0	0,000212	0	0,000395	0	0,000154
22	EDBN	0	0,000278966	0	0	0	0,000284	0	0,000707	0	0,000297	1,92E-05	0,000384
23	EDDB	9,3E-05	0,024923277	0,000134	0,026454	7,1E-05	0,0316	3,53E-05	0,027007	9,88E-05	0,025753	5,76E-05	0,024111
24	EDDC	0	0,002975637	4,48E-05	0,003676	0	0,003479	0,000106	0,003889	0	0,002965	5,76E-05	0,003187
25	EDDE	4,65E-05	0,001952853	0	0,002869	0,000107	0,002343	0	0,002545	4,94E-05	0,001433	3,84E-05	0,001689
26	EDDF	9,3E-05	0,015065563	0,000134	0,016679	7,1E-05	0,013989	3,53E-05	0,013221	0,000173	0,009541	9,6E-05	0,011134
27	EDDG	0,000139	0,005952104	0	0,006007	0,000213	0,006605	7,07E-05	0,006787	7,41E-05	0,005338	3,84E-05	0,004876
28	EDDH	0,000232	0,016090778	8,97E-05	0,019907	3,55E-05	0,01903	3,53E-05	0,017463	0,000173	0,017252	0	0,015894
29	EDDK	0,000837	0,017961843	0,000628	0,020904	0,000533	0,020673	0,000742	0,017829	0,000148	0,01562	0,000115	0,012632
30	EDDL	0,000651	0,0179585	0,000583	0,016507	0,000178	0,01953	0,000247	0,017325	2,47E-05	0,018238	7,68E-05	0,014129
31	EDDM	9,3E-05	0,028457175	0,000134	0,029054	0,000142	0,029045	7,07E-05	0,02821	0,000247	0,024076	9,6E-05	0,023574
32	EDDN	0,000976	0,010145669	0,000269	0,012646	0,000213	0,011363	3,53E-05	0,010676	0,000297	0,00791	9,6E-05	0,008101

	Letiště	OD_07	Ci_07	OD_08	Ci_08	OD_09	Ci_09	OD_10	Ci_10	OD_11	Ci_11	OD_12	Ci_12
2	BIAR	3,12E-05	0,000843	3,25E-05	0,000618	0	9,81E-05	0	0,000111	2,34E-05	9,35E-05	2,72E-05	0,000218
3	BIKF	0,000328	0,002406	0,000358	0,002341	0,000638	0,002421	0,0005	0,002444	0,000467	0,003833	0,001362	0,003164
4	BIRK	4,68E-05	0,002499	3,25E-05	0,00169	1,64E-05	0,001177	1,85E-05	0,000999	2,34E-05	0,001121	0,000245	0,000654
5	BKPR	3,12E-05	0,000718	3,25E-05	0,002048	4,91E-05	0,001504	0,000111	0,000777	4,67E-05	0,000748	2,72E-05	0,00109
6	EBAW	4,68E-05	0,008526	1,63E-05	0,008646	9,81E-05	0,007947	0,000185	0,010218	2,34E-05	0,011028	0,000109	0,010842
7	EBBR	0,000109	0,009901	8,13E-05	0,00972	6,54E-05	0,01452	0,000204	0,01492	4,67E-05	0,014065	0	0,016343
8	EBCI	0	0,001562	1,63E-05	0,001658	3,27E-05	0,001602	1,85E-05	0,001814	0,000117	0,002383	0,000109	0,001907
9	EBCV	0	9,37E-05	1,63E-05	6,5E-05	1,64E-05	6,54E-05	0	0,000296	0	0,00014	0	5,45E-05
10	EBKT	6,25E-05	0,004747	3,25E-05	0,004031	4,91E-05	0,005134	0	0,005219	7,01E-05	0,005047	8,17E-05	0,005339
11	EBLG	0,000172	0,002686	9,75E-05	0,004551	1,64E-05	0,003499	1,85E-05	0,002628	2,34E-05	0,002944	5,45E-05	0,002887
12	EBMB	0	0,000812	1,63E-05	0,000358	0	0,001046	1,85E-05	0,001073	7,01E-05	0,001075	2,72E-05	0,001035
13	EBOS	1,56E-05	0,001374	1,63E-05	0,0013	8,18E-05	0,001733	7,4E-05	0,002147	0	0,001916	2,72E-05	0,00207
14	EDAB	1,56E-05	0,000375	0	0,000228	1,64E-05	0,000458	1,85E-05	0,000703	2,34E-05	0,000607	2,72E-05	0,000436
15	EDAC	3,12E-05	0,000219	0	3,25E-05	0	0,000392	1,85E-05	0,000185			0	0,000272
16	EDAD					0	6,54E-05	1,85E-05	0			0	5,45E-05
17	EDAV	1,56E-05	0,000156	0	0,000228	1,64E-05	9,81E-05	1,85E-05	0,000259	4,67E-05	0,000234	2,72E-05	5,45E-05
18	EDAZ	1,56E-05	0,001187	3,25E-05	0,00078	3,27E-05	0,000883	1,85E-05	0,001147	4,67E-05	0,001075	5,45E-05	0,00049
19	EDBJ	0	3,12E-05	0	3,25E-05	1,64E-05	3,27E-05	0	3,7E-05	0	4,67E-05	0	0,000109
20	EDBK	0	3,12E-05	0	3,25E-05					0	4,67E-05	0	5,45E-05
21	EDBM	0	0,000125	0	3,25E-05	0	0,000262	0	0,000111	0	9,35E-05	0	0,000163
22	EDBN	3,12E-05	0,000562	0	0,00013	0	0,000229	0	0,000259	0	0,000327	0	5,45E-05
23	EDDB	3,12E-05	0,017021	0,000244	0,020711	3,27E-05	0,026096	1,85E-05	0,026687	0,000164	0,030518	0,000245	0,023431
24	EDDC	3,12E-05	0,002374	4,88E-05	0,002113	4,91E-05	0,002518	9,25E-05	0,002998	2,34E-05	0,003645	0	0,002397
25	EDDE	1,56E-05	0,001374	1,63E-05	0,001495	1,64E-05	0,001341	1,85E-05	0,001555	2,34E-05	0,002477	5,45E-05	0,001253
26	EDDF	9,37E-05	0,008808	0,000163	0,008745	8,18E-05	0,012656	0,00013	0,01092	0,00014	0,015656	0,000245	0,014222
27	EDDG	3,12E-05	0,003186	1,63E-05	0,004031	1,64E-05	0,005657	7,4E-05	0,003665	2,34E-05	0,004299	0,000136	0,004631
28	EDDH	0	0,014272	0,000114	0,013361	0	0,017004	0,000204	0,018363	0,00028	0,019397	0,000354	0,019183
29	EDDK	0,000328	0,011747	3,25E-05	0,012385	0,000262	0,015602	9,25E-05	0,014918	0,00028	0,014817	0,000109	0,016727
30	EDDL	6,25E-05	0,011431	6,5E-05	0,011605	9,81E-05	0,013245	9,25E-05	0,013289	0,00014	0,016403	0	0,01618
31	EDDM	7,81E-05	0,018146	0,000114	0,020285	9,81E-05	0,024266	1,85E-05	0,026058	0,00021	0,027014	2,72E-05	0,028547
32	EDDN	0,000265	0,006092	1,63E-05	0,007086	9,81E-05	0,008372	3,7E-05	0,007921	0,00028	0,009441	5,45E-05	0,010079

Figure 21 OD and Ci values for 2021

Figure 21 above shows merged values of OD and C_i of all airports for one year. My thesis is focused on connectivity, therefore only Flow Connectivity Indicator was used for further connectivity assessment.

3.5 Core network identification

As already mentioned above, the European business aviation network during 2019 – 2021 consists of almost 1200 active airports. It was necessary to narrow the selection to the most important airports of the network and then subject these airports to further analysis.

This was achieved by using boxplot data visualization (Figure 22) and evaluation. Apart from visualization of the distribution of data values, it identifies data outliers, the atypical observation that does not fit into probabilistic behaviour of the dataset. In my case it was a value more than 1.5 times the interquartile range (IQR) above the 3rd quartile. The assessed values were C_i values for each month of year 2019 separately.

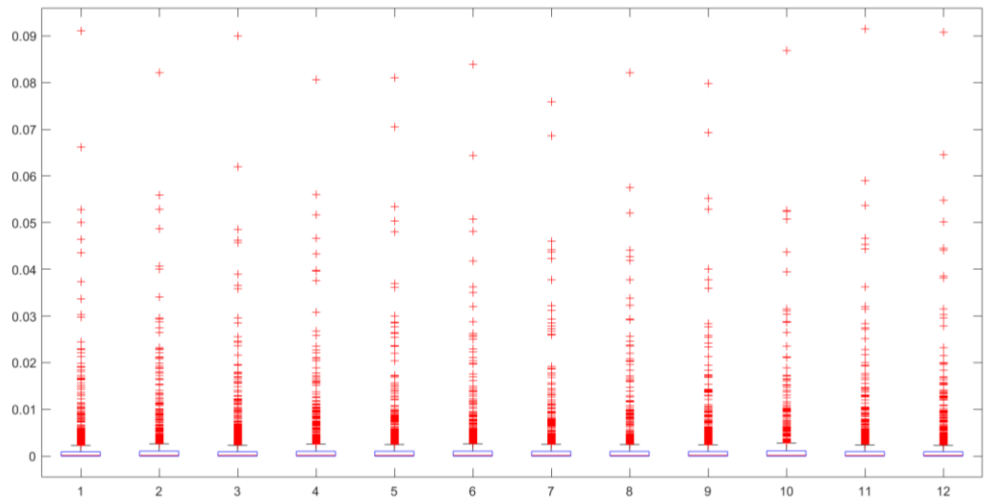


Figure 22 Connectivity Indicator boxplots

Next step was to compare number of occurrences of the outliers for every month of 2019 and only airports occurring as outliers for every month of 2019 were picked. The aim was to identify the core network of standard business aviation operation and analyse its behaviour during the COVID-19 pandemic and this selection identified 61 airports as the core network. These airports and their C_i values were then filtered from the tables for each year (Figure 21).

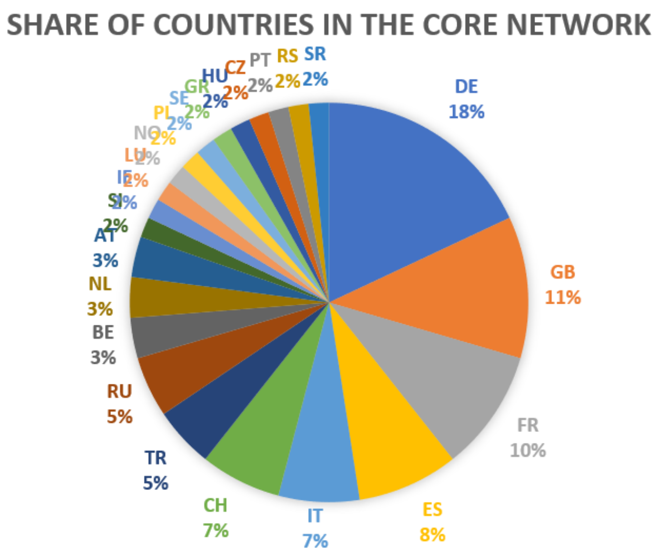


Figure 23 Share of countries in the core network

The graph above (Figure 23) shows shares of individual countries in the core network of airports. See the attachment n.1 for the list of core network airports.

The data for core network airports were also normalized through z-score normalization. As Aksu says [42], this method of normalization uses mean (μ_i) and standard deviation (σ_i) of each variable (x_i) for the whole dataset to normalize the vector of each feature. The values of z-score indicate distance of the raw value from arithmetic mean. The mean is represented by 0 value.

$$x' = \frac{x_i - \mu_i}{\sigma_i} \quad (13)$$

3.6 Methodology and data process summary

Regarding the available data and their limitations, the analysis was conducted on a monthly basis from January 2019 to December 2021. Data, in the form of Airport Pairs and the number of flights between them, were exported from EBAA E-STAT Dashboard and prepared for Gephi software, which calculated weighted degrees and other parameters for each airport.

Flow Centrality Indicator, from the methodology of Flow centrality, was subsequently calculated for each airport and month. Due to data limitation, the second indicator, Traffic Generation, was not used.

Data for 2019 were visualised using a box plot diagram and the outliers of all months, 61 airports, were chosen as the core network. The z-score data normalization was then used for better data comparison.

4 Data analysis

To describe behaviour of the core network during COVID-19 pandemic, it was necessary to choose a method that would clearly show the differences in its behaviour compared to pre-pandemic year 2019. PCA and cluster analysis were chosen for these purposes.

Both analyses were done in Orange, freeware software based on Python, which offers, according to its developers [43], an interactive visual-programming interface for different types of data analysis, visualisation and prediction.

Principal component analysis is a statistical tool for dimension reduction. The algorithm picks up dimensions with the largest variances and serves to reduce data noise, the corrupted or meaningless data information. Ding says [44], it is often used together with the k-mean clustering analysis to improve its results and coherent patterns can be detected more clearly.

4.1 Cluster analysis

Cluster analysis divides data into several groups – clusters with similar behaviour. One of the most efficient methods is the K-means method. *“The aim of the algorithm is to divide points in into clusters so the within-cluster sum of square is minimized”* [45]. The algorithm defines k centroids, one for each cluster. Then it takes each point of the data set and associates it to the nearest centroid. After completing this step with all points, it recalculates k new centroids as centres of clusters resulting from the previous step. Points are bonded to the new centroid. The steps are repeated until there is no movement of centroids [46]. Steps of the algorithm are represented in the Figure 24 below.

A silhouette number is assigned to each data point to determine its average distance to the other points in the cluster as well as to its closest neighbouring cluster points, says Wang [47]. According to Kumar [48], the score interval is -1 – 1, where negative numbers indicate incorrect clustering and number 1 represents very dense cluster. Wang [47] also confirms the Silhouette score serves as the most popular clustering validity evaluation.

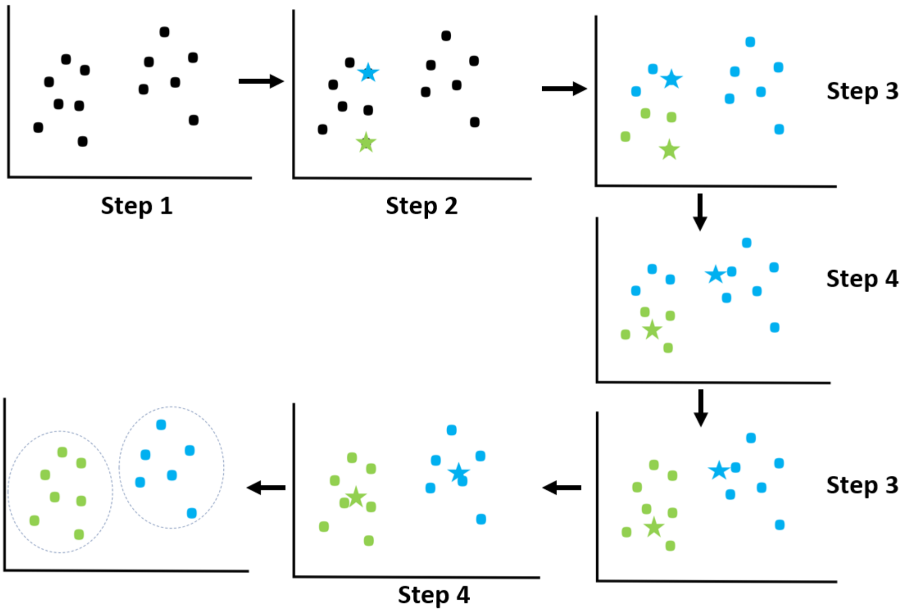


Figure 24 K-mean clustering algorithm [49]

The analysis was done for each year. Following figures (Figure 25, Figure 26, Figure 27) compare cluster analysis results in scatter plots for 3 and 4 clusters.

