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Connectivity and Network Robustness of European Integrators

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Abstract

Although redundancy is often associated with lower efficiency, redundant networks can provide integrators with the flexibility and capacity to respond to issues in the delivery network. This study analyzes the air transportation network strategies and robustness of the four largest European integrators, estimating the loss in connectivity when a node becomes unavailable. Accordingly, we develop a robustness index that accounts for the importance of airports in the network to each of the four main integrators, in terms of connections and freight capacity. The outcomes reveal that integrators operating within a hub-and-spoke type network are less resistant to network disruptions, while robustness is higher in less concentrated networks. The results highlight that integrators develop different network strategies to manage the trade-off between network efficiency and robustness, which may vary depending on the standardized or customized services expected by clients.

Keywords: connectivity; redundancy; robustness; air transport; freight

1. Introduction

Several researchers have investigated the connectivity of transportation networks (e.g., Burghouwt and Redondi, 2013; Tovar et al., 2015; Xu et al., 2018; Zhu et al., 2018), providing practical measures to support strategic decisions and investment choices (e.g., Burghouwt and Redondi, 2013; Zhu et al., 2018) and theoretical contributions, such as measuring the impact of connections on the local economy (e.g., Percoco, 2010).

However, few studies focus on the networks of integrators, mainly due to the difficulties in collecting reliable data on freight-operated connections and freight capacity (Boonekamp and Burghouwt, 2017; Lakew, 2014; Malighetti et al., 2019a, 2019b). Recent studies in the air transportation industry (Malighetti et al., 2019a, 2019b) analyze the network provided by the four main European integrators: DHL, UPS, FedEx, and TNT, demonstrating their

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differences and analyzing their level of connectivity in Europe and Asia. Although their network strategies often resemble the hub-and-spoke system of traditional carriers transporting passengers, some important differences emerge. For example, integrators tend to choose airport hubs located away from large cities (Bowen, 2012; Noviello et al., 1996) and, unlike passengers, freight can be transported along routes characterized by long connecting times, multiple stops, and long detours (Boonekamp and Burghouwt, 2017; Bowen, 2012; Lakew, 2014; Malighetti et al., 2019b).

One of the key characteristics of integrator networks is their apparent redundancy; there are generally several alternative paths to connect two nodes within the network. This may appear inefficient; however, redundancy boosts network robustness, providing flexibility and operational continuity (Lordan et al., 2016) in response to disruptions or overloading. Moreover, the itinerary of freight may vary according to agreed delivery times, transportation costs, and the integrator's network load. For example, if the delivery time is critical, integrators are likely to route the freight via the quickest path between origin and destination. Conversely, if the delivery time is not crucial, integrators may employ cheaper airports or several flights with one or more intermediate connections to minimize delivery costs. In some cases, integrators may even decide to employ trucks for part of the origin-destination path. Finally, redundancy reduces the risk associated to overloading; when an integrator's network is overloaded in peak times, such as the Christmas period (e.g., the delivery of Amazon packages), redundancy may facilitate the delivery of freight to meet the integrators obligations.

While redundancy is often criticized, it provides robustness to integrators' networks. This study contributes to the literature by analyzing the air transportation network robustness of European integrators. We rely on data concerning the operated flights of DHL, FedEx, UPS, and TNT in the week of June 11 to 17, 2019, to measure the loss in connectivity when a node in their network is unavailable. Accordingly, we develop a robustness index accounting for the importance of the removed node, weighted for its freight capacity.

The remainder of this study is structured as follows. An overview of the data and the method used in this study are presented in Section 2. Section 3 illustrates the results, providing a discussion on the overall robustness of the integrators and the relative importance of certain airports in their networks. Finally, Section 4 concludes our work and provides suggestions for future research.

2. Research Design

2.1. Data and sources

Our study relies on a detailed dataset comprehending information on the operated flights from/to Europe of the four selected integrators–DHL, FedEx, UPS, and TNT–during the week of June 11 to 17, 2019, and the related freight capacity.[†] The data on airport connections and frequencies are obtained directly from the website of the flight-tracking service Flightradar24. Flight information is combined with the maximum aircraft payload, which is used as a proxy for capacity (Malighetti et al., 2019a, 2019b). The maximum payload is directly derived from the manufacturer's technical datasheet.

