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Aviation resilience during the COVID-19 pandemic: A case study of the European aviation market

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ABSTRACT

The European aviation industry experienced an unprecedented disruption caused by the COVID-19 pandemic, which may have a profound impact on the industry in the years to come. An investigation of the European aviation market's performance during the pandemic and the recovery pattern is very important. Such an analysis provides an assessment of the aviation industry's actual resilience against large-scale disruptions thus that the sector can be better prepared for future disruptions and challenges. More importantly, it contributes to a better understanding of the best business practices and industry policies in a dynamic aviation environment, and how the aviation industry may sustain growth in the years to come. For these purposes, this study first presents an overview of the European aviation market's performance for the period of 2019–2020. In general, aviation connectivity (airports and airlines) recovered to around 60 % of the 2019 level, but less than 40 % in terms of flight movements at the end of 2020. Second, an ordered Probit model is applied to investigate the driving factors for airport and airline resilience in the European aviation market, respectively. Four key findings are obtained: (i) the number of flights is an important indicator of airport and airline resilience/recovery performance; (ii) higher airline concentration at an airport might have improved the airport's recovery from the COVID-19 crisis. On the airline side, an airline's higher concentration of flights at airports tends to benefit its resilience (iii) the implementation of the airport slot waiver policy, which suspended the "use it or lose it" rules, had positive impacts on airline resilience; (iv) airports with higher shares of full-service airlines (FSAs) services, or more low-cost carriers (LCCs) in service, are better positioned in recovery. There are no systematic differences caused by carrier types. Overall, our study of the European aviation market reveals positive resilience effects of market concentration and firm scale. The findings reveal another dimension in assessing the effects of market concentration and scale, in addition to their implications on competition and market power.

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1. Introduction

The aviation industry plays a crucial role in the economic development of regions and nations, creating employment opportunities and supporting international trade and various sectors, such as logistics, tourism, and high-value manufacturing (Doganis, 2005; Tretheway and Markhvida, 2014; Serrano and Kazda, 2020; da Silveira Pereira and de Mello, 2021; Dube et al., 2021; Fu et al., 2021; Tsui et al., 2021a, 2021b). According to the International Air Transport Association (IATA), the aviation industry transported goods worth up to US$6.5 trillion by air, contributing to 35 % of the value of international trade. Additionally, 54 % of international tourists travel by air globally. The direct and indirect activities of the aviation industry contribute up to 4.1 % of the gross domestic product (GDP) (IATA, 2021a).

The COVID-19 outbreak was first reported in late December 2019 in Wuhan, China, and it had catastrophic impacts on the global aviation industry (Amankwah-Amoah, 2020; Suau-Sanchez et al., 2020; Sun et al., 2020; Liu et al., 2021; Miani et al., 2021; Tisdall et al., 2021). In 2020, worldwide air passenger numbers declined by up to 60 % compared with the figures in 2019, with airlines only offering 50 % of seats. In April 2020, up to 80–90 % of international travel disappeared (International Civil Aviation Organization (ICAO), 2020; Dube et al., 2021; IATA, 2021a).

The effects of the COVID-19 pandemic on the performance and operations of airports and airlines have attracted the attention of scholars (Budd et al., 2021; Liu et al., 2021). Many studies have shed light on how the aviation industry has been affected by the pandemic and provided insights into the recovery of air services (Tanrıverdi et al., 2020; Dube et al., 2021; Miani et al., 2021; Zhang et al., 2021). The reduction in air travel demand led to network downsizing and the loss of flight connectivity, which could diminish the appeal of aviation services (Sun et al., 2021). These issues could lead to negative feedback effects on air travel demand, so it is important to quantify their impact. Dube et al. (2021) summarized the effects of COVID-19 on different aviation markets worldwide, including the Chinese, European, and American markets. Their study suggested that the resilience of airports and airlines in responding to this unexpected crisis tends to be slow, and there is a higher likelihood of COVID-19 resurgence in different geographic regions. Andreana et al. (2021) analyzed the impact of COVID-19 on global air transportation with an ITS SARIMA model and uncovered that LCCs were more resilient than FSAs under such a dramatic event affecting the whole industry.

To promote the recovery and sustainable development of the aviation industry, it is essential to obtain an updated assessment of the aviation sector's performance amid the COVID-19 pandemic. Various metrics had been developed to measure the sector's resilience, including the number of flights (Janic, 2015), air flight routes (Dunn and Wilkinson, 2016), airline scheduling and fleet assignment (Simsek and Akturk, 2022), and the ratios derived in terms of various measures (aircraft movements, air passenger and freight throughout) (Wang et al., 2019; Guo et al., 2021). Additionally, detailed data of the flight frequency level, delays and the recovery time of departures/arrivals were proposed as resilience indicators of airport operations (Belkoura et al., 2016; Zhou and Chen, 2020). Moreover, load factor, passenger yield, and aeronautical and non-aeronautical revenues are considered as important financial indicators for airlines and airports in the wake of the COVID-19 pandemic (Bae et al., 2021; Choi, 2021). Resilience can also be measured with network topology indices such as airport degrees, betweenness centrality, H-index and average inverse path length (Wang et al., 2019; Wong et al., 2020; Zhou et al., 2021). These airport performance studies shed light on the analysis of airport/airline performance in response to unexpected disturbances, including but not limited to bad weather, natural disasters, epidemics and pandemics. In addition to the above metrics, robustness is another dimension to understanding resilience (Bruneau et al., 2003; Zhou and Chen, 2020). Kahan et al. (2009) also included robustness to illustrate resilience from a framework perspective. Lordan et al. (2014) studied the robustness and resilience of the air transport network to identify critical airports by using topology characteristics to measure a network's robustness and evaluate the network's resilience under international attacks. Sun and Wandelt (2021) carried out a systematic review over 15 years to assess the robustness of the air transportation networks for a better understanding of the resilience of the aviation industry. The authors raised the question of what resilience would look like for the recovery of air transportation from COVID-19. However, in the meantime, robustness is also easily confused with resilience, which needs a clear definition. Janić (2022) clarified that robustness is the capability to retain performance regularly during disruptive events, while resilience is more about the ability to withstand and recover the performance from the impact of disruptive events (Chen and Miller-Hooks, 2012). Illustrations between the two concepts are visualized in prior studies (Zhou and Chen, 2020; Guo et al., 2021), which help better understand air transport resilience. In this study, we define the resilience for airports and airlines using the recovery performance of airport connectivity and airline connectivity, respectively. The airport connectivity is measured with the number of connected cities and the airline connectivity is measured with the number of origin–destination (O-D) city pairs. The recovery performance is defined as the ratio of airport/airline connectivity measured in 2020 to that in 2019.