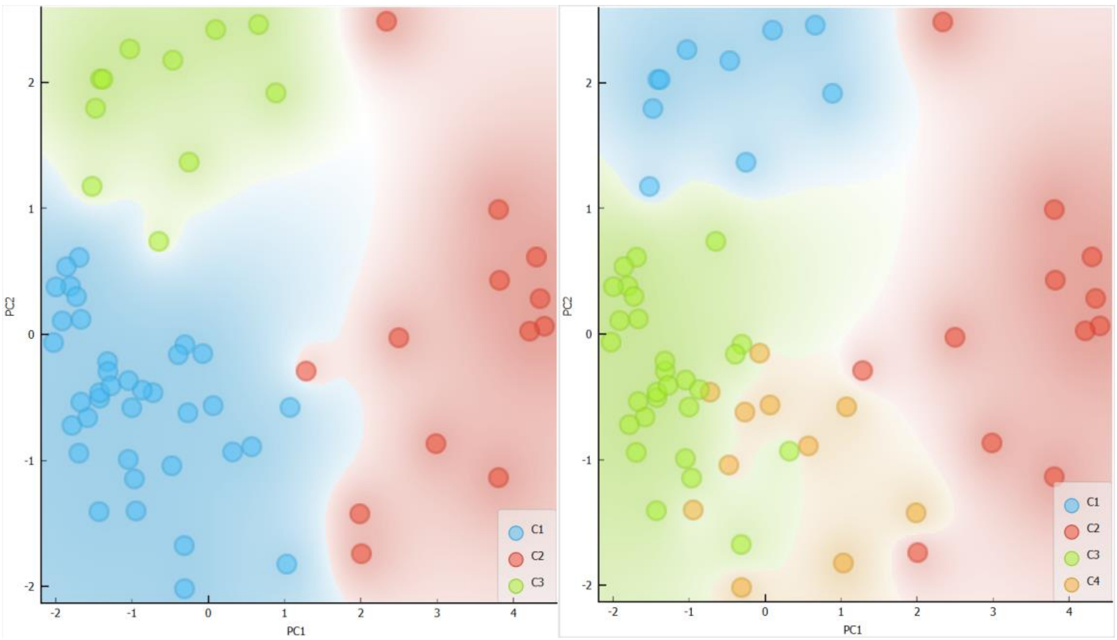


Figure 25 Cluster analysis results comparison, 2019

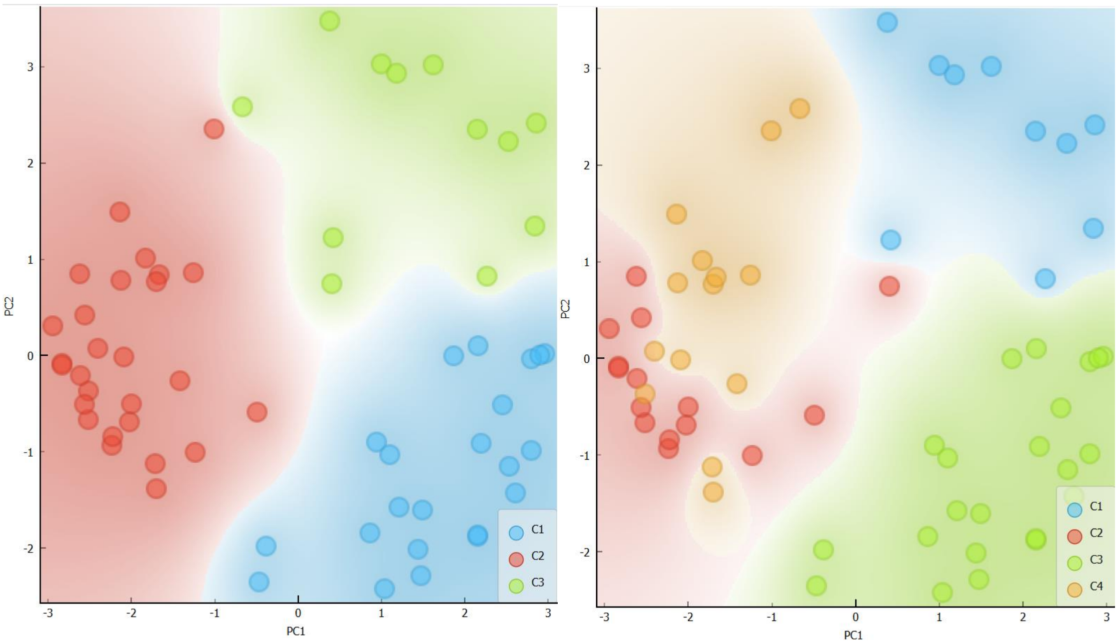


Figure 26 Cluster analysis results comparison, 2020

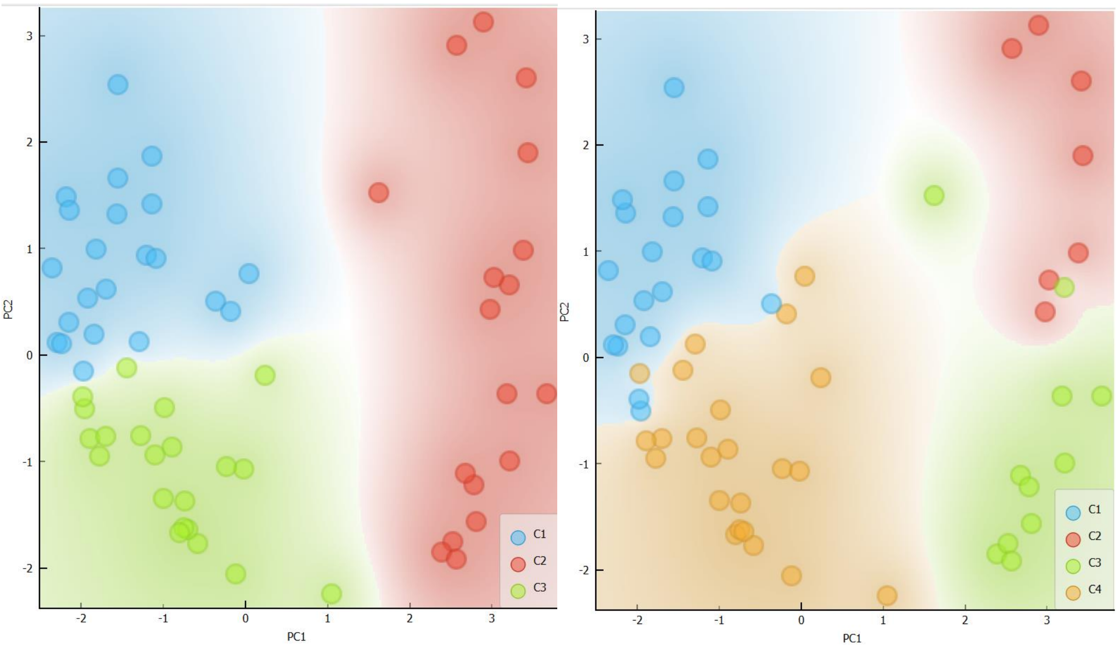


Figure 27 Cluster analysis results comparison, 2021

At all cases, the 3 clusters are heavily delimited and no points interfere into other clusters. In contrast, results for 4 clusters are already showing a few interferences. Therefore 3 clusters were chosen for further analysis for every year.

4.1.1 Year 2019

Year 2019 was considered as the exemplary, showing standard behaviour of airports during the year and as well as their classification to a given cluster. Changes of behaviour and cluster migration was subsequently analysed for years 2020 and 2021, compared to 2019 values. The clusters for 2019 and their members are shown below:

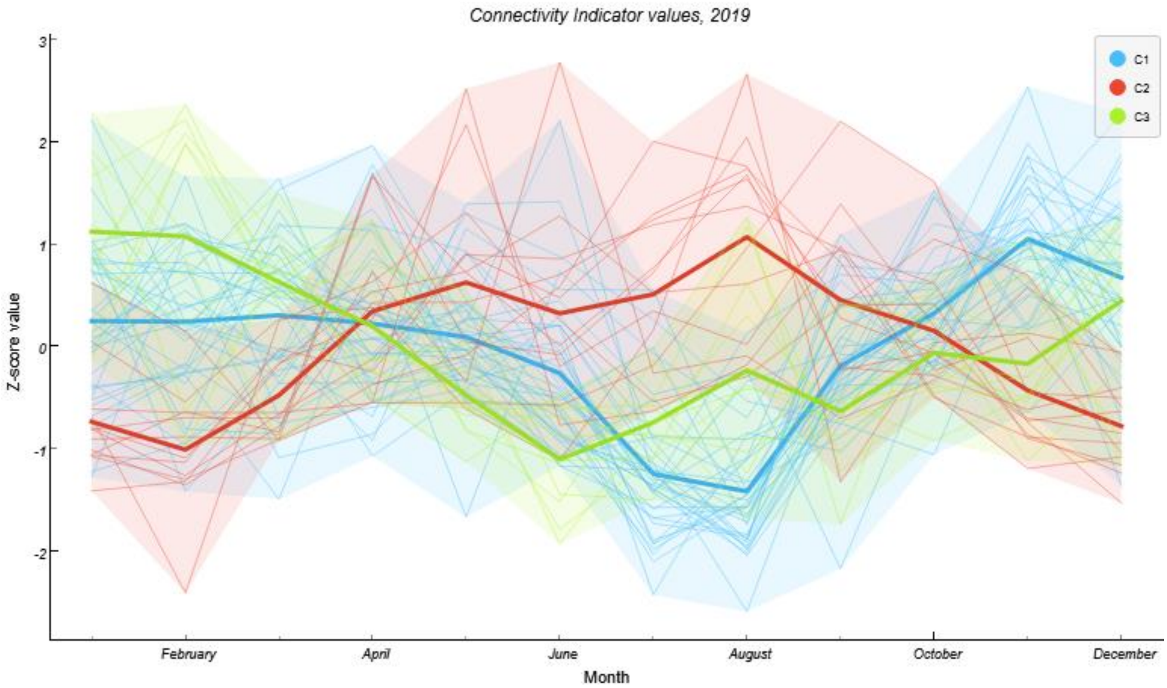


Figure 28 Graph of Connectivity Indicator values - all clusters, 2019

Figure 28 shows all clusters of core network airports of 2019 in joint graph. Their average values are represented by thick lines and coloured areas show their range of values. Each cluster is characterised by its specific progress over time. Generally, there is significant cluster C2 with highest values during summer and two clusters C1 and C3 that have their peaks during winter. Each cluster and its members will be described in more detail below.

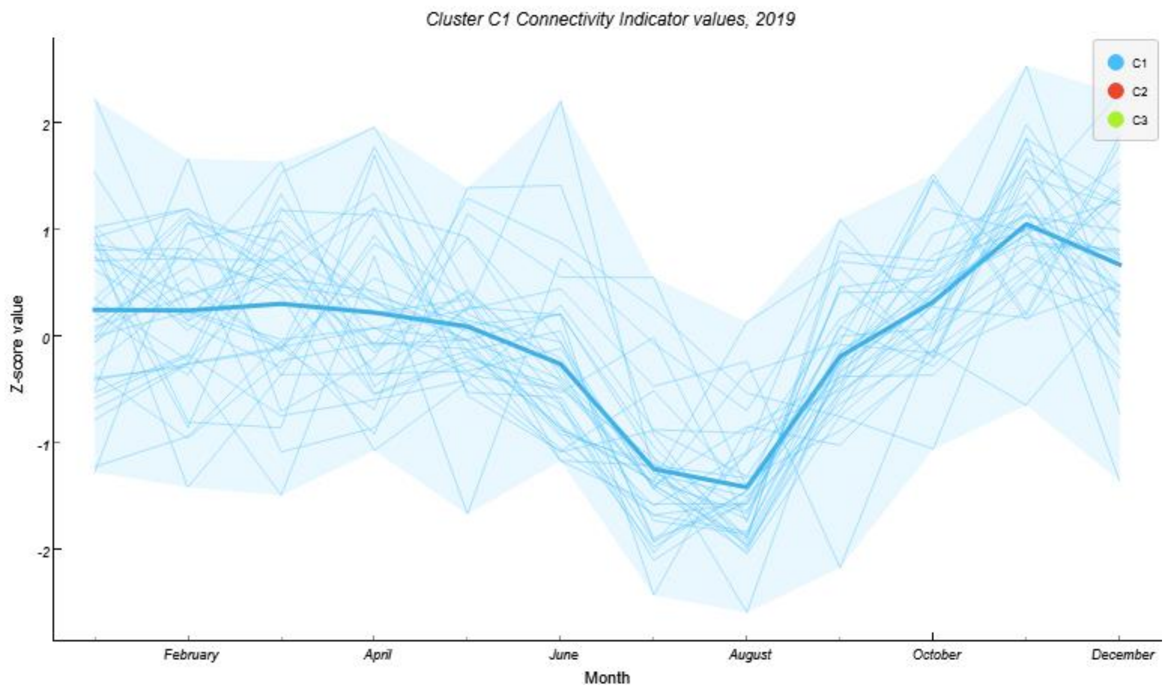


Figure 29 Graph of Connectivity indicator values – Cluster C1, 2019

Cluster C1 (Figure 29) is characterised by its significant drop of the average connectivity (thick line) over summer months and its following rise at the end of the year, and contains more than a half of core network airports. The range of values is represented by the coloured area. The particular airports of this cluster are listed in Table 2 below, the silhouette value, as described above, shows the average within cluster distance. In the table, we can see airports like Antwerp, Berlin, Brussels, Dusseldorf or Zurich. This indicates the airports could be mainly business related. The cluster also contains Czech Václav Havel Airport and Slovak M. R. Štefánik Airport.

Table 2 Cluster C1 airports, 2019

ICAO Code	Name	Cluster	Silhouette
EBAW	Antwerp Intl. (Deurne)	C1	0,541492
EBBR	Brussels	C1	0,596576
EDDB	Berlin-Schoenefeld	C1	0,591091
EDDF	Frankfurt am Main	C1	0,554396
EDDH	Hamburg	C1	0,586556
EDDK	Cologne Bonn	C1	0,557539
EDDL	Dusseldorf	C1	0,543606
EDDM	Munich	C1	0,577737
EDDN	Nuremberg	C1	0,548706
EDDS	Stuttgart	C1	0,55159
EDDW	Bremen	C1	0,56002
EDSB	Karlsruhe Baden-Baden	C1	0,550397
EFHK	Helsinki Vantaa	C1	0,541776

EGGW	London Luton	C1	0,571456
EGJJ	Jersey	C1	0,563265
EGKB	London Biggin Hill	C1	0,535813
EGLF	Farnborough	C1	0,581261
EGSS	London Stansted	C1	0,550361
EHAM	Amsterdam Schiphol	C1	0,594138
EHRD	Rotterdam The Hague	C1	0,594974
EIDW	Dublin	C1	0,615729
ELLX	Luxembourg-Findel Intl.	C1	0,596752
ENGM	Oslo Gardermoen	C1	0,575977
EPWA	Warsaw Chopin	C1	0,560649
ESSB	Stockholm-Bromma	C1	0,554159
LEBL	Barcelona Intl.	C1	0,505026
LEMD	Adolfo Suárez Madrid–Barajas	C1	0,586899
LFPB	Paris-Le Bourget	C1	0,595648
LFSB	Euro Basel-Mulhouse-Freiburg	C1	0,533587
LHBP	Budapest Liszt Ferenc Intl.	C1	0,565149
LIRA	Ciampino–G. B. Pastine Intl.	C1	0,524798
LKPR	Václav Havel Prague	C1	0,585675
LOWW	Vienna Intl.	C1	0,590832
LSGG	Geneva Cointrin Intl.	C1	0,529434
LSZH	Zurich	C1	0,52178
LZIB	M. R. Štefánik	C1	0,540029
UKKK	Kiev Zhuliany Intl.	C1	0,553911

Cluster C2 (Figure 30) shows, in contrast to C1, very strong average values (thick line) during spring and summer months, and below average values for winter months. This trend indicates more leisure related destinations. The cluster contains 13 airports. The range of connectivity values is represented by the coloured area.