Fig. 1 illustrates the network structure of the largest European integrators, and Table 1 provides key descriptive statistics for the integrators. DHL has the largest network in terms of both the number of airports (125) and routes (377), followed by TNT with 99 airports and 281 routes. However, while FedEx and UPS operate through a limited number of airports in comparison (64 and 44, respectively), their freight capacity is more than double that of TNT. Concentration measures, such as the Herfindahl-Hirschman Index (HHI) and the network structure shown in Fig. 1, suggest that the four carriers rely on different network strategies. UPS has the highest HHI (1,291), and flows in its network usually depart from the company's main hub in Cologne, Germany. The TNT network is characterized by several routes connecting European airports, and its HHI (445) indicates that freight capacity is more evenly distributed among the different nodes. Although different in terms of network size, DHL and FedEx share similar

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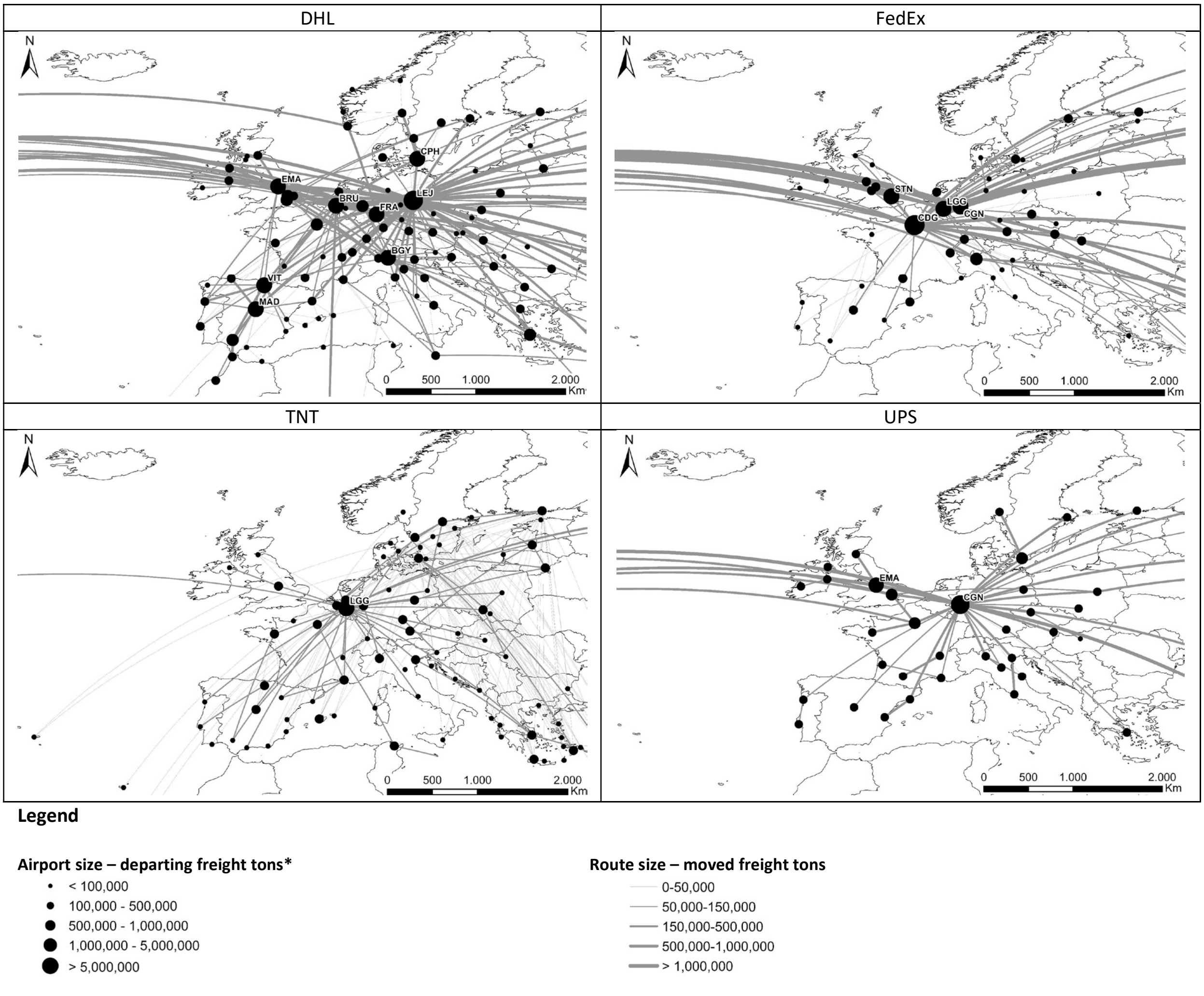
[†] The data also include flights operated by carriers owned by, flying on behalf of, and operating under the brand of one of the selected integrators, as in Malighetti et al. (2019a, 2019b).