In response to the COVID-19 pandemic, countries around the world implemented various travel-related restrictions such as health declarations, quarantine measures, lockdowns, and border closures, among others. Although some of these restrictions have been lifted, the increased use of online meeting tools during the pandemic may continue to have mixed impacts on air travel demand (Chen et al., 2022a; 2022b). As a result, the aviation industry may continue to experience disruptions, and full recovery to pre-pandemic levels may take a considerable amount of time, even under optimistic scenarios (e.g., IATA, 2020; ICAO, 2020; Molenaar et al., 2020; Serrano and Kazda, 2020; Gudmundsson et al., 2021; Linden, 2021; Ng et al., 2022).

Airport and airline management need to prepare for future challenges posed by fluctuating air travel demand and other operational uncertainties in the long term (Serrano and Kazda, 2020). However, the resilience of different categories and sizes of airports and airlines may vary in their ability to recover from the impact of COVID-19 while facing reduced air travel demand (Suau-Sanchez et al., 2020). Therefore, it is essential to evaluate and provide an overview of the recovery capacity of airports and airlines in response to the unexpected influence of COVID-19 and identify the key factors that drive aviation resilience. In this study, we focus on aviation resilience in terms of recovery/restorative capacity, although the definition of resilience can vary and may be measured using a wide range of indicators related to network, operation statistics and financial performance.[1]

After COVID-19 was first reported in Wuhan China, European countries were soon affected by the pandemic, with an outbreak in February and March 2020 (Mavragani, 2020). As reported in many studies and our analysis, almost 90 % of the aviation market in Europe disappeared in the second quarter of 2020 (Budd et al., 2020; Janić, 2022). The European aviation market plays an important role in the global aviation industry because of its large market size. As a well-developed and liberalized market, it hosted four of the world's ten top most connected airports in 2019 before the pandemic (Official Airline Guide (OAG), 2020). Understanding this important market will provide useful insights into the development of the global aviation market notably the impacts of the COVID-19 pandemic, and how the aviation landscape will change along with the market's recovery (Suau-Sanchez et al., 2020). Therefore this market is selected for our study to analyze the resilience of air transportation.

The current study provides valuable contributions to the literature on aviation resilience by investigating two key areas. Firstly, the study reports on the resilience and recovery status of the European aviation market, which is a mature and free market that plays a critical role in the global aviation industry's recovery. Understanding the aviation resilience in this market is essential for the future of the industry, given the important position of Europe in global air travel. Secondly, the study explores the key determinants that influence airport and airline recovery from exogenous shocks, thus providing useful insights for governments and aviation stakeholders in developing appropriate strategies and policies to facilitate aviation recovery and growth in the post-COVID-19 era, which will ultimately boost economic development.

The remainder of the paper is organized as follows: Section 2 presents the aviation development and the performance of the European aviation market under the shocks of the COVID-19 pandemic. Section 3 presents data and methodologies for analyzing airport and airline resilience/recovery. Section 4 reports the estimated results of the resilience of airports and airlines. Section 5 discusses the results. Finally, Section 6 summarizes and concludes the paper.

2. The influence of COVID-19 on aviation development in Europe

The impact of COVID-19 on the European aviation market has been significant, with unprecedented disruptions to its development (Dube et al., 2021; IATA, 2021b). The industry experienced a sharp decline in air passenger traffic, resulting in a loss of up to 70 % of passenger traffic and 62 % of revenues in 2020 compared with 2019 (IATA, 2021c). This is a major setback for the European aviation market, which had shown steady growth of 38 % from 2014 to 2019 (IATA, 2021a). The onset and spread of the COVID-19 pandemic had undone much of the development achieved in the pre-COVID era, adversely affecting air connectivity in terms of O-D city pairs and total direct flights.

Fig. 1 shows the weekly O–D city pairs and total direct flights in the European aviation market for the years 2019 and 2020. During the first two months of 2020, the number of connected O-D cities and total direct flights were nearly identical to the previous year. However, beginning in March 2020, a decline in both O-D city pairs and total direct flights was observed due to the rapid spread of COVID-19 throughout Europe. Many European countries implemented travel restrictions, including lockdowns and border closures, to prevent the spread of the virus, which significantly decreased air travel demand in the region. As a result, air travel demand reached its lowest level in April 2020, with nearly 80 % fewer O-D city pairs (only 3042 O-D European cities had flight services during the third week of April 2020, compared with the weekly average of over 11,700 in 2019) and a 90 % decrease in total direct flights (only 16,697 direct flights offered during the third week of April 2020, compared with the weekly average of 151,133 in 2019).