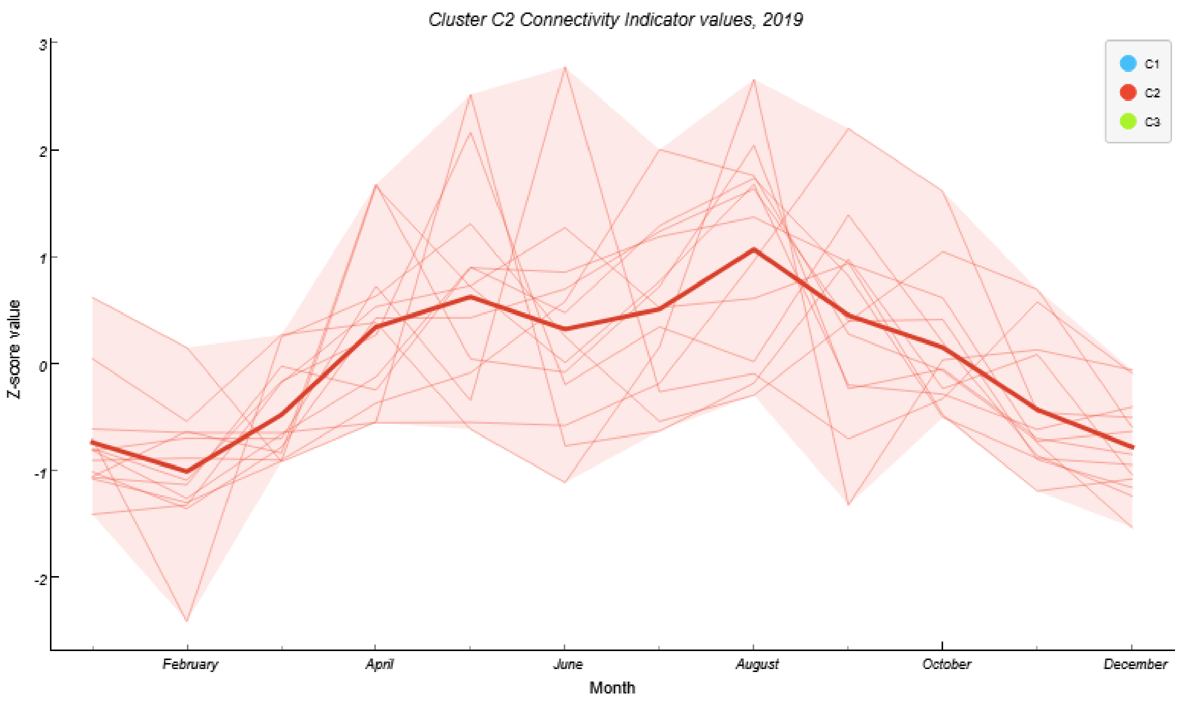


Figure 30 Graph of Connectivity indicator values – Cluster C2, 2019

The table of Cluster C2 airports (Table 3) altogether confirm this assumption with majority of airports belonging to summer destinations:

Table 3 Cluster C2 airports, 2019

ICAO Code	Name	Cluster	Silhouette
EGTK	Oxford (Kidlington)	C2	0,509104
LEMG	Málaga	C2	0,630735
LEPA	Palma De Mallorca	C2	0,655302
LFBD	Bordeaux-Mérignac	C2	0,5359
LFMD	Cannes-Mandelieu	C2	0,646349
LFMN	Nice-Côte d'Azur	C2	0,651188
LGAV	Eleftherios Venizelos Intl.	C2	0,63352
LIMC	Malpensa Intl.	C2	0,569184
LIPZ	Venice Marco Polo	C2	0,606177
LIRQ	Peretola	C2	0,634888
LPFR	Faro	C2	0,619521
LTBA	Ataturk Intl.	C2	0,497731
ULLI	Pulkovo	C2	0,517178

The last and the smallest cluster of 2019, cluster C3 (Figure 31) contains 11 airports. It shows a great average connectivity (thick line) during winter with steady decline during spring and its lowest low in summer. The coloured area represents the range of value.

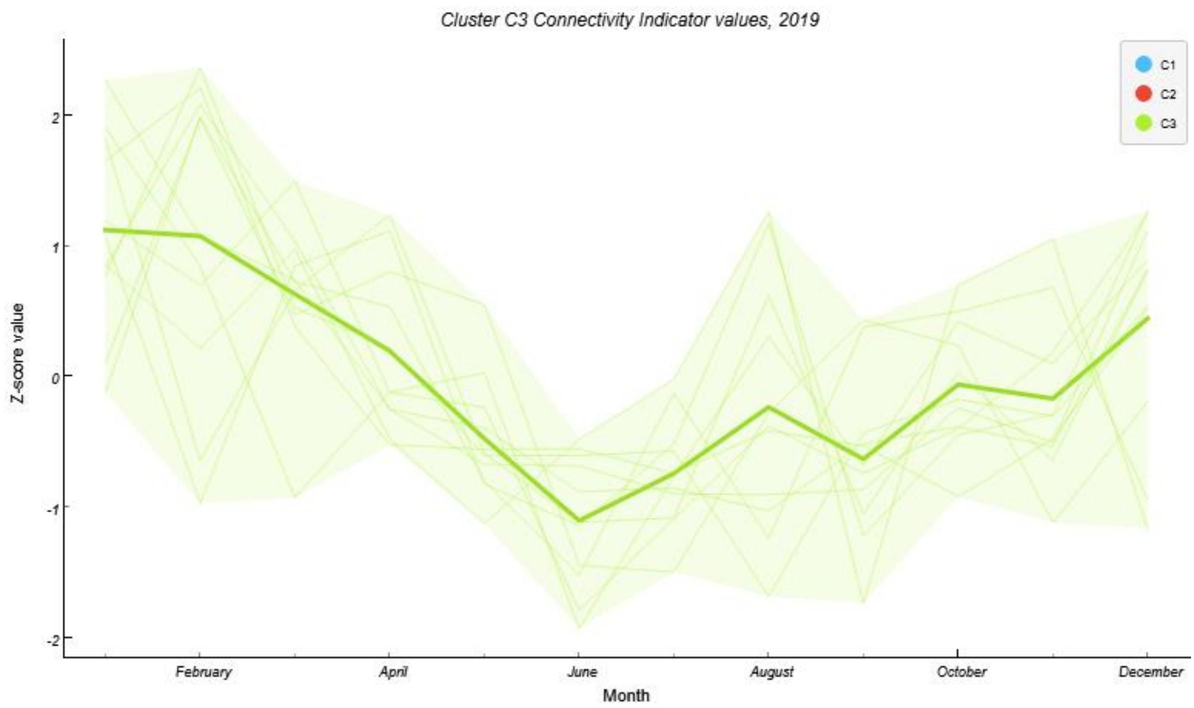


Figure 31 Graph of Connectivity indicator values – Cluster C3, 2019

The list of airports belonging into this cluster is presented in Table 4 below.

Table 4 Cluster C3 airports, 2019

ICAO Code	Name	Cluster	Silhouette
EDMO	Oberpfaffenhofen	C3	0,507484446
EGCC	Manchester	C3	0,544580114
LEVC	Valencia	C3	0,535928415
LFLY	Lyon-Bron	C3	0,545569175
LOWI	Innsbruck	C3	0,574305906
LSZB	Bern Belp	C3	0,588267552
LSZR	St Gallen Altenrhein	C3	0,574099378
LTAC	Esenboğa Intl.	C3	0,558130885
LYBE	Belgrade Nikola Tesla	C3	0,559036415
UUEE	Sheremetyevo Intl.	C3	0,563783128
UUWW	Vnukovo Intl.	C3	0,554570119

4.1.2 Year 2020 (COVID)

Next graph (Figure 32) shows behaviour of clusters during 2020, i.e., the first year of the COVID-19 pandemic. The thick lines show averages of each cluster, the colour areas represent their range. Clusters C1 and C3 experienced a sharp decline during the first months of the pandemic, when the restrictions were the strictest. On the contrary, cluster C2 shows skyrocket increase of the connectivity during these months. In the overall view, the connectivity of these clusters seems to be complementary. Please note the clusters may not correspond to clusters of the previous year. Please see Attachment 2 with list of all core network airports and their clusters for each year.

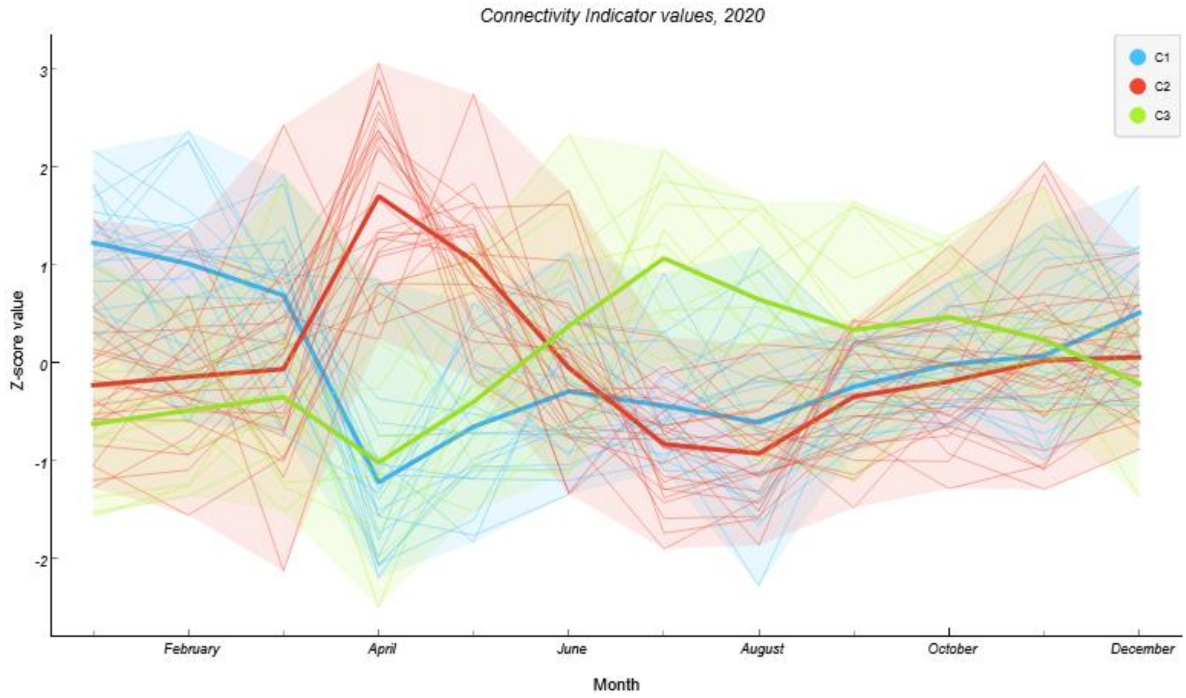


Figure 32 Graph of Connectivity Indicator values - all clusters, 2020

Airport migrations between clusters were observed and cluster do not have the same number of members they had in 2019.

Cluster C1 has 22 members and contains airports mainly from cluster C1 of 2019. Figure 33 shows its average (thick lane) as well as its range (coloured area).

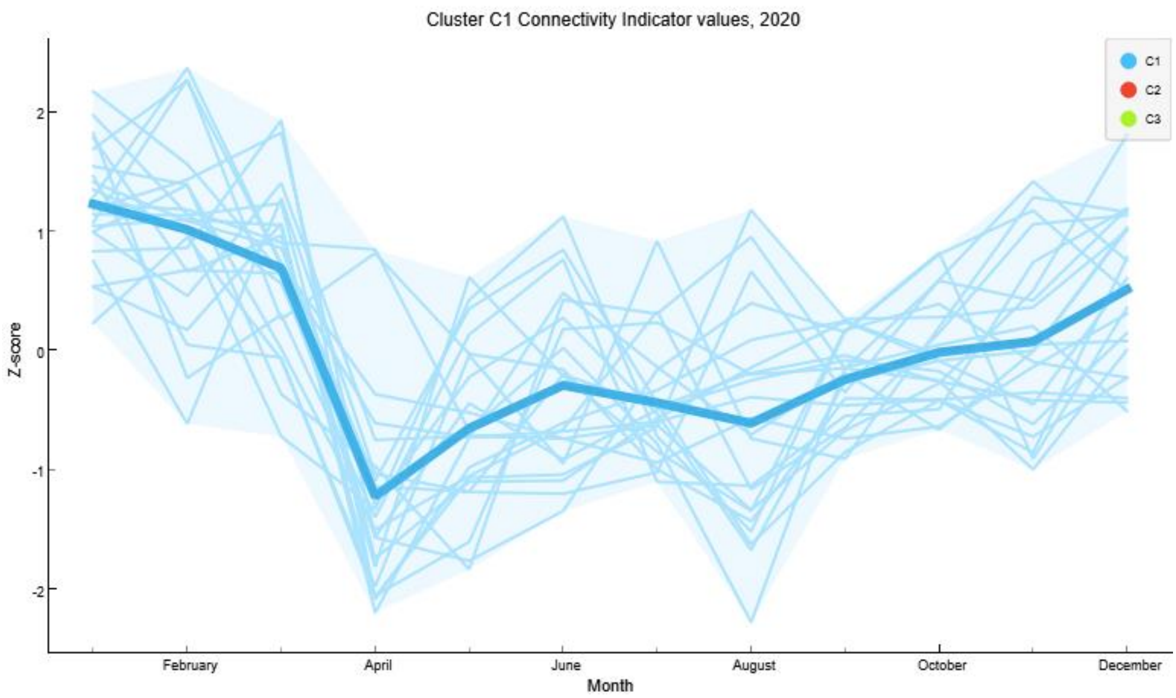


Figure 33 Cluster C1, 2020

Next graph (Figure 34) color-codes airports according to their 2019 cluster affiliation. As already mentioned, most of the airports (16) belonged cluster C1 in 2019, which is more than 43% of the member of C1 of 2019, one was in C2 and the remaining 5 used to be C3 (almost 46% of C3 members in 2019).