features, such as a multi-hub network structure (see Fig. 1), a similar market concentration (947 for DHL and 1,038 for FedEx), and comparable available ton kilometers (ATK), which are above 100 billion for both integrators. UPS and TNT have lower ATK values (46.5 and 17.1 billion, respectively). Differences arise also in terms of average flight distances. Specifically, FedEx is more long-route oriented, with an average distance of 4,366 km, in contrast to the average distances of the other integrators, which range from 1,851 to 2,517 (see Table 1).



** only labels for airports with more than 1 million departing tons are displayed.*

Fig. 1. The European network structures of DHL, FedEx, TNT, and UPS. Source: authors' elaboration from flightradar24.com data, June 11 to 17, 2019.

Table 1. The integrators' network characteristics.

Integrator	No. airports	No. Routes	No. Flights	Freight HHI	Freight (ton)	Average distance	ATK (million)
DHL	125	377	1,559	947	48,738,935	2,312	112,674
FedEx	64	157	527	1,038	23,842,095	4,366	104,103
UPS	44	99	428	1,291	18,472,405	2,517	46,489
TNT	99	281	525	445	9,221,458	1,851	17,072

Notes: HHI is the Herfindahl-Hirschman Index; ATK is the available ton kilometers.

2.2. Method

To evaluate network robustness, we test how the connectivity of each integrator's network changes when a node is unavailable. As a first step, we develop a connectivity index, A , which accounts for both the capacity of a node, in terms of freight tons, and the level of connectivity among the network nodes. Specifically, we employ the shortest path length (SPL) measure, which is defined as the minimum number of steps needed to connect two nodes of the same network (Malighetti et al., 2008; Redondi et al., 2011; Shaw and Ivy, 1994). In the case of air transportation networks, this index (SPL_{ij}) corresponds to the minimum number of non-stop flights necessary to connect two airports (i and j) belonging to the same network (Redondi et al., 2011); therefore, the higher the SPL_{ij}, the more flights it takes to connect airports i and j. When two airports are not connected, directly or indirectly, SPL_{ij} is set to infinite. By relying on this measure, for each integrator k, we compute the network connectivity index (A_k) as:

$$A_k = \frac{\sum_{i \neq j \in K} \frac{1}{SPL_{ij}} \cdot T_j^k}{\sum_{i \in K} T_i^k}, \tag{1}$$

where SPL_{ij} represents the minimum number of links between airports i and j belonging to network K and T_i^k, and T_j^k are the freight tons moved at airports i and j, respectively, by integrator k. Considering the inverse measure of SPL_{ij} allows us to evaluate equal to zero those airport-pairs with neither direct nor indirect connections available.

A_k portrays the level of connectivity of a network characterized by n_k nodes. To evaluate the robustness of each integrator's network, we explore the decrease in the overall connectivity when a single node is unavailable, thus leading to a total number of airports equal to $n_K - 1$. For each airport i, we simulate its removal from the network and compute its relative importance in terms of connectivity loss (CL_i), such as:

$$CL_i = \frac{A_k^i}{A_k} - 1, \tag{2}$$

where A_k and A_k^i stand for the overall connectivity of integrator k's network when all nodes are available and node i is no more available, respectively, computed as in Equation (1). The higher the CL_i, the greater the importance of node i in the network. For each integrator k, airports with high CL_i are the most central nodes in the network (i.e., hubs) and offer high-capacity flights.

Accordingly, the robustness of integrator k's network (R_k) is computed as:

$$R_k = \frac{\sum_{i \in K} \frac{A_k^i}{A_k} \cdot T_i^k}{\sum_{i \in K} T_i^k}. \tag{3}$$

3. Results and Discussion

Table 2 reports the results of our analysis, showing the connectivity loss (CL) for each integrator due to the disconnection of its major European airports in terms of freight traffic and the number of airports in the network that are no longer accessible. For example, if DHL's main European hub (Leipzig, Germany) is no longer available, overall connectivity declines by 59%, and a total of 19 airports in the network are no longer accessible. Even if it ranks only fourth in terms of freight capacity, if Frankfurt airport, in Germany, is unavailable, DHL experiences the second highest connectivity loss equal to 13%, and 10 airports are disconnected from the network.