With the effectiveness of travel control and social distance restrictions, the number of COVID-19 confirmed cases showed a downward trend or kept stable at an acceptable level across European countries since early 2020. Thus, many European countries began to relax their travel restriction policies from June 2020. In particular, leisure travel within Europe with the purposes of visiting friends and family stimulated air travel demand in the summer months (IATA, 2021a). The number of O–D city pairs and total direct flights showed a noticeable recovery after June 2020 back to around 60 % of the 2019 level. However, the recovery of total direct flights was not that strong, and only rebounded 10–30 % compared with the same periods in 2019. Such recovery differences in O–D city pairs and total direct flights indicated that although air connectivity resumed to some extent in many European key cities or countries, air travel demand had yet far from fully recovered (Budd et al., 2021). Moreover, travel restrictions, especially border closures and quarantine/isolation upon arrivals seriously impacted international air travel and tourism flows to and from Europe, which significantly affected the operations of European airports and airlines (Pillai et al., 2020).

3. Data and methodology

The methodology used to investigate the resilience of the European aviation market is presented in this section. Airports' and airlines' resilience often involves some similar determinants. Therefore, this study investigates the effects of key driving factors upon their respective resilience in the European market together. The airport and airline data, and the COVID-19 pandemic-related information used for analysis were collected from the OAG database and the Our World In Data website, respectively. The weekly airport and airline data were collected from January 2019 to December 2020, including information on direct flights within the European continent: O–D airports, operational airlines, total direct flights and total scheduled seats. A total of 1,635,881 weekly records are

[1] For example, Wong et al. (2020) argued that resilience can be defined by (a) the absorptive capacity, (b) the adaptive capacity, and (c) the restorative capacity (i.e., the ability to recover from a disruptive event to normal conditions). This study focuses on the restorative aspect of resilience as measured by aviation operations and performance (airports and airlines).

Fig. 1. Weekly O − D city pairs and direct flights in the European aviation market (2019 vs. 2020).

included in this study, covering 705 airports and 22,236 routes operated by 248 airlines during the study period. The COVID-19 pandemic-related data were collected at the country level, including the number of COVID-19 confirmed cases and international travel controls.

The research framework of this study is presented in Fig. 2, which uses airports as an example for illustration. For estimation, we first ranked and labeled the sampled airports' resilience based on the recovery performance of airport connectivity, which is defined as the number of connected cities. Recovery performance is calculated as the ratio of this connectivity metric in each month of 2020 to that of the end of 2019 (the weekly average of the last quarter), denoted as y_{it}. For the purpose of removing possible holiday effects, the weekly average is used for showing airport connectivity in the months of 2020, while the weekly average of the last 2019 quarter is used as a reference of the "pre-COVID" level. Airports were ranked into three groups: (i) the most resilient airports (top 1/3 of the airports, labeled as Group (3); (ii) the moderately resilient airports (between 1/3 and 2/3, labeled as Group (2); and (iii) the least resilient airports (bottom 1/3, labeled as Group (1). It should be noted that airports which operated less than seven flights per week before the COVID-19 pandemic (i.e., the last quarter of 2019) were excluded from this study, thus leaving 568 European airports for analysis. When constructing the airport data, other variables of interest were also collected for analysis and arranged in the panel data format (y_{it}, x_{it}). For estimation, the ordered Probit model was applied to investigate key driving factors which affect airport resilience/ recovery performance in the European aviation market.

Previous studies suggested that airport performance is closely linked with airline services at airports (Oum and Fu, 2009; Yang et al., 2015; Tavalaei and Santalo, 2019) and the analysis of airport resilience will also contribute to the understanding of airline resilience, and *vice versa*. Therefore, we applied the same research framework of airport resilience to analyze airline resilience for the European aviation market. An airline's resilience is measured by the ratio of O–D city pairs served by the airline in each month in 2020 to that of the end of 2019 (the weekly average flights within the last quarter). Airlines that operated with less than seven flights per week will be filtered out, thus leaving 152 airlines remained for analysis. Similar to the grouping of airports, airlines were clustered into three groups based on their resilient performance: (i) the most resilient airlines (labeled as 3); (ii) the moderately resilient airlines (labeled as 2); and (iii) the least resilient airlines (labeled as 1).

3.1. *Variables of interest*

In terms of variables of interest in this study, various flight operations-related data were collected and a number of variables had been processed, such as the number of direct flights ($Num\_flights_{it}$), the proportion of full-service airline (FSA) flights ($FSA\_flight\_\%_{it}$), and the number of low-cost carrier (LCC) flights (Num_LCC_{it}). To capture the potential effects of national aviation environments/ operations on aviation resilience, some variables were also developed at the country level, for example, the number of direct flights of a country ($Num\_flights\_country_{xt}$). In addition, airport and airline competition variables are included in this study, including the Herfindahl-Hirschman Index (HHI) of an airport ($HHI\_destinations_{it}$) and the variables representing airline dominance at an airport (i.e., the maximum and share of airline flight at an airport ($Max\_share\_flights_{it}$ and $Highest\_share\_flights_{it}$). Moreover, the previous month's COVID-19 confirmed cases of a country ($COVID\_case_{xt}$) and international travel controls imposed by the European governments were included to control the COVID-19 pandemic-related effects (i.e., $Thermalbodyscreening_{xt}$, $Quarantine_{xt}$, and $Bordercontrol_{xt}$) on airport and airline demand and operations. The variable of HSR_t was also included to capture the effect of high-speed rail (HSR). The dummy