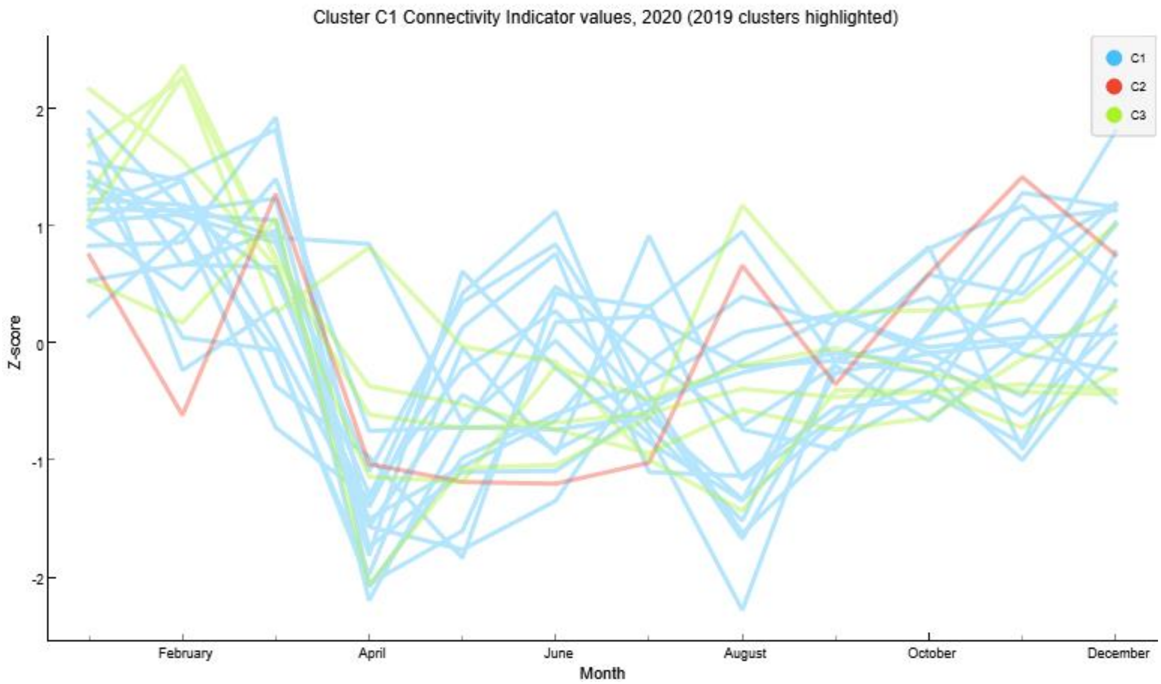


Figure 34 Cluster C1, 2020 (2019 clusters highlighted)

The one airport from C2, marked red, was Russian airport Pulkovo (ULLI). The airports from C3 were Lyon-Bron (LFLY), Innsbruck (LOWI) ,Bern Belp (LSZB), St Gallen Altenrhein (LSZR) and Vnukovo Intl. (UUWW).

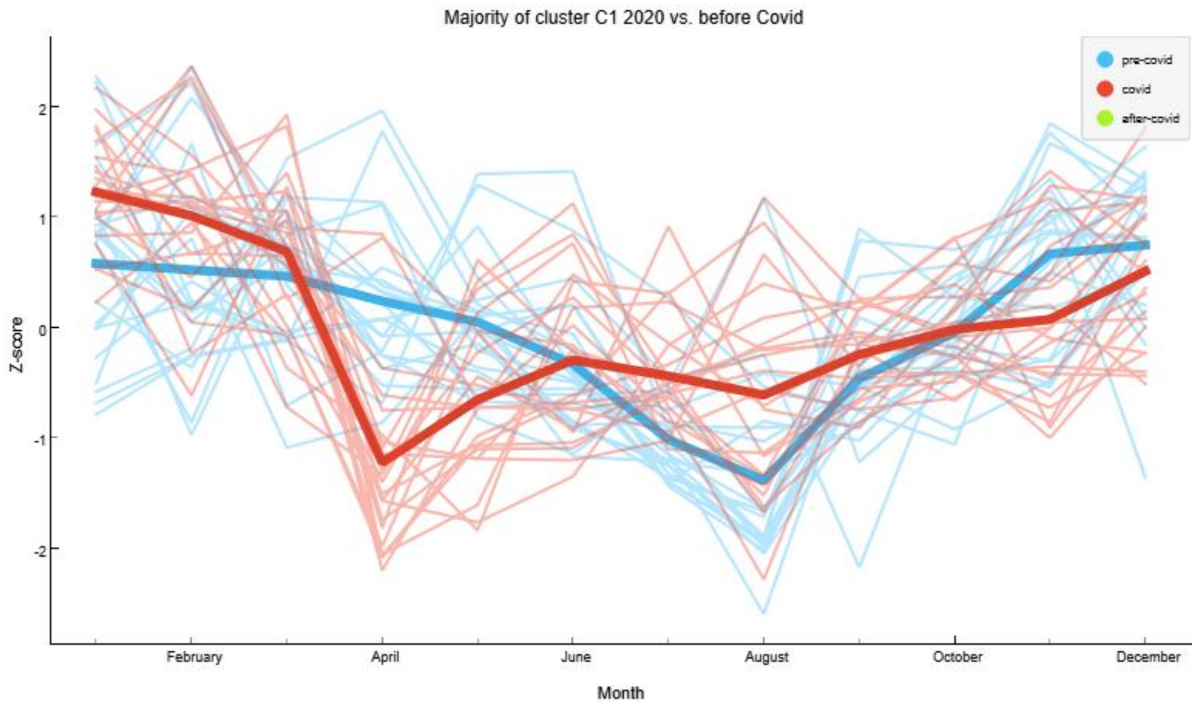


Figure 35 Cluster C1 majority 2020 and 2019 comparison

Figure 35 compares majority of airports, belonging to clusters C1 and C3 in 2019, of this cluster to their values before Covid. It shows significant decline during April 2020 and subsequent increase over their pre-covid values Mid-May. The thick lines show the average values of each year.

Cluster C2 was again significantly different from the other clusters. Its reaction to COVID-19 was dramatical increase of connectivity during March and April and subsequent decline. Its graph is shown in Figure 36. The average values are shown by the thick line, the coloured area represents the range.

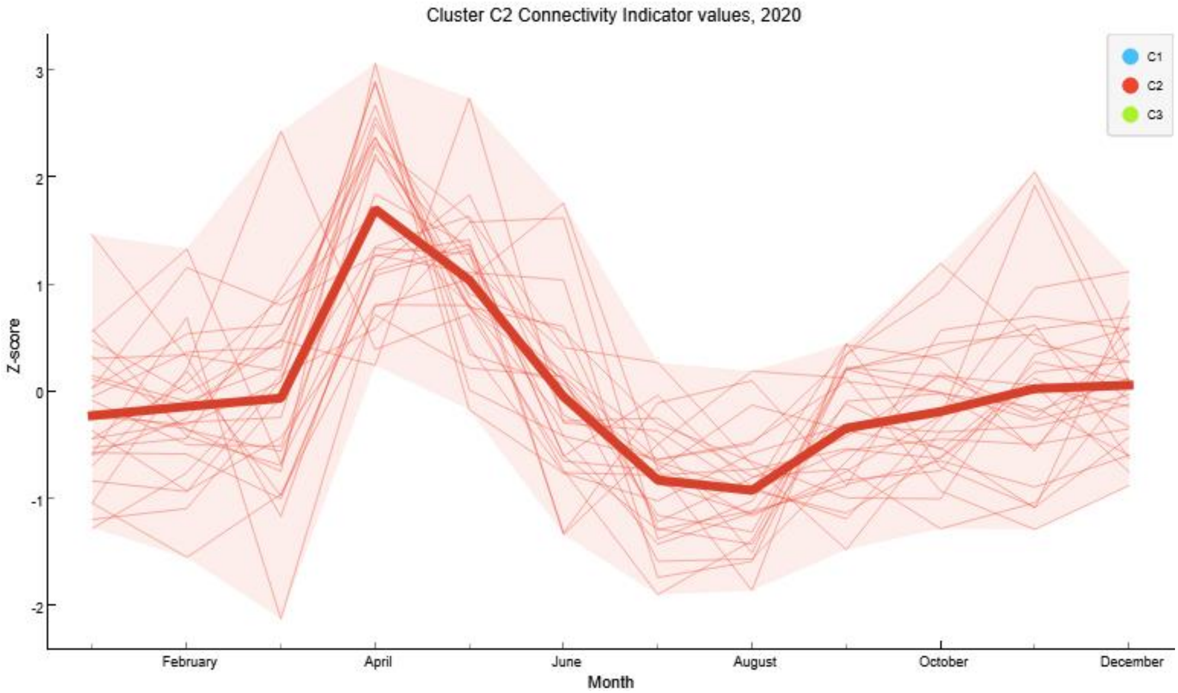


Figure 36 Cluster C2, 2020

This cluster contains the largest number of airports (27) and 20 of them are from cluster C1 of 2019 (over 54% of 2019 members). The rest of the airports is from C2 (3) and C3 (4). Figure 37 colour-codes their graphs according to their 2019 cluster affiliation.

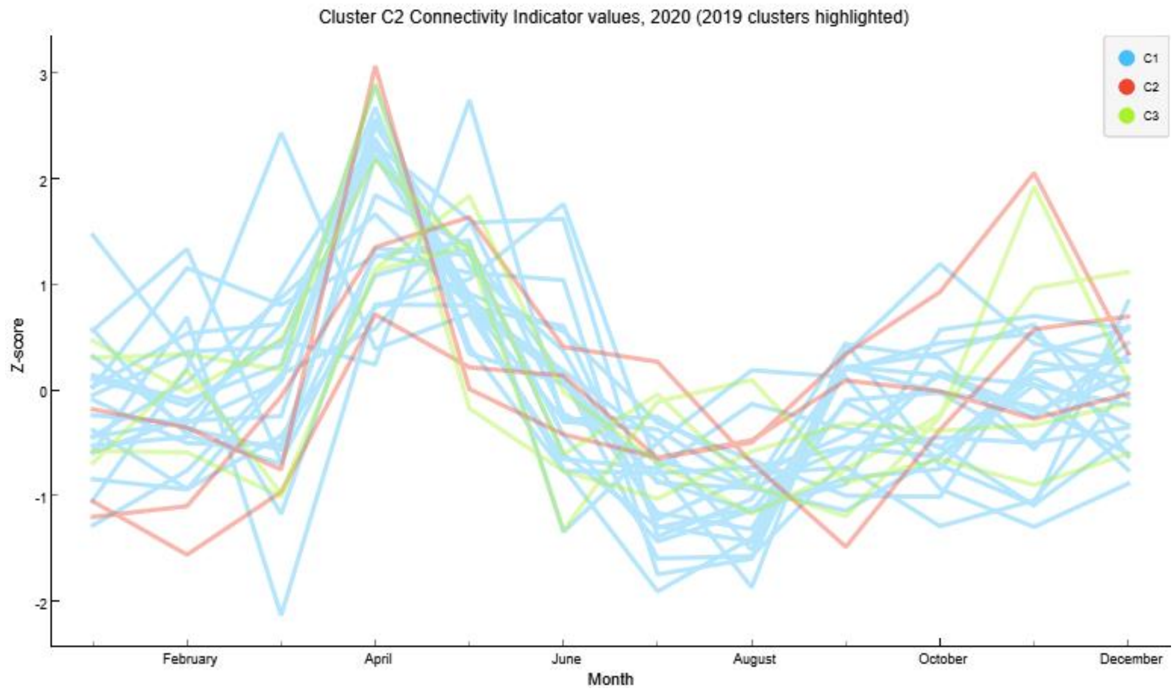


Figure 37 Cluster C2, 2020 (2019 clusters highlighted)

The airports from cluster C2 were Bordeaux-Mérignac (LFBD), Malpensa Intl. (LIMC) and Ataturk Intl. (LTBA). And from cluster C3 Manchester (EGCC), Valencia (LEVC), Esenboğa Intl. (LTAC) and Sheremetyevo Intl. (UUEE).

Graph (Figure 38) comparing pre-covid and covid values of the majority of airports in cluster C2 (belonging to cluster C1 in 2019) shows skyrocket increase of connectivity during the first wave of Covid 19 in April 2020 up to its pre-covid values. This trend stays until September 2020, where it stays relatively stable to the end of the year. In contrast, pre-covid values tend to rise. The average values of each year are shown by the thick lines.

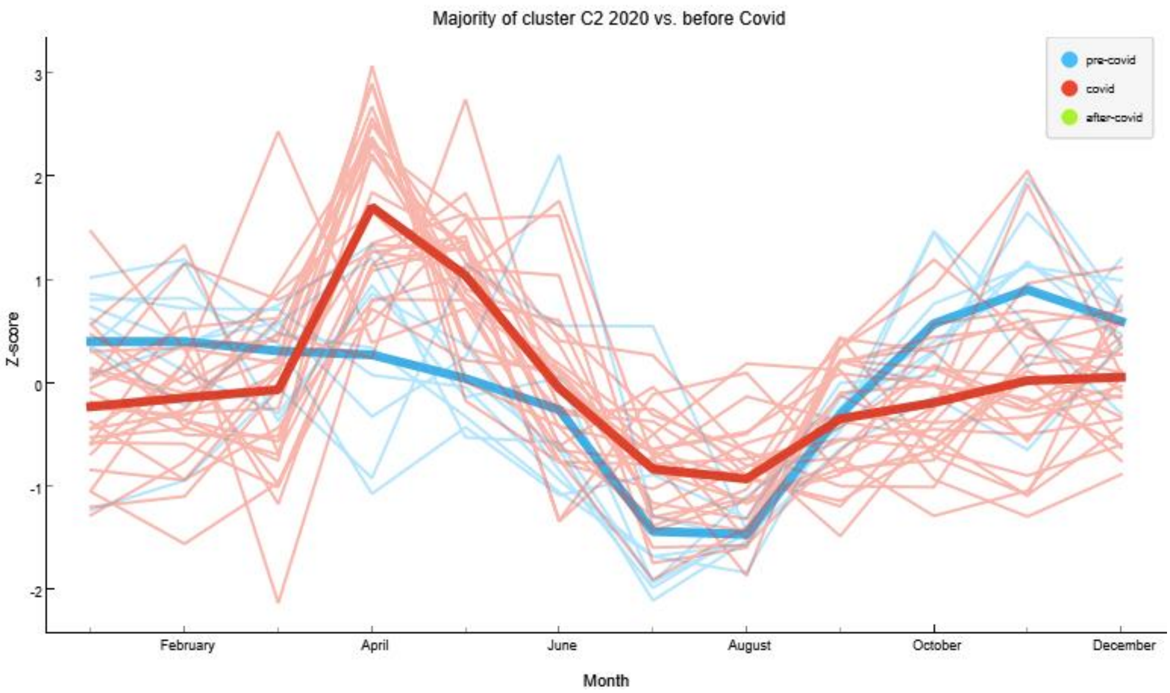


Figure 38 Cluster C2 2020 majority compared to 2019

The last cluster C3 reacted similarly to C1 but reached better connectivity values after the great dip (Figure 39). The thick line represents the average values, the coloured area shows the range.