Similar outcomes can be observed for UPS, FedEx, and TNT; we find the highest loss in connectivity when simulating the removal of their most important European hub (Cologne, Germany; Paris Charles De Gaulle, France; and Liège, Belgium, respectively). While FedEx and TNT present a 57% and 54% decrease in connectivity, respectively, the UPS network appears to be particularly vulnerable to a shutdown of Cologne, Germany, with a 92% decrease in connectivity. This can be explained by the UPS network configuration, which resembles a typical hub-and-spoke structure (see Fig. 1), where 33.5% of freight is moved through Cologne.

Table 2. The number of disconnected airports and connectivity loss in case the 10 major European airports are unavailable in the integrators' networks.

	DHL					UPS				
	Simulation	Freight %	Disc. Airp.	A	CL	Simulation	Freight %	Disc. Airp.	A	CL
Rank	Basic scenario		0	68.36	0%	Basic scenario		0	25.85	0%
1	Leipzig (LEJ)	27.8%	19	27.71	-59%	Cologne (CGN)	33.5%	11	2.09	-92%
2	East Midlands (EMA)	7.3%	3	60.45	-12%	East Midlands (EMA)	5.7%	2	23.22	-10%
3	Brussels (BRU)	5.4%	1	63.92	-6%	Paris (CDG)	4.2%	2	23.73	-8%
4	Frankfurt (FRA)	5.4%	10	59.71	-13%	Malmo (MMX)	3.7%	2	23.97	-7%
5	Milan (BGY)	3.7%	3	64.29	-6%	London (STN)	3.7%	1	24.34	-6%
6	Vitoria (VIT)	2.8%	3	64.82	-5%	Barcelona (BCN)	2.2%	2	24.24	-6%
7	Madrid (MAD)	2.6%	1	66.40	-3%	Venice (VCE)	2.2%	2	24.24	-6%
8	Copenhagen (CPH)	2.3%	1	66.22	-3%	Milan (BGY)	2.1%	1	24.74	-4%
9	Cologne (CGN)	1.6%	2	66.92	-2%	Lyon (LYS)	1.7%	2	24.33	-6%
10	London (LHR)	1.6%	1	67.01	-2%	Warsaw (WAW)	1.8%	1	24.82	-4%
	FedEx					TNT				
	Simulation	Freight %	Disc. Airp.	A	CL	Simulation	Freight %	Disc. Airp.	A	CL
Rank	Basic scenario		0	36.38	0%	Basic scenario		0	42.38	0%
1	Paris (CDG)	24.1%	13	15.49	-57%	Liege (LGG)	17.4%	11	19.53	-54%
2	Cologne (CGN)	10.1%	1	32.29	-11%	Copenhagen (CPH)	5.6%	8	36.27	-15%
3	Liege (LGG)	9.8%	7	24.37	-33%	Helsinki (HEL)	3.9%	5	38.68	-10%
4	London (STN)	5.0%	2	33.49	-8%	Vilnius (VNO)	2.6%	1	41.22	-4%
5	Milan (MXP)	3.2%	1	34.78	-4%	Orebro (ORB)	2.4%	1	39.37	-8%
6	Basel (BSL)	1.8%	2	34.70	-5%	Leipzig (LEJ)	1.3%	1	41.63	-3%
7	Munich (MUC)	1.7%	1	35.26	-3%	Eindhoven (EIN)	2.5%	6	39.62	-7%
8	Frankfurt (FRA)	1.5%	1	35.24	-3%	Katowice (KTW)	1.8%	1	41.68	-3%
9	Vienna (VIE)	1.5%	2	34.72	-5%	East Midlands (EMA)	2.1%	2	41.07	-4%
10	Stockholm (ARN)	0.9%	1	35.54	-2%	Riga (RIX)	1.9%	1	41.80	-2%