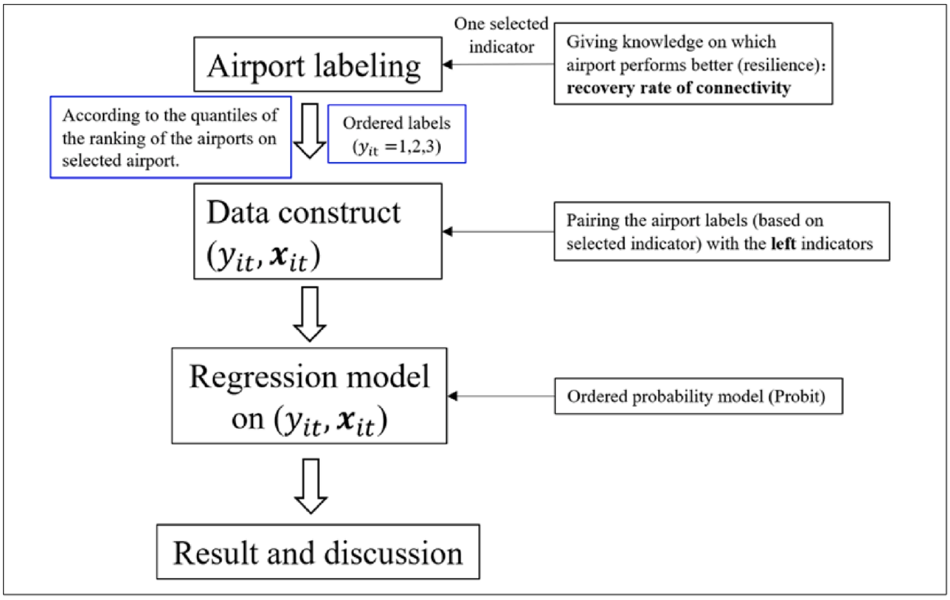

Fig. 2. The research framework of airport resilience.

variable *Slot_waiver* stands for the implementation of the suspension of the "use it or lose it" rule for airport slots, effective from 30 March 2020. Table 1 presents the definition of variables of interest and descriptive statistics for analyzing airport and airline resilience.

3.2. Formulation of resilience metric and potential indicators

With the airport and airline resilience variables identified and constructed in Section 3.1, the sampled airports or airlines in the European aviation market were labeled into different clustered groups, respectively, which are y_{it} and x_{it}. (i.e., 3 = the most resilient performance; 2 = the moderately resilient performance; and 1 = the least resilient performance). An ordered Probit model was subsequently applied to examine and identify key factors that affect airport and airline resilience, respectively. To examine the impact of explanatory variables on airport or airline resilience, the econometric specification was formulated as follows:

$$y_{it}^{*} = \beta_0 + \beta^T x + \varepsilon = \beta_0 + \sum_{j=1}^{J} \beta_j x_{it}^{j} + \varepsilon_{it} \tag{1}$$

where x_{it}^{j} is the j th potential indicator of the resilience for airport or airline i, β_j is the coefficient of x^j to be estimated, and ε_{it} is the error term. According to the clustering processes, three groups of airports or airlines are determined as follows:

$$\begin{aligned} y_{it} &= 1, \quad y_{it}^{*} \leq \mu_0 \\ y_{it} &= 2, \quad \mu_0 < y_{it}^{*} \leq \mu_1 \\ y_{it} &= 3, \quad \mu_1 < y_{it}^{*} \end{aligned} \tag{2}$$

Table 1
Definition and descriptive statistics of the variables for airport and airline resilience.

Variables	Definition	Obs	Mean	Std	Min	Max
Airport resilience variables						
Airport_group	= 3 for the most resilient airports	2268				
	= 2 for the moderately resilient airports	2280				
	= 1 for the least resilient airports	2268				
$Num\_flights_{it}$	The number of direct flights departed from airport i at time t	6816	119.33	276.25	0	3,536
$HHI\_destinations_{it}$	The HHI of airport i at time t, which is measured by the number of connected cities	6816	5040.92	3,182.33	0	10,000
$Num\_flights\_country_{xt}$	The number of direct flights of a country x at time t where the airport is located	6816	4005.13	3,578.70	4	15,972
$FSA\_flight\_\%_{it}$	The proportion of direct flights operated by FSAs among the total direct flights departing from airport i at time t	6816	0.66	0.36	0	1
Num_LCC_{it}	The number of LCCs offering direct flight services at airport i at time t	6816	1.57	2.27	0	15
$COVID\_case_{xt}$	COVID-19 confirmed cases of country x at time t where the airport is located	6816	28,169	54,770.12	0	377,405
HSR_t	= 1 if an airport located city at time t is connected by high-speed rail, 0 otherwise	6816	0.19	0.40	0	1
$Thermalbodyscreening_{xt}$	= 1 if an airport located at a country which implemented thermal body screening, 0 otherwise	6744	0.08	0.28	0	1
$Quarantine_{xt}$	= 1 if an airport located at a country which required quarantine from high-risk regions, 0 otherwise	6744	0.13	0.35	0	1
$Bordercontrol_{xt}$	= 1 if an airport located at a country which closed the border or banned travelers from high-risk regions, 0 otherwise	6744	0.64	0.48	0	1
$Slot\_waiver_{it}$	= 1 if the airport slot waiver policy implemented from April to December 2020, while 0 from January to March 2020	6816	0.75	0.43	0	1
Airline resilience variables						
Airline_group	= 3 for the most resilient airlines	602				
	= 2 for the moderately resilient airlines	608				
	= 1 for the least resilient airlines	614				
$Highest\_share\_flights_{it}$	The highest share of direct flights operated by airline i out of the total direct flights departed from an airport at time t	1824	0.53	0.23	0	1
$Max\_share\_flights_{it}$	The maximum share (in percentage) of airport i contributed to the airline's network at time t	1824	0.31	0.18	0	1
$COVID\_case_{xt}$	COVID-19 confirmed cases of country x at time t where the airline's primary operational base located	1824	27,368.46	52,136.63	0	377,405
FSA	= 1 if the airline is FSA, 0 otherwise	1824	0.84	0.37	0	1
$Thermalbodyscreening_{xt}$	=1 if the airline's headquarter is located at a country which implemented thermal body screening, 0 otherwise	1800	0.08	0.27	0	1
$Quarantine_{xt}$	= 1 if the airline's headquarter is located at a country which required quarantine from high-risk regions, 0 otherwise	1800	0.11	0.32	0	1
$Bordercontrol_{xt}$	= 1 if the airport is located at a country which closed the border or banned travelers from high-risk regions, 0 otherwise	1800	0.67	0.47	0	1
$Slot\_waiver_{xt}$	= 1 if the airport slot waiver policy implemented from April to December 2020, while 0 from January to March 2020	1824	0.75	0.43	0	1