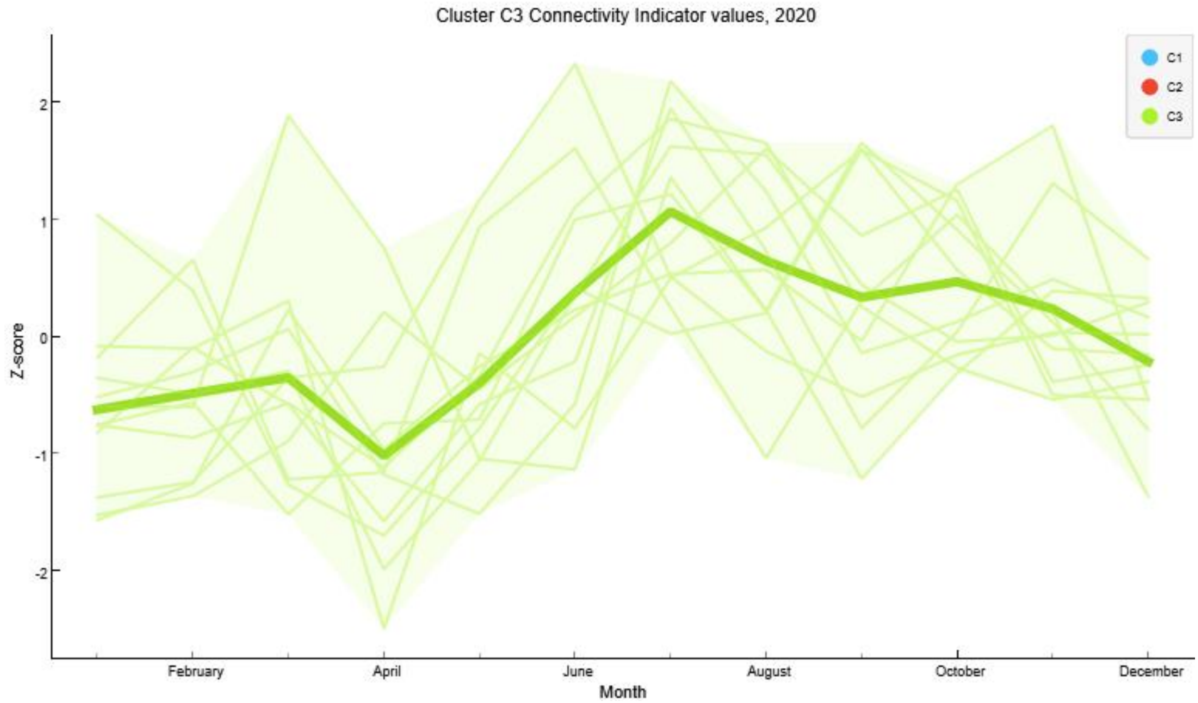


Figure 39 Cluster C3, 2020

It is the smallest cluster, where the majority of airports, 9 out of total 12, were from cluster C2 of 2019 (69% of 2019 members), one airport, Budapest Liszt Ferenc Intl. (LHBP), was from C1 and 2 airports, Oberpfaffenhofen (EDMO) and Belgrade Nikola Tesla (LYBE) from C3. Figure 40 shows their distribution in the graph.

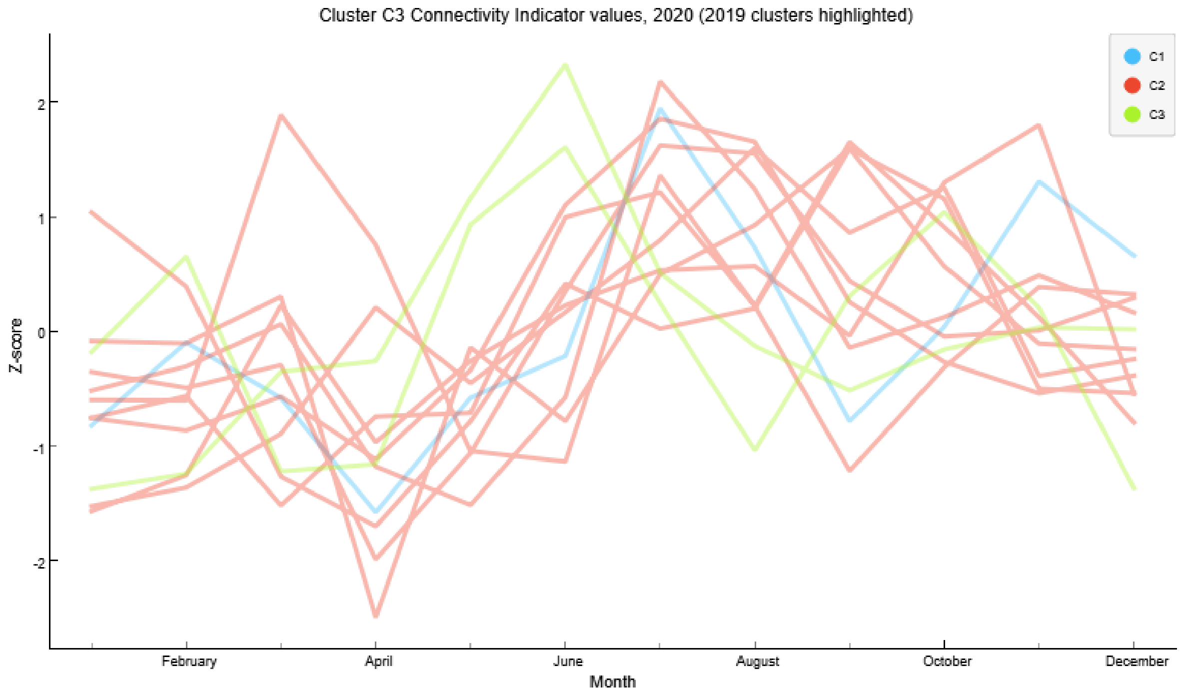


Figure 40 Cluster C3, 2020 (2019 clusters highlighted)

When comparing majority of the cluster (Figure 41), belonging to cluster C2 in 2019, there is visible similarity of both graphs of average values (thick lines) except the drop in April 2020. Overall, the values seem to complement each other.

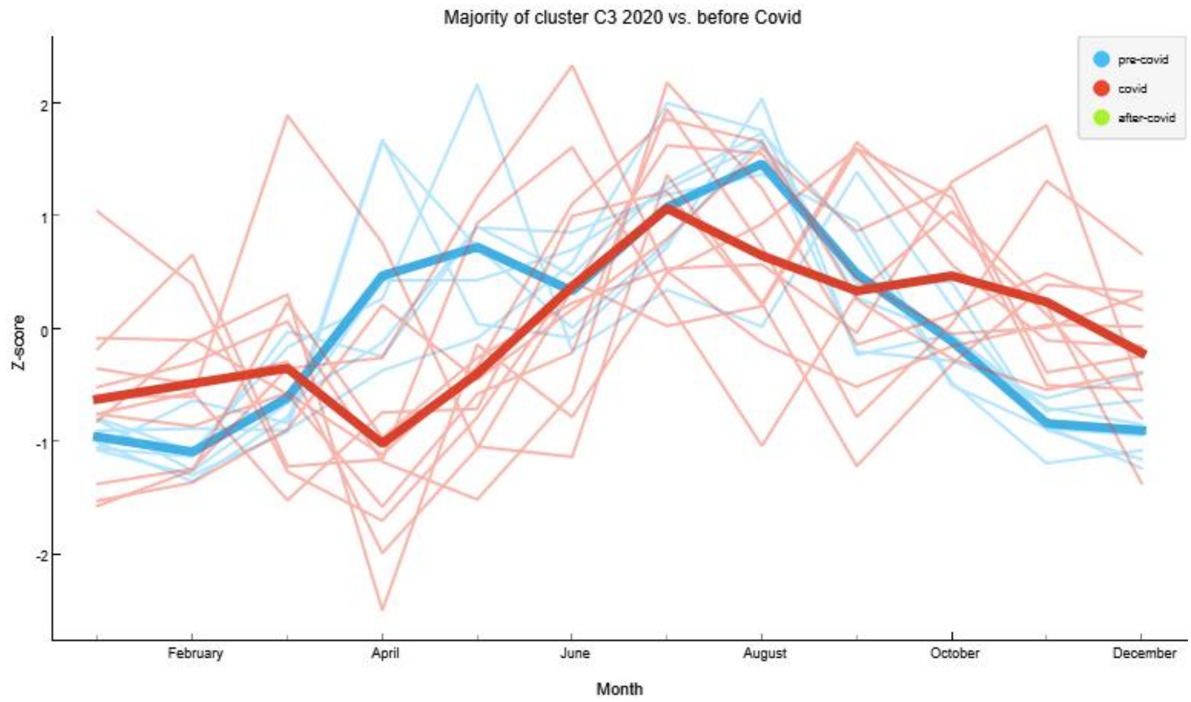


Figure 41 Cluster C3 2020 majority compared to 2019

4.1.3 Year 2021 ('after' COVID)

The last analysed year was 2021. As mentioned, the sample year is 2019 so the clusters will be compared only to 2019 clusters. Cluster C2 is again very different from other clusters with its highest values from May to October. This trend looks similar to C2 cluster during pre-covid year 2019. The other two clusters seem to return to their pre-covid characteristics as well, with their peaks during winter months and lowest lows during summer. All clusters of 2021, their average values (thick lines) and range (coloured area) are shown in Figure 42.

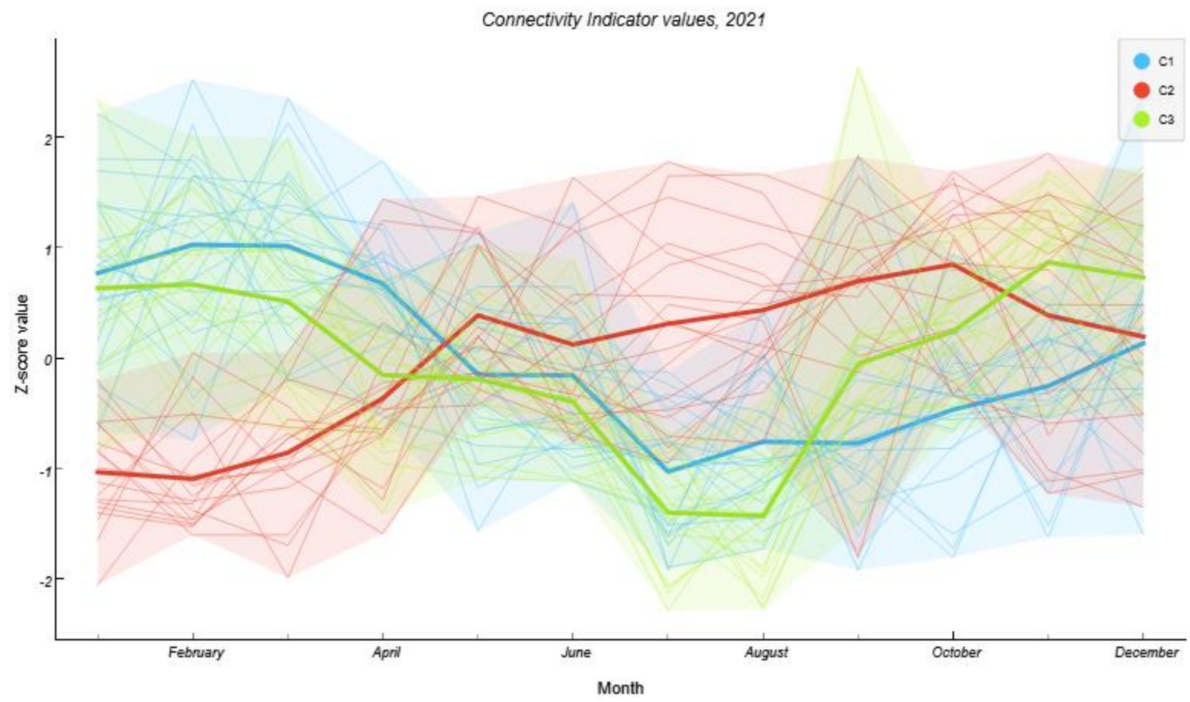


Figure 42 Graph of Connectivity Indicator values - all clusters, 2021

The first cluster, C1, is characterised by its low average values (thick line) during summer months, as well as high values during beginning of the year (Figure 43). The range is represented by the coloured area. This is very similar to cluster C3 (Figure 31) during 2019.

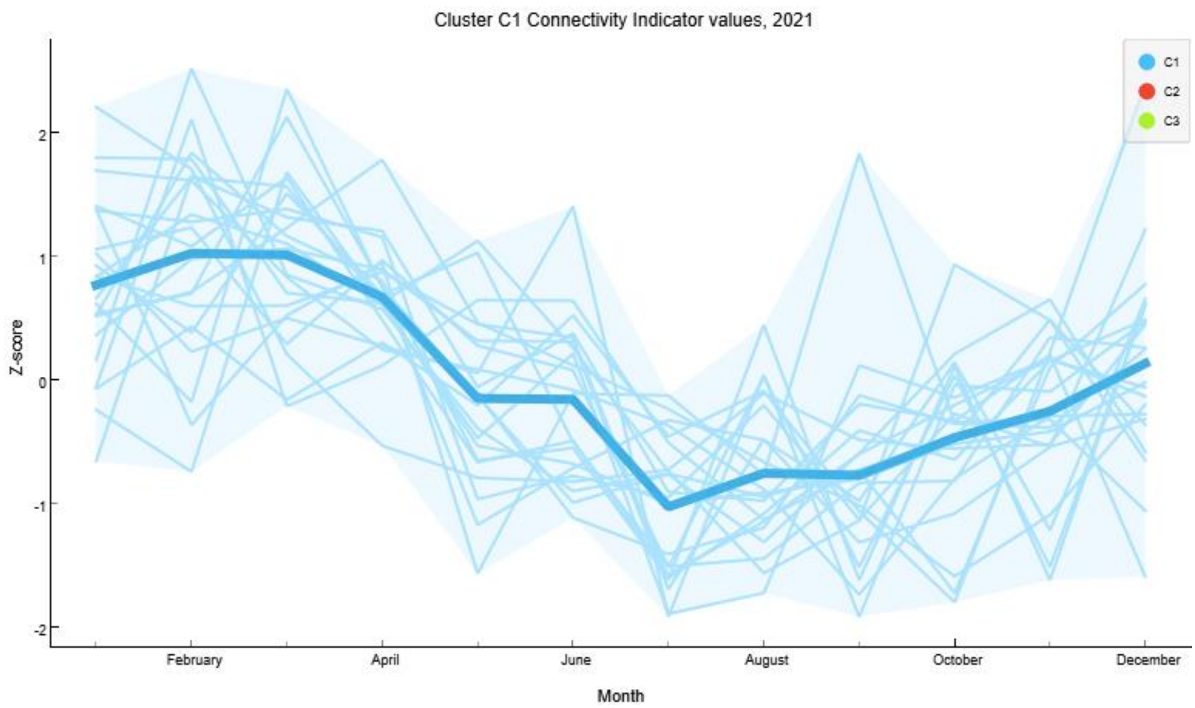


Figure 43 Cluster C1, 2021

Cluster consists of 22 airports and almost half of them (10) are from cluster C1 of 2019, 9 airports are from C3, which is almost 82% airports the 2019 cluster, and the remaining 3 are from C2. The clusters of 2019 within the cluster C1 are distinguished in Figure 44.