Table 3 illustrates the results of the robustness analysis for the integrators' entire networks compared with other measures representing the weighted average SPL, the ATK per flight, and the network efficiency (Latora and Marchiori, 2001; Zhou et al., 2019). Robustness estimations for DHL and FedEx are equal to 80.4% and 78.6%, respectively. UPS has the lowest robustness index (65.7%), while TNT appears to have the most robust network, with a value of 87.3%. The rational of these outcomes can be found by examining the differences between the integrators' networks, as described in Section 2.1. DHL and FedEx, sharing similar features, such as a multi-hub network structure, have similar robustness estimates. The literature provides evidence of lower robustness in hub-and-spoke networks when compared to dispersed point-to-point networks (e.g., Sun and Wandelt, 2018). Consistently, UPS, with a hub-and-spoke type network, and TNT, with a low market concentration, register the lowest and highest level of robustness, respectively. These differences in network configuration also emerge in the results shown in Table 2. More than 5% of DHL's and FedEx's freight traffic is managed by four airports. While both UPS and TNT mainly rely on two airports ($Freight\ \% > 5\%$), TNT's freight traffic is more diversified; its main airport, Liège, Belgium, operates around the half the freight traffic of the main UPS airport, Cologne, Germany.

Table 3. The average shortest path length, robustness index, and other network indexes for the integrators.

Integrator	ATK (million) per flight	SPL	Robustness (R)	Network Efficiency (E)
DHL	72.3	2.15	80.4%	39.6%
FedEx	197.5	2.01	78.6%	42.6%
UPS	108.6	1.96	65.7%	43.7%
TNT	32.5	2.84	87.3%	35.7%

Table 3 also reports a measure of network efficiency, computed as in Latora and Marchiori (2001), which confirms that the less robust networks are the most efficient ones, and vice versa. The network efficiency measure is defined as the overall connectivity generated by the network, computed as $\sum_{i \neq j \in K} \frac{1}{SPL_{ij}}$, divided by the maximum number of possible direct routes; that is, $n_k(n_k - 1)$, where n_k represents the number of network nodes (Latora and Marchiori, 2001; Zhou et al., 2019). This measure is the 'connectivity density' generated by each integrator in its network. The UPS network is confirmed as the most efficient (44%) followed by FedEx (43%), DHL (40%), and TNT (36%). The integrator with the most robust network, TNT, is the least efficient, even considering this measure, as it provides less connectivity density.

However, there exists a well-known trade-off between network robustness and efficiency (Malighetti et al., 2019b). Fig. 2(a) shows the relationship between the robustness index and ATK per flight. On average, TNT offers 32.5 million ATK per flight, less than half of DHL, less than one-third of UPS, and six times smaller than FedEx. With its network configuration similar to a point-to-point, TNT has a high number of routes and flights, but it employs aircraft with a lower capacity. One would expect a negative relationship between the robustness index and ATK per flight; however, FedEx shows a robustness index similar to DHL but with significantly higher ATK per flight. This can be explained by its higher average distance of routes compared to the other integrators (see Table 1); the FedEx network is more reliant on intercontinental flows than the other integrators, which have more developed intra-European networks.

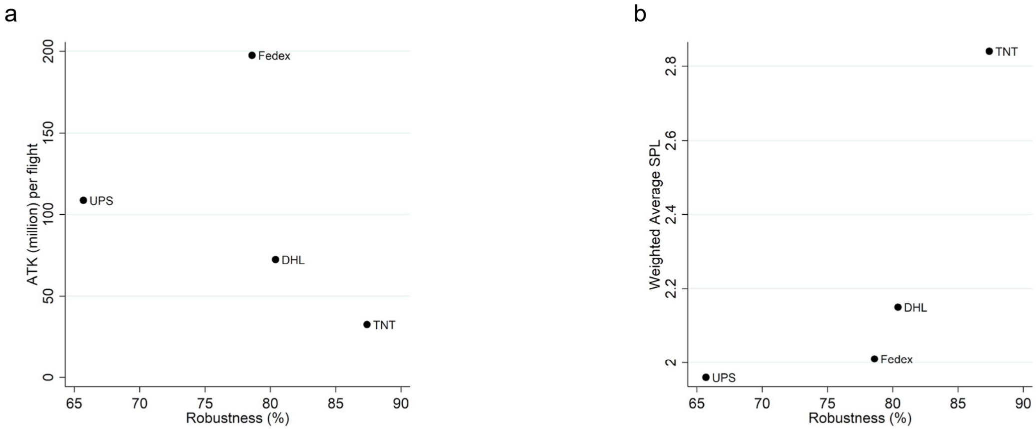


Fig. 2. (a) The relationship between the robustness index and available ton kilometers (ATK) per flight; (b) The relationship between the robustness index and weighted shortest path length (SPL).