Note: Travel control policies for some countries (e.g., Montenegro and Armenia) are not available.

where $\mu_k(k = 0, 1)$ is the threshold parameter estimated from the airport and airline resilience data. Then, the probability of y^*_{it} under the normal distribution assumption is:

$$\begin{cases} P(y_{it} = 1) = \varnothing\left(\mu_0 - \sum_{j=1}^{J}\beta_j x^j_{it}\right) \\ P(y_{it} = 2) = \varnothing\left(\mu_1 - \sum_{j=1}^{J}\beta_j x^j_{it}\right) - \varnothing\left(\mu_0 - \sum_{j=1}^{J}\beta_j x^j_{it}\right) \\ P(y_{it} = 3) = 1 - \varnothing\left(\mu_1 - \sum_{j=1}^{J}\beta_j x^j_{it}\right) \end{cases} \tag{3}$$

where,

$$\varnothing(u) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{u} e^{-\frac{1}{2}w^2}dw \tag{4}$$

Prior to the estimation, the correlations among all the explanatory variables were tested, and no problem of high correlation was raised, with the highest values of −0.45 and −0.23 obtained for airport and airline data, respectively. Moreover, all the variables of interest (dependent and explanatory variables) need to be stationary and to be free from the problem of spurious correlation (Wooldridge, 2015). Hence, the panel unit root tests (augmented Dickey–Fuller, ADF; Phillips–Perron, PP) were performed to check whether all the variables of interest were stationary. The variables of $Num\_flights_{it}$ and $FSA\_flight\_\%_{it}$ in the airport resilience model, and $COVID\_case_{xt}$ in both airport and airline resilience models were found to be non-stationary. Therefore, first-differencing was used to make them stationary.

The empirical results of the ordered probit models for airport and airline resilience are presented in Section 4. Note that the marginal effects were also computed, which measure the change in the dependent variable (airline and airline resilience) as a function of the change in a set of explanatory variables, thus providing more information than the estimated coefficients themselves (e.g., (Liao, 1994; Greene, 2003; De Groot et al., 2009; Wooldridge, 2015).

4. Empirical results

Tables 2 and 3 report the estimation results of the ordered Probit models and the marginal effects for the airport and airline resilience groups, respectively. It should be noted that the coefficient estimates (columns a and b) in the ordered Probit models cannot reveal the magnitude of changes in the probability of observing different resilience of airports or airlines (i.e., the most resilient, the

Table 2
Estimation results of airport resilience.

Dependent variable = *airport group*	**(a)**	**Marginal effects**		
Explanatory variables	**Coefficients**	**(a1) Most resilient**	**(a2) Moderate resilient**	**(a3) Least resilient**
$Num\_flights_{it}$	6.11e−05 (1.20e−04)	1.54e−05 (2.96e−05)	2.42e−07 (6.74e−06)	−1.57e−05 (3.01e−05)
$HHI\_destinations_{it}$	1.56e−04*** (1.44e−05)	3.95e−05*** (3.6e−06)	6.18e−07 (1.23e−07)	−4.01e−05*** (3.90e−06)
$Num\_flights\_country_{xt}$	8.81e−05*** (1.39e−05)	2.23e−05*** (3.69e−06)	3.49e−07 (6.83e−07)	−2.26e−05*** (3.66e−06)
$FSA\_flight\_\%_{it}$	0.149* (0.083)	0.038* (0.021)	0.001 (0.001)	−0.038* (0.021)
Num_LCC_{it}	0.254*** (0.027)	0.064*** (0.007)	0.001 (0.002)	−0.065*** (0.007)
$COVID\_case_{xt-1}$	−1.79e−07 (6.38e−07)	−1.07e−08 (1.66e−07)	−1.68e−10 (6.97e−09)	1.09e−08 (1.69e−07)
HSR_t	−0.972*** (0.106)	−0.246*** (0.027)	−0.004 (0.008)	0.250*** (0.026)
$Thermalbodyscreening_{xt}$	0.347 (0.156)	0.054 (0.041)	−0.003 (0.003)	−0.050 (0.039)
$Quarantine_{xt}$	−0.359*** (0.121)	−0.108*** (0.033)	−0.020** (0.007)	0.128*** (0.031)
$Bordercontrol_{xt}$	0.104 (0.130)	0.019 (0.033)	0.0003 (0.001)	−0.019 (0.033)
$Slot\_waiver_{it}$	0.366*** (0.081)	0.093*** (0.021)	0.001 (0.003)	−0.94*** (0.021)
Observations	5620			
Log-likelihood	−5019.89			

Notes: *, ** and *** indicate that the explanatory variable is significant at the 10 %, 5 % and 1 % significance levels, respectively. Robust standard errors are presented in parentheses.

Table 3
Estimation results of airline resilience.