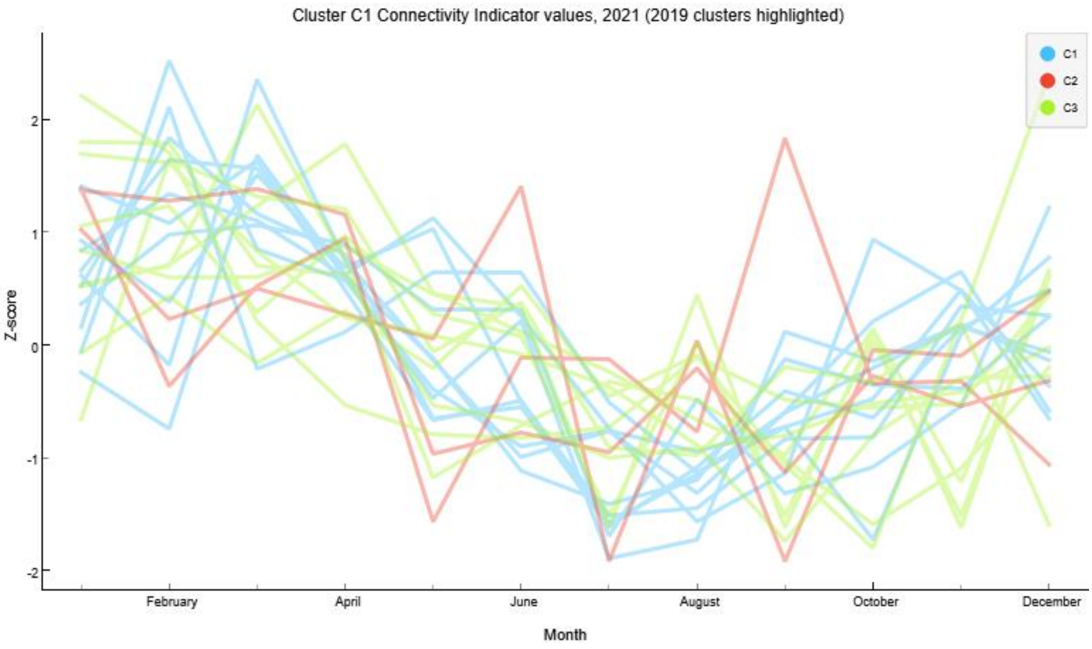


Figure 44 Cluster C1, 2021 (2019 clusters highlighted)

The 3 airports from C2 are Bordeaux-Mérignac (LFBD), Ataturk Intl. (LTBA) and Pulkovo (ULLI). All these airports were in minority in clusters of 2020. LFBD and LTBA were in C2 and ULLI was in C1.

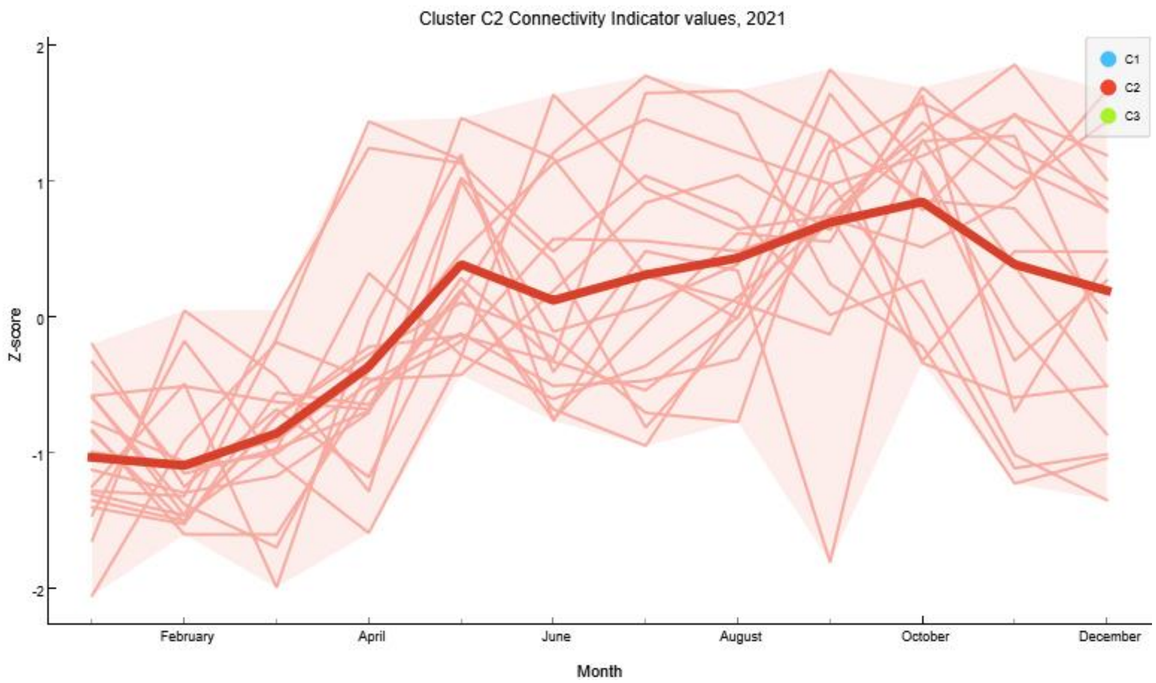


Figure 45 Cluster C2, 2021

Cluster C2 (Figure 30), the typical ‘summer cluster’ of 2019, returns back to its characteristics during 2021 (Figure 45). It contains 18 members, where most of them (10) are from C2 of 2019 as well. It means almost 77% or airports got back into the C2 cluster after the first year of the pandemic. Other members were from C1 (7) and only Manchester (EGCC) was from C3. The 2019 clusters within C2 of 2021 are presented in Figure 46.

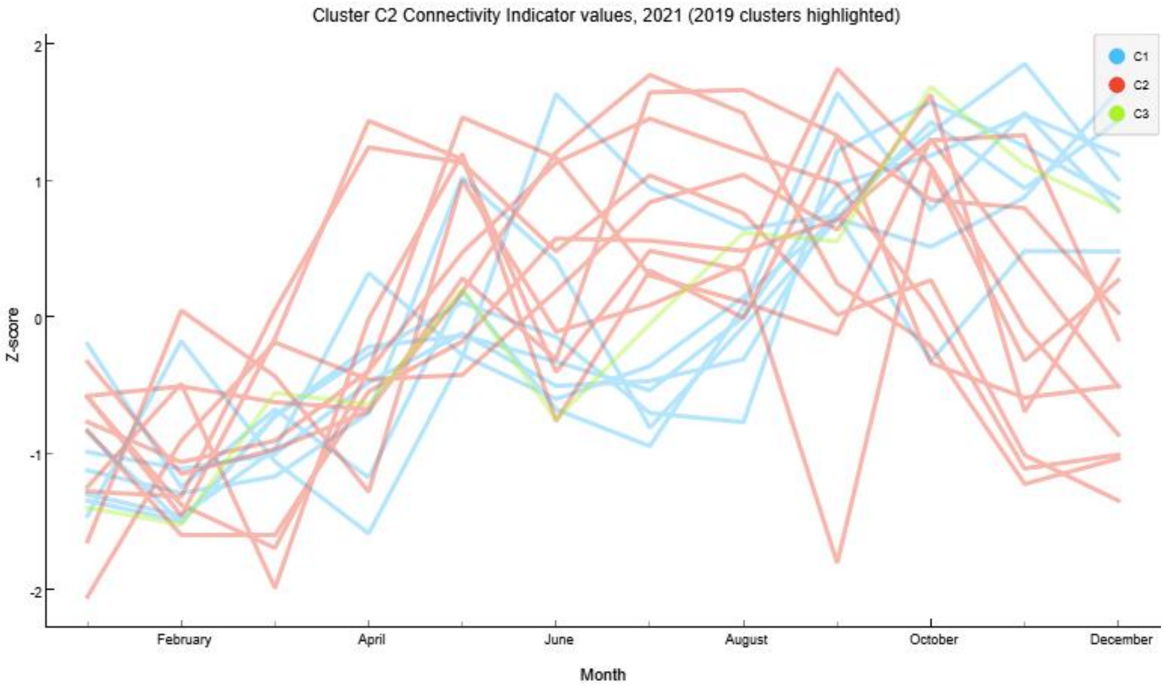


Figure 46 Cluster C2, 2021 (2019 clusters highlighted)

Last cluster, C3 (Figure 47), and its average values (thick lines) reminds the pre-pandemic shape characteristic for C1 in 2019 (Figure 29). The range is represented by the coloured area. Also 20 out of its 21 members are from the C1 cluster. The one airport remaining is Lyon-Bron (LFLY) from C3. Their distribution is shown in Figure 48.

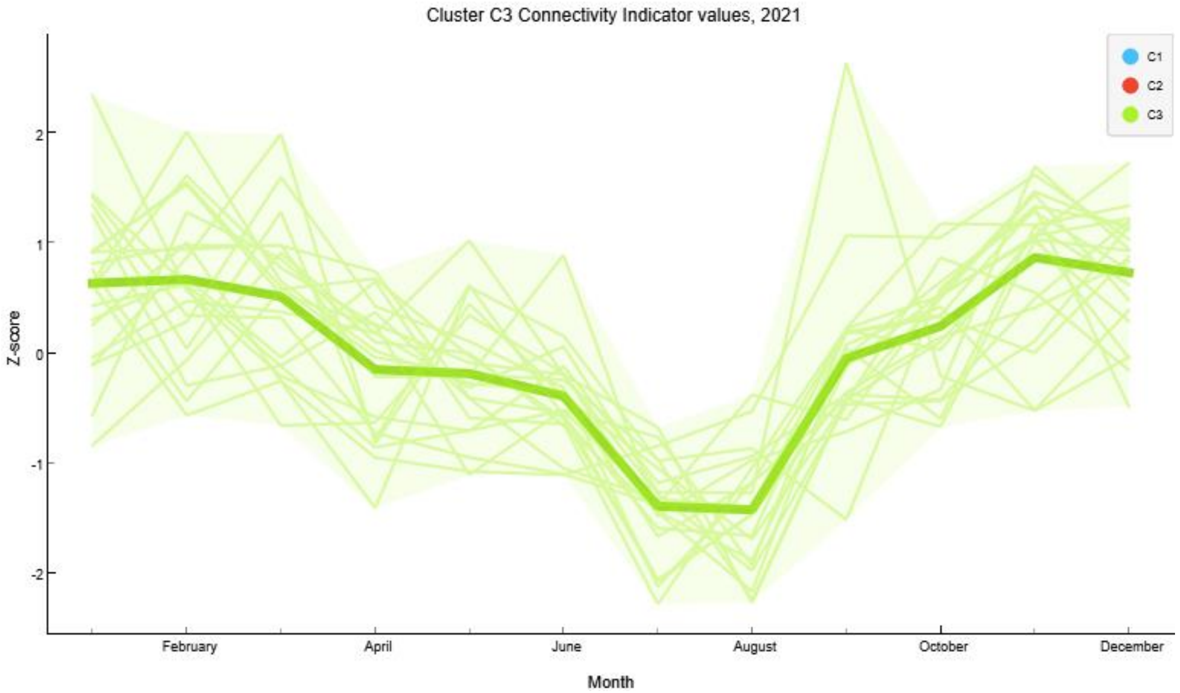


Figure 47 Cluster C3, 2021

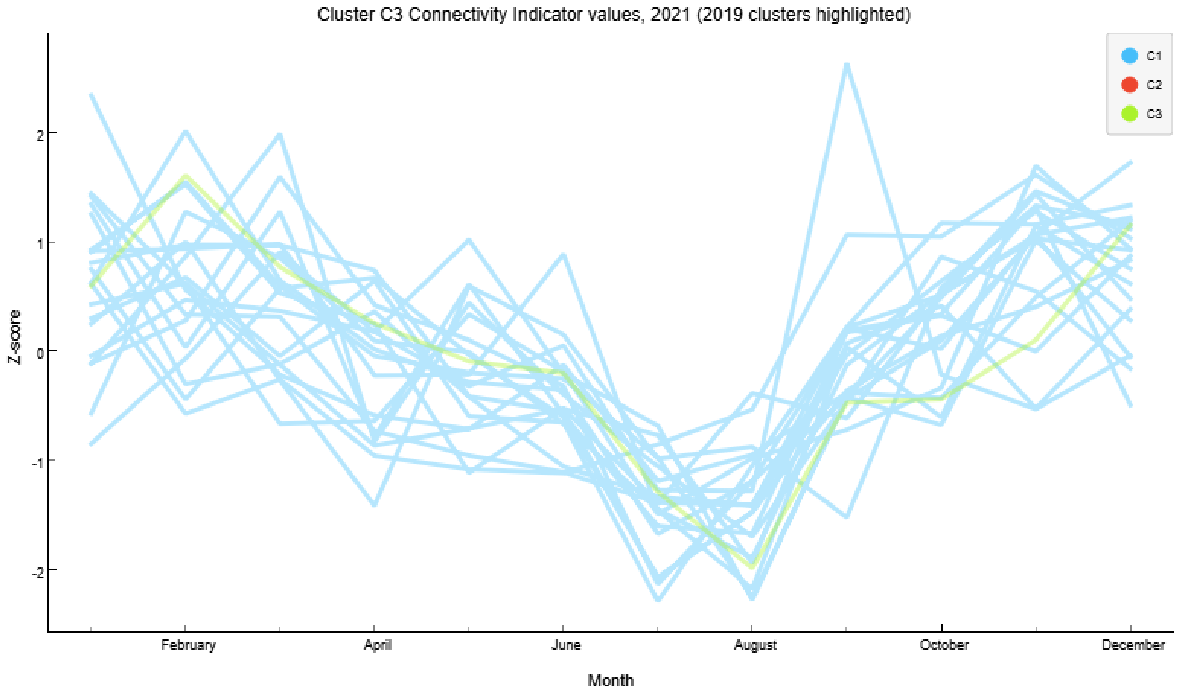


Figure 48 Cluster C3, 2021 (2019 clusters highlighted)

Following graphs (Figure 49, Figure 50, Figure 51) compare clusters before and 'after' the pandemic. All graphs show the clusters managed to almost meet its pre-Covid characteristics. Cluster C1 2019 was compared to C3 2021, C2 2019 to C2 2021 and C3 2019 to C1 2021. The thick lines represent the average values, the coloured area show the range.