Fig. 2(b) illustrates the relationship between the robustness index and the capacity-weighted average SPL. The latter variable indicates the average number of flights needed to connect any two airports in the network. The TNT network has the highest SPL value of 2.84. From a client perspective, operating with a network more similar to a point-to-point configuration has a positive effect on robustness, as alternative freight paths are more readily available. However, this leads to a negative effect on delivery times, as the freight undergoes an average of 1.84 transfers before reaching its final destination, all else being equal. As expected, there is a positive relationship between the robustness index and SPL. UPS has the most connected network in terms of SPL because it can connect any airport pair with 1.96 flights–less than one transfer on average–due to its more pronounced hub-and-spoke network. However, this reduces robustness in the event of failures in its key nodes. DHL and FedEx have similar values in terms of both the robustness index and SPL, situated between the point-to-point oriented network of TNT and the hub-and-spoke oriented network of UPS.

The results of this study have both market and managerial implications. For industrial customers, a lack of robustness in the supply of raw materials or initial components could result in delivery delays or even production delays. Moreover, the recent crises related to COVID-19 highlight the relevance of network robustness, demonstrating that extreme events can result in significant disruption to an integrator's network. Thus, industrial clients may be willing to pay a premium for a more robust network.

However, standard package delivery to customers of large online companies, such as Amazon and Alibaba, will likely still depend on price rather than on robustness, as those companies have internal diversification strategies, employing different integrators or establishing their own delivery companies. Regardless, robustness is gaining relevance as a marketing factor.

In response to the increasing growth of e-commerce, integrators have started to integrate business-to-consumer services into their typical business-to-business model, and these services have different delivery and cost requirements (Malighetti et al., 2019b). Our analysis suggests that each integrator sets its network structure to target its client mix. For example, the UPS network, which is aligned to the hub-and-spoke model, appears to target price-sensitive clients with standard, short delivery-time requirements. Conversely, the TNT network, which resembles a point-to-point model, appears to satisfy clients with special needs that require higher flexibility and reliable delivery times. DHL and FedEx networks are positioned in between these two configurations.

The increasing sensibility of clients toward reliable deliveries may justify a robustness-oriented strategy. Setting alternative paths to connect the same airport-pair will provide the integrator the flexibility to satisfy specific client needs, in terms of reliability, expected delivery times, and costs. However, increasing robustness also increases network redundancy, which increases costs and reduces efficiency in freight flows. Determining a robustness level that optimizes the cost-benefit trade-off would increase integrators' competitiveness, especially in a dynamic context. In this regard, this study highlights to integrator managers the link between robustness and the network configuration and provides reliable metrics to monitor over time.

4. Conclusion

This study contributes to the literature by analyzing the levels of connectivity and robustness in integrators' networks. Using a simulation analysis, we test the variation in the level of connectivity resulting from a node removal. Furthermore, by combining this measure for each airport in the integrators' network with the related freight capacity, we estimate the level of robustness of the four major European integrators: DHL, FedEx, UPS, and TNT. The results confirm that integrators that rely on a configuration similar to hub-and-spoke are less robust. This is demonstrated by the case of UPS, which concentrates its operations in Cologne, Germany. Conversely, TNT relies on a network that resembles a point-to-point structure and has a 21.6% higher robustness level than UPS. The robustness of the DHL and FedEx networks is in between TNT and UPS values, reflecting their multi-hub configuration.

Robustness is integral to fulfilling clients' requirements; however, it is important to compare robustness with other measures, reflecting estimates of delivery times and costs, when analyzing integrators' network strategies. Therefore, we compare our measure of robustness with other indexes, indicating the weighted average SPL, the ATK per flight, and the level of network efficiency. We find negative relationships between robustness and delivery times (i.e., higher SPL), ATK per flight, suggesting the employment of aircraft with a lower capacity, and network efficiency. The comparison among these measures highlights the differences in the strategies adopted by integrators.