Dependent variable = *airline group* Explanatory variables	(b) Coefficients	Marginal effects		
		(b1) Most resilient	(b2) Moderate resilient	(b3) Least resilient
$Num\_flights_{it}$	0.001***	1.21e−04***	5.72e−06	−0.0001***
	(9.45e−05)	(2.25e−05)	(8.01e−06)	(2.21e−05)
$Max\_share\_flights_{it}$	3.620***	0.802***	0.038	−0.840***
	(0.570)	(0.123)	(0.054)	(0.133)
$Highest\_share\_flights_{it}$	0.812**	0.180**	0.008	−0.188**
	(0.382)	(0.083)	(0.013)	(0.089)
$COVID\_case_{xt-1}$	−8.43e−07	−1.87e−07	−8.82e−09	1.96e−07
	(1.42e−06)	(3.13e−07)	(3.46e−08)	(3.31e−07)
FSA	−0.146	−0.032	−0.002	0.034
	(0.273)	(0.060)	(0.004)	(0.063)
$Thermalbodyscreening_{xt}$	−0.228	−0.053	0.003	0.050
	(0.357)	(0.084)	(0.009)	(0.077)
$Quarantine_{xt}$	−0.663**	−0.144*	−0.010	0.154**
	(0.273)	(0.064)	(0.016)	(0.058)
$Bordercontrol_{xt}$	−0.255	−0.059	0.003	0.056
	(0.309)	(0.073)	(0.009)	(0.065)
$Slot\_waiver_{xt}$	0.309**	0.068**	0.003	−0.72**
	(0.135)	(0.030)	(0.005)	(0.031)
Observations	1500			
Log-likelihood	−1227.15			

Notes: *, ** and *** indicate that the explanatory variable is significant at the 10 %, 5 % and 1 % significance levels, respectively. Robust standard errors are presented in parentheses.

moderately resilient, and the least resilient) on changes in the explanatory variables. Therefore the corresponding marginal effects (columns a1 − a3 and b1 − b3) were calculated (Wooldridge, 2015).

When considering airport resilience in Table 2, the insignificant and positive coefficient estimate for $Num\_flights_{it}$ is reported (see column a), which partially suggests that European airports served by more direct flights are more likely to be resilient airports. The statistically significant and positive coefficient estimate is also reported for $Num\_flights\_country_{xt}$, which indicates that the probability of being a resilient airport increases when more direct flights are operated from a country where the airport is located (column a). Such results hold true for the marginal effects correspondingly (see columns a1 − a3). Moreover, the competition between airlines at an airport, as measured by $HHI\_destinations_{it}$, is also a key factor to explain variations of airport resilience. The positive and significant coefficient estimate of $HHI\_destinations_{it}$ suggests that *ceteris paribus,* an airport served by fewer airlines experienced better recovery from the COVID-19 pandemic (see column a), which is also confirmed by both the significance and sign of the coefficient estimates and the marginal effects of $HHI\_destinations_{it}$ (see columns a1 − a3).

Additionally, the statistically significant variables of both $FSA\_flight\_\%_{it}$ and Num_LCC_{it} suggest a lower probability of being a least resilient airport and an increased likelihood of being a most resilient airport (see columns a). In other words, flight services offered by both FSAs and LCCs contributed to an airport's resilience. The statistically significant and negative coefficient estimate for HSR_t suggests that HSR-connected airports tended to be less resilient. This finding supports evidence from Manello et al. (2022), which suggested that the presence of HSR connections seems to affect significantly the survival probability of an air route (see column a), due to the significant substitution and competition effects between HSR and flight services, especially in short- to medium-distance routes (Fu et al., 2014; Jiang and Li, 2016; Su et al., 2020). Furthermore, international travel controls are widely accepted as one of the most effective measures in controlling the spread of the COVID-19 virus (Chinazzi et al., 2020; Zhang et al., 2020). It is anticipated that travel control policies (i.e., thermal body screening, quarantine, and border control) implemented by the European governments affected their airports' resilience. Compared with the case without COVID-19 related measures taken (i.e., the base model without such travel control variables), and the probability of being a most resilient airport is reduced by a higher value of $Quarantine_{xt}$ (see column a). Moreover, the significant variable, $Slot\_waiver_{it}$, shows that the airport slot waiver policy implemented by the member states of the European Commission contributes to the recovery of airports' performance (European Commission, 2020).

In terms of airline resilience, as reported in Table 3, the statistically significant and positive coefficient estimate is reported for $Num\_flights_{it}$ (see column b). Similar to the scenario of airport resilience, airlines operating more flights are more likely to become more resilient airlines. Moreover, the marginal effects for $Max\_share\_flights_{it}$ and $Highest\_share\_flights_{it}$ suggest that both variables decreased the probability of an airline being a least resilient airline and increased its likelihood of being a most resilient airline, respectively (see columns b1 − b3). In other words, airlines that concentrated their flight operations at an airport and/or achieved the dominant market position at an airport, are expected to achieve better recovery performance (Hou et al., 2021). In addition, *Quarantine* is found to decrease the likelihood of airlines being the most resilient airlines (see column b) when compared with none of COVID-19 related travel measures being implemented. It is important to note that the value of $Quarantine_{xt}$ depends on a country's travel policy in which the airline's headquarter is located. This holds true for the results of the marginal effects (see columns b1 − b3). Finally, we also find similar contributions of the airport slot waiver policy, $Slot\_waiver_{xt}$, which helps the recovery of airlines.