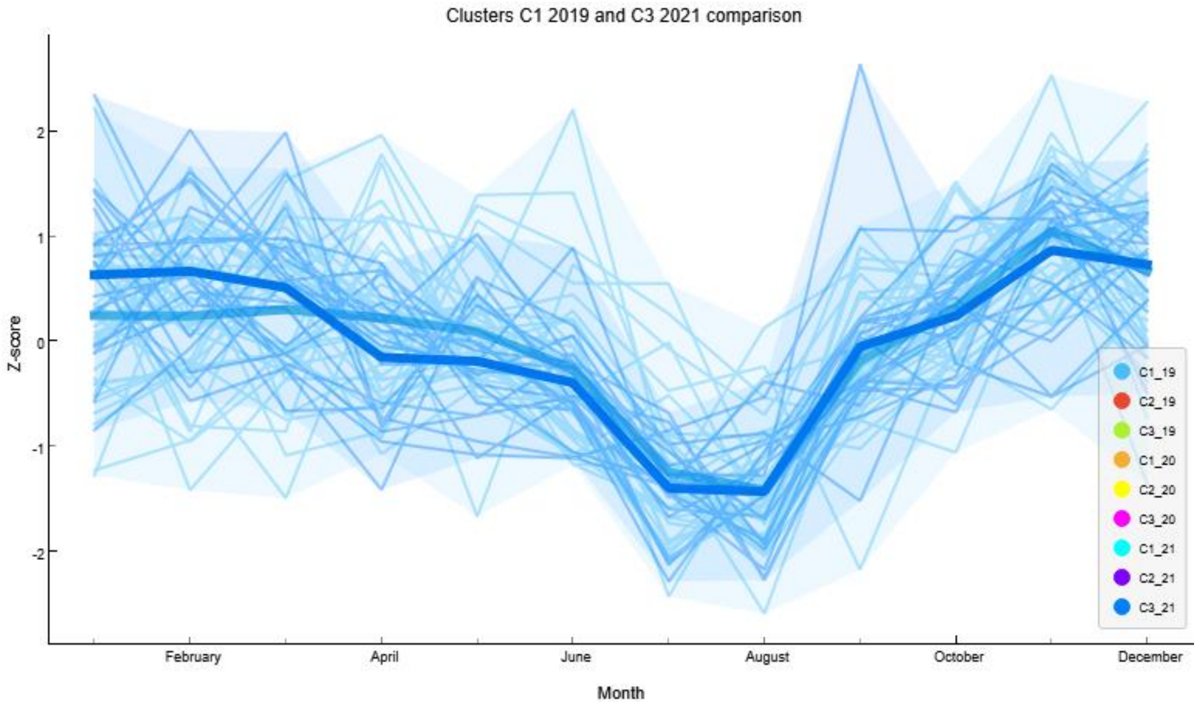


Figure 49 Clusters C1 2019 and C3 2021 comparison

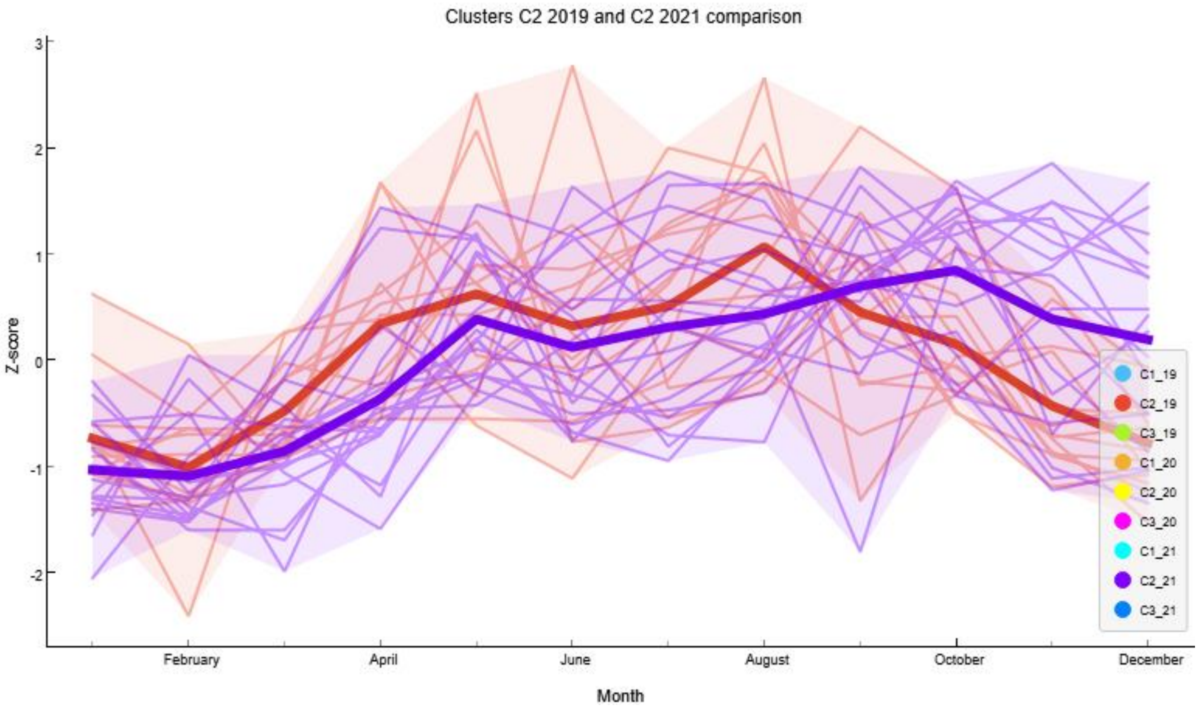


Figure 50 Clusters C2 2019 and C2 2021 comparison

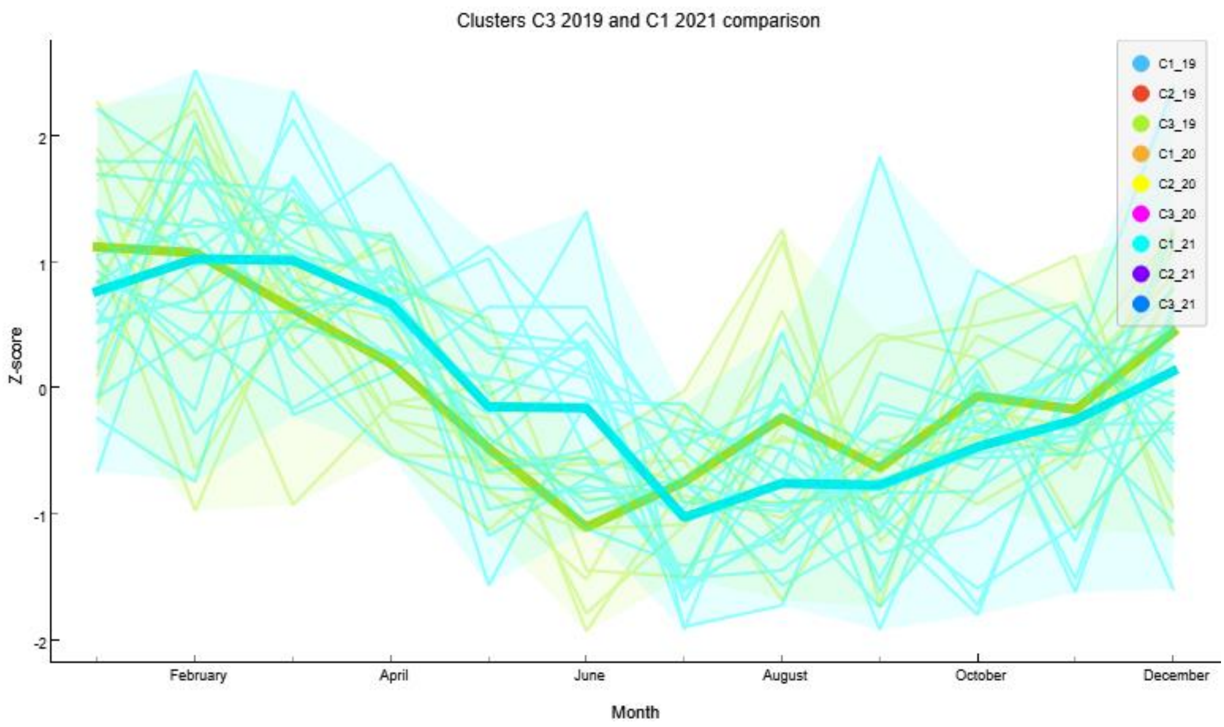


Figure 51 Clusters C3 2019 and C1 2021 comparison

4.2 Covid impact analysis

This section is focused on impact of COVID-19 on selected airport cases. Five airports with best and worst connectivity values during April 2020 were chosen for more detailed study.

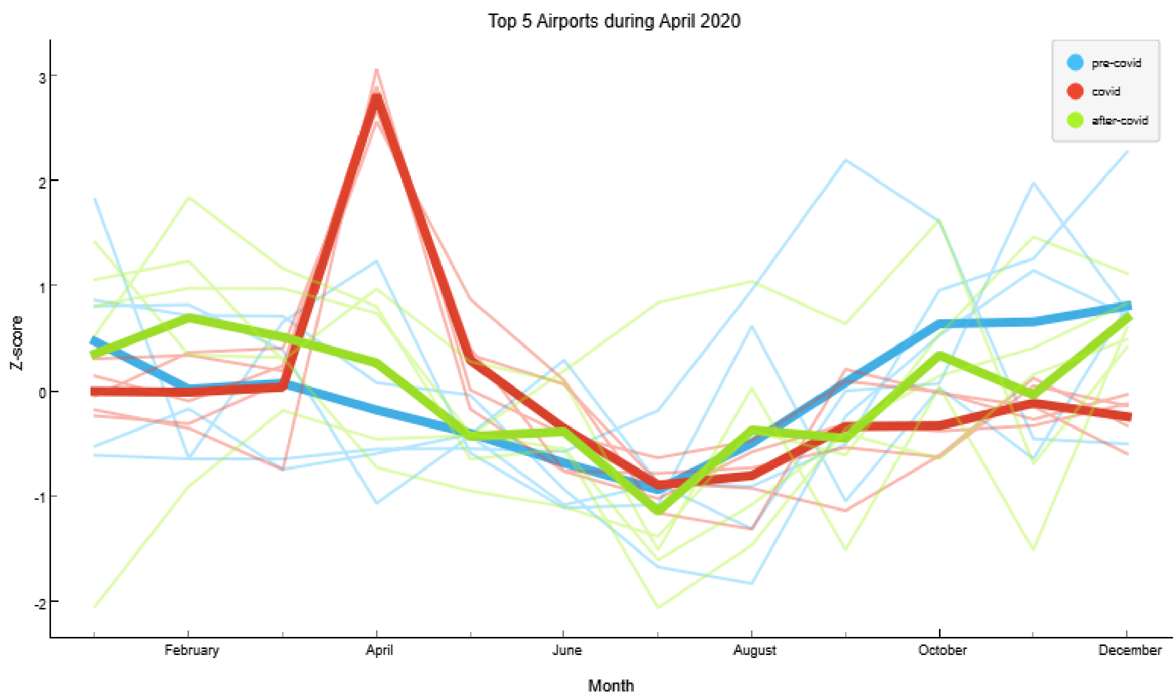


Figure 52 Top 5 airports of April 2020 compared to 2019 and 2021

Figure 52 shows graphs of 5 airports, and their averages for each year (thick lines) with best Connectivity Index z-score values during April 2020 when the biggest decline in traffic was observed. There is a significant peak followed by steep decline to its normal values with slightly less values at the end of the year 2020. Year 2021 shows almost the same progress as 2019. The list of top 5 airports with their number of flights and connectivity index value during April 2019, 2020 and 2021 is in the Table 5.

Table 5 Top 5 Airports, comparison of April 2020 and 2021 to April 2019

ICAO code	April 2019		April 2020				April 2021			
	Flights	**Ci**	**Flights**	**Ci**	**Δ flights 2019**	**Δ Ci 2019**	**Flights**	**Ci**	**Δ flights 2019**	**Δ Ci 2019**
EDDM	939	0,0268	384	0,0440	-59%	64%	800	0,0282	-15%	5%
EDDN	297	0,0084	243	0,0277	-18%	228%	303	0,0107	2%	26%
ENGM	254	0,0072	188	0,0216	-26%	199%	162	0,0056	-36%	-23%
LIMC	241	0,0068	136	0,0151	-44%	123%	216	0,0074	-10%	9%
UUEE	293	0,0081	134	0,0151	-54%	86%	192	0,0066	-34%	-18%

Even though their number of flights decreased during 2020, their Connectivity Indicator value increased even by hundreds of percent in some cases. This indicates that these airports, despite the decrease in the number of flights, connected the largest volume of flights during April 2020, since the connectivity index represents the ratio to the total number of flights in the network.

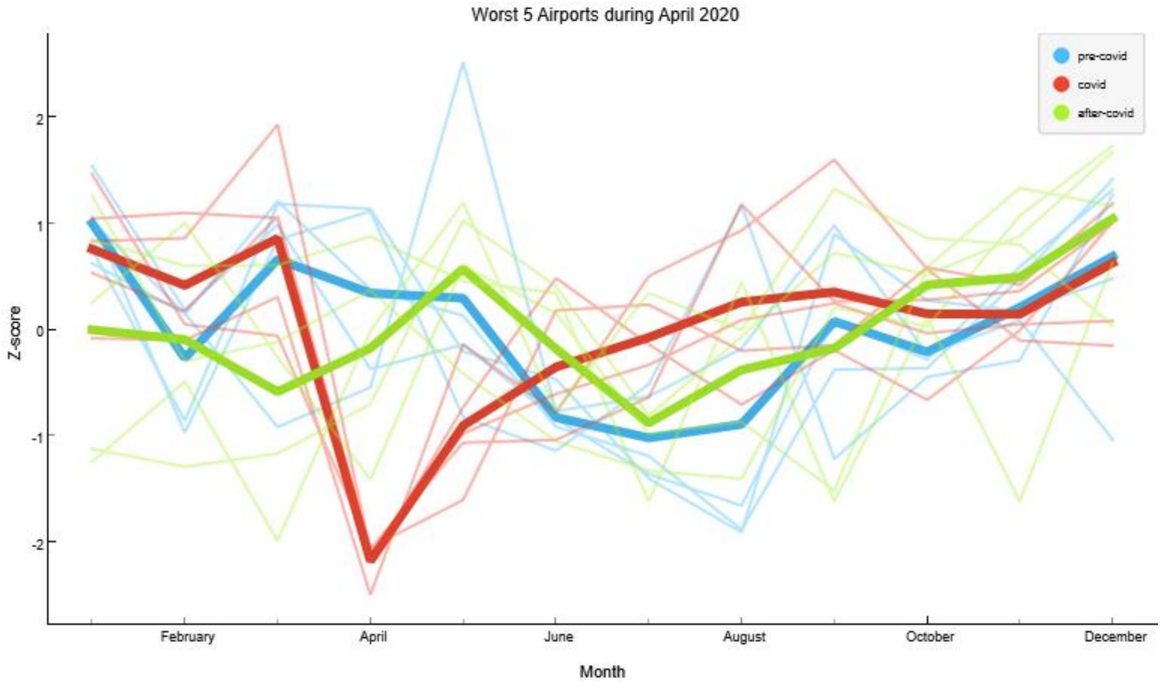


Figure 53 Worst 5 airports during April 2020, compared to 2019 and 2021

The same comparison was done with the worst 5 airports during April 2020 in terms of connectivity z-score. Their graph, including their average values for each year presented by the thick lines, (Figure 53) shows a plummet since March 2020, followed by steady increase and even exceeding its pre-covid values during summer.

Table 6 Top 5 Airports, comparison of April 2020 and 2021 to April 2019

ICAO code	April 2019		April 2020				April 2021			
	Flights	**Ci**	**Flights**	**Ci**	**Δ flights 2019**	**Δ Ci 2019**	**Flights**	**Ci**	**Δ flights 2019**	**Δ Ci 2019**
EBAW	303	0,0087	42	0,0044	-86%	-49%	234	0,0081	-23%	-7%
EGJJ	365	0,0105	14	0,0016	-96%	-84%	165	0,0058	-55%	-45%
EGTK	256	0,0071	36	0,0042	-86%	-41%	221	0,0076	-14%	6%
LSGG	1811	0,0517	254	0,0288	-86%	-44%	1525	0,0533	-16%	3%
UUWW	1323	0,0375	166	0,0182	-87%	-52%	1297	0,0457	-2%	22%

Table 6 shows comparison of number of flights and connectivity values of April 2020 and 2021 to April 2019 values for each airport. Unlike for top 5 airports, these airports reported decrease in both number of flights and Connectivity Indicator values. This indicates they connected smaller ratio of flights during the pandemic’s most critical month.