5. Discussion

5.1. Common factors affecting aviation resilience

Some common factors are identified to affect aviation resilience in the European aviation market amid the disruptions caused by the COVID-19 pandemic and the recovery followed (Chinazzi et al., 2020; Dube et al., 2021). Travel restrictions clearly have significant and negative impacts. When the COVID-19 cases across Europe rebounded, quarantine measures for travelers and tourists were immediately enforced by the European governments until there was a clear sign that the spread of the COVID-19 virus decreased or effectively controlled (Chinazzi et al., 2020; Zhang et al., 2020). European countries with a high number of COVID-19 confirmed cases were recognized as high-risk countries and regions, and travelers and tourists from these regions/countries were required to be quarantined/isolated for certain days upon arrival. In addition to the inconvenience and costs associated with quarantine/isolation, the perceived safety risks associated with air travel can also influence travelers' decisions to travel during the pandemic (Teeroovengadum et al., 2021). With decreasing air travel demand, airlines cut off routes and reduced flight connectivity, thus impacting and reducing European airports' and airlines' resilience. Furthermore, with respect to total direct flights offered in a country positively contributed to airports' resilience of that country identified in this study. Intuitively, airlines within a larger aviation market often have more opportunities. This is the case for the U.S. and mainland China, where airlines can resort to domestic markets when their international markets face strong head winds. On the other hand, countries and regions with smaller domestic aviation markets, notably Dubai, Hong Kong, Singapore, the South Pacific regions, and to some extent South Korea, had no domestic aviation markets to hide when international aviation markets collapsed (Czerny et al., 2021; Tsui et al., 2021a, 2021b; Salesi et al., 2022). In addition, with more flight services flying to and from a country, it should be fair to say that travel restrictions for visiting the country are somewhat relaxed. This will be a positive sign for the country's airport(s) to reconnect to other international cities and destinations.

5.2. Factors affecting airport resilience

The findings of this study show that LCCs' traffic volumes contributed to airport resilience in the European aviation market. With limited air travel demand due to the COVID-19 pandemic, virtually all airlines would operate minimum services by cutting flights, slashing routes and minimizing operating costs as much as possible, thus maintaining only the most essential connectivity (Budd et al., 2020). As known, the hub-and-spoke networks operated by FSAs can consolidate air traffic to and from their spoke markets, which play a critical role in maintaining essential inbound and outbound flows for airports. With lower marginal costs, LCCs can serve relatively "thin" routes, which allow them to extend their flight networks to the relatively smaller aviation markets and drive the region's capacity recovery (Mueller et al., 2021; Zhang et al., 2023). While the COVID-19 pandemic is under control and travel restrictions are relaxed, both FSAs and LCCs may resume and increase flight services in their respective competitive market segments.

Additionally, this study shows the number of flights offered at an airport has a close relationship with airport recovery in the European aviation market, which is consistent with Arora et al. (2021). This finding suggests that an airport's resilience will heavily rely on the performance of the operating airlines of the airport. Despite larger airports typically suffering a greater decline in air services than smaller airports, larger airports may also experience a quicker rebound of air traffic throughput when air travel demand is set to make a promising start to recovery (Gudmundsson et al., 2021). Furthermore, the HHI value for the European airports in terms of flight connectivity indicates that higher market concentration, which usually corresponds to less airline competition at airports, would make airports more resilient. It has been well recognized that a competitive airline market brings greater social welfare by reducing airfares and improving air services (Fu et al., 2015a; 2015b). In such a fiercely competitive environment of the European aviation market, airlines need to attract more travelers and tourists to achieve profitability and survive (Alderighi et al., 2012; Tu et al., 2020). However, under the unprecedented, long-lasting and heavy strike of the COVID-19 pandemic, almost every major European FSAs suffered significant economic losses and smaller LCCs stopped serving thin markets. In general, airlines under financial pressure often cut capacity to reduce losses during difficult operating environments. Such a strategy limits their abilities to respond quickly to changes in market dynamics, notably swift demand recovery. Therefore, European airports with highly competitive airline markets did not always achieve superior resilience. On the other hand, airports served by fewer carriers are more likely to be local or regional airports rather than large hub airports. Local and regional airports predominantly serve domestic travel, which experienced comparatively fewer restrictions during the pandemic than international travel, particularly with regard to border closures and the quarantine upon arrivals across countries (Budd et al., 2020; Suau-Sanchez et al., 2020; Andreana et al., 2021; Suau-Sanchez et al., 2021). In contrast, larger hub airports faced the challenge of reduced travel demand and resorted to operating unprofitable ghost flights to maintain their slots (Sun et al., 2022). This mismatch between minimal flights and actual passenger demand affected major airports, while airports with fewer carriers efficiently adjusted their schedules to meet demand, enhancing their resilience. Lastly, HSR did not help European airports to recover. A few recent studies concluded that HSR expansions decreased the provision of airline services in specific routes (Dobruszkes et al., 2014; Manello et al., 2022; Yang et al., 2022) as HSR and aviation services can be complementary. The negative effects of HSR on airport recovery identified in this study are probably due to the unprecedented disruptions brought by the COVID-19 pandemic, which outweigh its competitive benefits under normal market conditions.

5.3. Factors affecting airline resilience

It has been observed in this study that an airline that operated more flights during the COVID-19 period tended to achieve better recovery. Intuitively, this may be due to the economies of scale effects as well as the network effect, as larger FSAs may be better positioned to explore network benefits (Zhang, 1996). Although empirical studies have identified significant network configuration strategies for FSAs and LCCs (Fu et al., 2019; 2020; 2021), in this study no significant differences have been identified between FSAs and LCCs in terms of their operations and network configuration's impacts on resilience. The reasons might be that FSAs serveed more international markets before COVID-19, which had to be suspended during the COVID-19 period as a result of more strict border constraints across countries even within the European continent (Budd et al., 2020; Suau-Sanchez et al., 2020; Suau-Sanchez et al., 2021). Consequently, these two groups of airlines (FSAs vs. LCCs) were expected to adjust their operating strategies accordingly. For example, during the COVID-19 pandemic, European FSAs can utilize point-to-point networks when the long-haul international routes witnessed a slower recovery (Bauer et al., 2020; Suau-Sanchez et al., 2020). Whereas European LCCs tended to avoid head-to-head competitions with other LCCs (even FSAs), a few LCCs such as EasyJet, Ryanair, and Wizz Air have increasingly expanded their networks during the COVID-19 pandemic (Zhang et al., 2023). As mentioned above, no statistically significant patterns have been observed between these two airline groups in this study. Again, this is probably due to the fact that when airlines' abilities recovered from the unprecedented crisis decline, inter-airline differentiation did not play a critical role.