5 Discussion

The cluster analysis revealed that business aviation airports created 3 significant groups for each analysed year. The most visible difference in 2019 was visible between clusters C1, C3 and C2, where both C1 and C3 have above average values at the beginning and the end of the year and conversely below average values during summer months. In contrast, cluster C2 is dominant just in the summer months and has therefore completely opposite progress.

The same trend was observed in response to the onset of the pandemic. Where 2 clusters (C1 and C3) recorded significant decrease in connectivity, cluster C2 balanced this with its sky rocket increase. The graph (Figure 54) below shows the average Connectivity Indicator value (thick lines) before, during and after COVID-19.

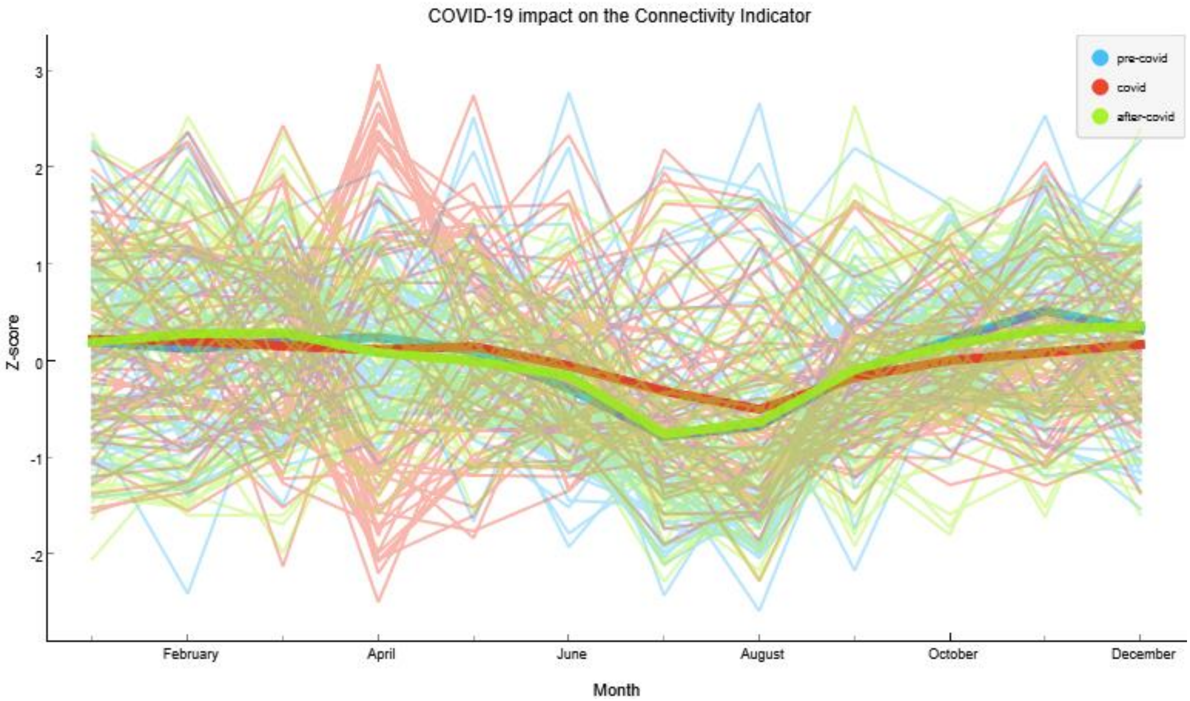


Figure 54 Average Connectivity Indicator values during 2019, 2020 and 2021

Unlike the strong decrease of flights, as presented in Figure 4, Figure 5 and Figure 6 and discussed in Chapter 1.6, the values of Connectivity Indicator do not show any significant impact of the pandemic. There is only a very slight decrease in April and, on the contrary, and increase of connectivity during summer months.

As mentioned in Chapter 4.2 in Top 5 Airports analysis, number of flights does not completely correspond to the value of the Connectivity Indicator, since the Indicator represents ratio of connected flights and number of total network flights in the certain period. In general, it can therefore be said the overall connectivity in the selected core network was not significantly affected by the pandemic, however the effects can be observed in individual clusters or airport cases.

More detailed effects could be visible with smaller data interval or when analysing international flights only, since the restrictions forbidding entry to the certain countries were observed.

Year 2021 showed return of pre-pandemic behaviour for the clusters. Also, the majority of members were the same as in the original clusters. This also corresponds to the characteristics described by EBAA [32] in Chapter 1.6.

As discussed above, the characteristics of connectivity are incomparable with the number of flights. The difference can be observed in Figure 6 for the number of flights and Figure 54 for connectivity. Unlike connectivity, number of flights reported a significant drop in spring 2020 and steady return to its pre-covid numbers. Connectivity shows only a slight drop in spring, followed by an increase in its values during summer. However, the ability to compare these values is not as important since connectivity reflects the demand for flights from destinations.

Future studies should focus on connectivity analysis with smaller data intervals, as well as including the second indicator, Traffic Generation, to refine the results.

6 Conclusion

The aim of the thesis was to map the operation of business aviation in Europe, determine its core network and analyse its behaviour during the COVID-19 pandemic. Business aviation has great economic value for European countries, as well as for aircraft operators or users. It showed its full potential during COVID-19 pandemic as an alternative to airlines, when new clients began using private jets to avoid travelling in big planes full of potentially sick people and to be able to travel when most scheduled airline flights were cancelled. The importance of the sector was also shown through medical and repatriation flights. Thus, business aviation was able not only meet but even exceed its pre-covid number of flights yet in summer 2020 (Figure 2).

Connectivity measures are a really common tool for analysing airline and airport performance. The performance of business aviation is often determined only by the number of flights, but no more complex approach was found for this sector. Therefore, the Flow centrality measure was chosen and adapted for these purposes. This two-dimensional measure is capable of assessing the Traffic Generation and Connectivity Indicator for each airport, which can provide more precise information about the importance in the network.

The data was acquired from European Business Aviation Association in the form of the number of flights between all active pairs during each month from January 2019 and December 2021. Then it was processed through Gephi software to obtain the number of inbound and outbound flights from each airport. Subsequently, the Flow centrality indicators were calculated; however, due to the data limitation of a one-month interval, only Connectivity Indicator was used for further analysis.

Through box plot visualization of each month in 2019, the outliers of all months were determined as the core network, which contained only 61 airports out of almost 1 200 airports in the network. The values were normalized with z-score normalization and prepared for cluster analysis with PCA analysis.

The cluster analysis, described in Chapter 4.1, was done for each year and showed 3 significant clusters for each year but containing different airports. The year 2019 contained two clusters with their peak activity during the winter months and one with its peaks in the summer. Taking into account the year 2019 as a standard year, these clusters were compared to the clusters of the following years, impacted by the pandemic. In 2020, two out of three clusters recorded a significant drop in connectivity values during spring 2020, when the pandemic hit Europe. In contrast, cluster C2 recorded its peak during this time, containing more than 54% of the airports in cluster C1 of 2019. The 2021 had very similar graphs, compared to 2019 (Figure 49, Figure 50, Figure 51), indicating that the connectivity returned to its standard characteristics. Furthermore, the clusters contained the majority of airports from their 2019 equivalents.

Detailed view on top and worst 5 airports during April 2020 showed that the values of Connectivity Indicator may not always correlate to number of flights since it represents the ratio of flights to the number of total network flights. Thus, the Connectivity Indicator represents a proportion of the total traffic volume connecting through the particular airport. In case of the top five airports, during April 2020, the connectivity showed better values, even by hundreds of percent, in contras of almost 70% decline in number of flights.

In general, the effect of the COVID-19 pandemic on the connectivity of the core network was not as significant as on the number of flights. Figure 54 shows that the average connectivity only slightly decreased during spring 2020, compared to 2019, and inversely increased in summer. This indicates that the flights were better connected due to greater demand.

This thesis should demonstrate the value of business aviation in Europe as the well as potential of Flow centrality and its utilization for this sector. Although it had large data intervals, it was able to demonstrate the behaviour of business aviation before and during the COVID-19 pandemics. With more detailed data, both the Traffic Generation and Connectivity Indicator could provide better insight into airport performance, especially for business aviation charter companies.

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Attachment 1 Table of core network airports

ICAO CODE	NAME	CITY (COUTRY)
EBAW	Antwerp Intl. (Deurne)	Antwerp (BE)
EBBR	Brussels	Brussels (BE)
EDDB	Berlin-Schoenefeld	Berlin (DE)
EDDF	Frankfurt am Main	Frankfurt am Main (DE)
EDDH	Hamburg	Hamburg (DE)
EDDK	Cologne Bonn	Cologne (DE)
EDDL	Dusseldorf	Dusseldorf (DE)
EDDM	Munich	Munich (DE)
EDDN	Nuremberg	Nuremberg (DE)
EDDS	Stuttgart	Stuttgart (DE)
EDDW	Bremen	Bremen (DE)
EDMO	Oberpfaffenhofen	Munich (DE)
EDSB	Karlsruhe Baden-Baden	Baden-Baden (DE)
EFHK	Helsinki Vantaa	Helsinki (SI)
EGCC	Manchester	Manchester (GB)
EGGW	London Luton	London (GB)
EGJJ	Jersey	Saint Helier (GB)
EGKB	London Biggin Hill	London (GB)
EGLF	Farnborough	London (GB)
EGSS	London Stansted	London (GB)
EGTK	Oxford (Kidlington)	London (GB)
EHAM	Amsterdam Schiphol	Amsterdam (NL)
EHRD	Rotterdam The Hague	Rotterdam (NL)
EIDW	Dublin	Dublin (IE)
ELLX	Luxembourg-Findel Intl.	Luxembourg (LU)
ENGM	Oslo Gardermoen	Oslo (NO)
EPWA	Warsaw Chopin	Warsaw (PL)
ESSB	Stockholm-Bromma	Stockholm (SE)
LEBL	Barcelona Intl.	Barcelona (ES)
LEMD	Adolfo Suárez Madrid–Barajas	Madrid (ES)
LEMG	Málaga	Málaga (ES)
LEPA	Palma De Mallorca	Mallorca (ES)
LEVC	Valencia	Valencia (ES)
LFBD	Bordeaux-Mérignac	Bordeaux (FR)
LFLY	Lyon-Bron	Lyon (FR)
LFMD	Cannes-Mandelieu	Cannes/Mandelieu (FR)
LFMN	Nice-Côte d'Azur	Nice (FR)
LFPB	Paris-Le Bourget	Paris (FR)
LFSB	Euro Basel-Mulhouse-Freiburg	Basel (FR)
LGAV	Eleftherios Venizelos Intl.	Athens (GR)
LHBP	Budapest Liszt Ferenc Intl.	Budapest (HU)
LIMC	Malpensa Intl.	Milan (IT)
LIPZ	Venice Marco Polo	Venice (IT)

LIRA	Ciampino–G. B. Pastine Intl.	Rome (IT)
LIRQ	Peretola	Firenze (IT)
LKPR	Václav Havel Prague	Prague (CZ)
LOWI	Innsbruck	Innsbruck (AT)
LOWW	Vienna Intl.	Vienna (AT)
LPFR	Faro	Faro (PT)
LSGG	Geneva Cointrin Intl.	Geneva (CH)
LSZB	Bern Belp	Bern (CH)
LSZH	Zurich	Zurich (CH)
LSZR	St Gallen Altenrhein	Altenrhein (CH)
LTAC	Esenboğa Intl.	Ankara (TR)
LTBA	Ataturk Intl.	Istanbul (TR)
LYBE	Belgrade Nikola Tesla	Belgrade (RS)
LZIB	M. R. Štefánik	Bratislava (SR)
UKKK	Kiev Zhuliany Intl.	Kiev (UA)
ULLI	Pulkovo	St. Petersburg (RU)
UUEE	Sheremetyevo Intl.	Moscow (RU)
UUWW	Vnukovo Intl.	Moscow (RU)

Attachment 2 Table of airports and their clusters, 2019, 2020, 2021

ICAO code	Name	Cluster 2019	Cluster 2020	Cluster 2021
EBAW	Antwerp Intl. (Deurne)	C1	C1	C3
EBBR	Brussels	C1	C1	C3
EDDB	Berlin-Schoenefeld	C1	C2	C3
EDDF	Frankfurt am Main	C1	C2	C3
EDDH	Hamburg	C1	C2	C3
EDDK	Cologne Bonn	C1	C2	C1
EDDL	Dusseldorf	C1	C2	C1
EDDM	Munich	C1	C2	C3
EDDN	Nuremberg	C1	C2	C1
EDDS	Stuttgart	C1	C1	C3
EDDW	Bremen	C1	C2	C1
EDMO	Oberpfaffenhofen	C3	C3	C1
EDSB	Karlsruhe Baden-Baden	C1	C2	C1
EFHK	Helsinki Vantaa	C1	C2	C3
EGCC	Manchester	C3	C2	C2
EGGW	London Luton	C1	C1	C2
EGJJ	Jersey	C1	C1	C2
EGKB	London Biggin Hill	C1	C2	C2
EGLF	Farnborough	C1	C1	C2
EGSS	London Stansted	C1	C2	C2
EGTK	Oxford (Kidlington)	C2	C3	C2
EHAM	Amsterdam Schiphol	C1	C2	C2
EHRD	Rotterdam The Hague	C1	C2	C1
EIDW	Dublin	C1	C1	C3
ELLX	Luxembourg-Findel Intl.	C1	C1	C3
ENGM	Oslo Gardermoen	C1	C2	C3
EPWA	Warsaw Chopin	C1	C1	C3
ESSB	Stockholm-Bromma	C1	C2	C3
LEBL	Barcelona Intl.	C1	C1	C1
LEMD	Adolfo Suárez Madrid–Barajas	C1	C1	C3
LEMG	Málaga	C2	C3	C2
LEPA	Palma De Mallorca	C2	C3	C2
LEVC	Valencia	C3	C2	C1

LFBD	Bordeaux-Mérignac	C2	C2	C1
LFLY	Lyon-Bron	C3	C1	C3
LFMD	Cannes-Mandelieu	C2	C3	C2
LFMN	Nice-Côte d'Azur	C2	C3	C2
LFPB	Paris-Le Bourget	C1	C1	C3
LFSB	Euro Basel-Mulhouse-Freiburg	C1	C2	C3
LGAV	Eleftherios Venizelos Intl.	C2	C3	C2
LHBP	Budapest Liszt Ferenc Intl.	C1	C3	C1
LIMC	Malpensa Intl.	C2	C2	C2
LIPZ	Venice Marco Polo	C2	C3	C2
LIRA	Ciampino–G. B. Pastine Intl.	C1	C2	C3
LIRQ	Peretola	C2	C3	C2
LKPR	Václav Havel Prague	C1	C2	C3
LOWI	Innsbruck	C3	C1	C1
LOWW	Vienna Intl.	C1	C2	C1
LPFR	Faro	C2	C3	C2
LSGG	Geneva Cointrin Intl.	C1	C1	C3
LSZB	Bern Belp	C3	C1	C1
LSZH	Zurich	C1	C1	C3
LSZR	St Gallen Altenrhein	C3	C1	C1
LTAC	Esenboğa Intl.	C3	C2	C1
LTBA	Ataturk Intl.	C2	C2	C1
LYBE	Belgrade Nikola Tesla	C3	C3	C1
LZIB	M. R. Štefánik	C1	C1	C2
UKKK	Kiev Zhuliany Intl.	C1	C1	C1
ULLI	Pulkovo	C2	C1	C1
UUEE	Sheremetyevo Intl.	C3	C2	C1
UUWW	Vnukovo Intl.	C3	C1	C1