Additionally, this study finds that the concentration of an airline's flight services at a particular European airport shows a significant positive effect on its resilience. This effect can be attributed to the advantages associated with economies of scale or the hub-and-spoke model operated by FSAs. By focusing their services at a particular airport, FSAs can effectively manage their operations, optimize their resources, and enhance connectivity for their passengers. This approach facilitates improved coordination of flight schedules, maintenance facilities, and ground services, resulting in enhanced operational efficiency and resilience. Hou et al. (2021) also found that being a dominant carrier at an airport – normally the airline's hub or hub-based airport – contributed to its resilience. A dominant airline is often better positioned in competition (e.g., able to charge "hub premium") and network development. These advantages may help an airline to more quickly recover during the post-pandemic era.

Finally, the implementation of the airport slot waiver policy, which suspended the "use it or lose it" rules of the airports from 30 March 2020, had a positive impact on airline resilience. During the pandemic period, when travel demand was low, airlines were still under pressure to operate "ghost flights" with low passenger loads to maintain their slot rights at the airports if the airport slot waiver policy had not been in place. A study by Sun et al. (2022) observed a significant increase in ghost flights in March 2020. Undoubtedly, these flights could not benefit the airlines; instead, they incurred additional operational costs and added to their financial burden, which was detrimental to their survival during the crisis. The airport slot waiver policy allowed airlines to suspend routes with low demand. This policy provided assurance to airlines that they would not lose their slot rights at airports during this exceptional period, thereby facilitating their survival and recovery.

6. Conclusion

Resilience provides airports and airlines with the ability to recover more quickly from the disruptions caused by the COVID-19 pandemic. This study contributes to the aviation literature by presenting an overview of the COVID-19′s disruptions to the European aviation market, and identifies key determinants influencing airport and airline resilience. Importantly, this study helps us understand aviation recovery from the unprecedented shocks. Our empirical analysis of the European aviation market suggests that the resilience of individual airports and airlines influenced by external factors such as the country-level recovery and travel restrictions implemented. An airport's resilience is heavily reliant on the total number of flights, no matter they are operated by FSAs or LCCs. Moreover, high airline concentration at airports might benefit airport resilience amid an exogenous shock. With respect to airline resilience, a larger and dominant airline is better positioned for recovery. Overall, these key findings reveal the positive resilience effects of market concentration and firm scale. Although the benefits of economies of scale on airports' and airlines' costs and/or operations are well understood, market concentration and firm scale have often been linked to (negative) market power and threat of competition loss. Our study provides fresh insights and evidence on their positive resilience effects in the presence of major market shocks.

The unprecedented impact of the COVID-19 pandemic on the aviation industry over the past three years serves as a valuable lesson for aviation managers. Both airport and airline managers should prioritize preparedness for potential disruptive events to maintain their operational performance as smoothly as possible. In light of the future disruptions, airports can undertake several operational improvements to enhance their efficiency and, more importantly, instill confidence in travelers regarding their journey safety from infections. Close collaborations between airports and government entities are crucial to ensure that health control facilities are adequately equipped to meet air travel requirements. Additionally, implementing self-service and contactless technologies or facilities for check-in and other services at airports can help reduce the risk of virus exposure during boarding and landing at airports (Serrano and Kazda, 2020; Dube et al., 2021).

Regarding airline operation, it is important for managers to be aware of potential financial and operational risks Long-term planning for airline development should include financial stress tests taking into account the uncertainties associated with disruptive events. Furthermore, during the COVID-19 pandemic, FSAs that heavily depended on international flights were less resilient compared with those that had a more balanced portfolio of operations (i.e., domestic and international flights). Moreover, it is crucial to establish a fast response mechanism to adjust operation strategies and adapt to changing circumstances. For instance, during periods of international flight suspension, redirecting international operations to domestic services or converting passenger flights into cargo operations may help retain the workforce and mitigate the risk of labor shortages once the recovery phase begins (Suau-Sanchez et al., 2020).

As cautioned, resilience can be defined through different aspects whereas our study only focuses on restorative resilience, which is measured by the flight operations of airports and airlines. Further study may incorporate other indicators such as airports' and airlines' financial performances to examine their resilient capability/recovery performance. Furthermore, it is important to consider the impact of government bailouts provided to airports and airlines in Europe during the COVID-19 period on the competition dynamics within the aviation market, potentially influencing the aviation industry's resilience (Suau-Sanchez et al., 2020). These financial aid/interventions aimed to assist airports and airlines in surviving the crisis and might have altered the competitive landscape of the European aviation market. Another factor that could affect the European aviation market's recovery is the reduction in the available labor force during the COVID-19 pandemic, which could limit the operations of airports and airlines once travel restrictions are lifted and travel demand rebounds (Murray and Green, 2022). However, this study lacks access to comprehensive data that allow the accurate quantitative analysis of the effects of government bailouts and labor shortages on the resilience of the European aviation market. Therefore, future research should be conducted when relevant information becomes available to provide a more thorough analysis of these factors. Our study focuses on the European aviation market which is a mature and fullly deregulated aviation market. Analysis of other aviation markets, especially those in developing countries featuring significant legacy regulations might offer different patterns and insights.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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