By highlighting the trade-off between network robustness and efficiency, this study provides a measure of robustness which can be used by integrators to improve their flexibility and strategic decision-making when assessing the importance of nodes and which airports to add (or remove) to (from) their network. Furthermore, our results open avenues for future research. First, it would be useful to analyze the differences in connectivity and robustness of integrators in different geographical areas. This study focuses on all the operated flights from/to Europe by DHL, FedEx, UPS, and TNT, which are recognized as the largest integrators in the Americas, Middle East, and Africa (Bowen, 2012; DHL, 2014). However, the geographical characteristics of territories and the role played by each integrator in the analyzed area may contribute to varying strategies. Second, future studies could use the proposed indexes to simulate the simultaneous shutdown of more than one node, providing additional evidence of the level of robustness of integrators and their resilience.

References

Boonekamp, T., & Burghouwt, G. (2017). Measuring connectivity in the air freight industry. Journal of Air Transport Management, 61, 81–94. https://doi.org/10.1016/j.jairtraman.2016.05.003

Bowen, J. T. (2012). A spatial analysis of FedEx and UPS: Hubs, spokes, and network structure. Journal of Transport Geography, 24, 419–431. https://doi.org/10.1016/j.jtrangeo.2012.04.017

Burghouwt, G., & Redondi, R. (2013). Connectivity in air transport networks an assessment of models and applications. Journal of Transport Economics and Policy, 47(1), 35–53.

DHL. (2014). Annual Report - When you think of logistics.

Lakew, P. A. (2014). Economies of traffic density and scale in the integrated air cargo industry: The cost structures of FedEx Express and UPS Airlines. Journal of Air Transport Management, 35, 29–38. https://doi.org/10.1016/j.jairtraman.2013.11.001

Latora, V., & Marchiori, M. (2001). Efficient behavior of small-world networks. Physical Review Letters, 87(19), 198701-1-198701–198704. https://doi.org/10.1103/PhysRevLett.87.198701

Lordan, O., Sallan, J. M., Escorihuela, N., & Gonzalez-Prieto, D. (2016). Robustness of airline route networks. Physica A: Statistical Mechanics and Its Applications, 445, 18–26. https://doi.org/10.1016/j.physa.2015.10.053

Malighetti, P., Martini, G., Redondi, R., & Scotti, D. (2019a). Integrators' Air Transport Networks in Europe. Networks and Spatial Economics, 19(2), 557–581. https://doi.org/10.1007/s11067-018-9390-5

Malighetti, P., Martini, G., Redondi, R., & Scotti, D. (2019b). Air transport networks of global integrators in the more liberalized Asian air cargo industry. Transport Policy, 80, 12–23. https://doi.org/10.1016/j.tranpol.2019.04.021

Malighetti, P., Paleari, S., & Redondi, R. (2008). Connectivity of the European airport network: "Self-help hubbing" and business implications. Journal of Air Transport Management, 14(2), 53–65. https://doi.org/10.1016/j.jairtraman.2007.10.003

Noviello, K., Cromley, E. K., & Cromley, R. G. (1996). A comparison of the air passenger and air cargo industries with respect to hub locations. Great Lakes Geographer, 3(2).

Percoco, M. (2010). Airport Activity and Local Development: Evidence from Italy. Urban Studies, 47(11), 2427–2443. https://doi.org/10.1177/0042098009357966

Redondi, R., Malighetti, P., & Paleari, S. (2011). New Routes and Airport Connectivity. Networks and Spatial Economics, 11(4), 713–725. https://doi.org/10.1007/s11067-010-9131-x

Shaw, S. L., & Ivy, R. L. (1994). Airline mergers and their effect on network structure. Journal of Transport Geography, 2(4), 234–246. https://doi.org/10.1016/0966-6923(94)90048-5

Sun, X., & Wandelt, S. (2018). Complementary strengths of airlines under network disruptions. Safety Science, 103, 76–87. https://doi.org/10.1016/j.ssci.2017.11.010

Tovar, B., Hernández, R., & Rodríguez-Déniz, H. (2015). Container port competitiveness and connectivity: The Canary Islands main ports case. Transport Policy, 38, 40–51. https://doi.org/10.1016/j.tranpol.2014.11.001

Xu, W., Zhou, J., Yang, L., & Li, L. (2018). The implications of high-speed rail for Chinese cities: Connectivity and accessibility. Transportation Research Part A: Policy and Practice, 116, 308–326. https://doi.org/10.1016/j.tra.2018.06.023

Zhou, Y., Wang, J., & Huang, G. Q. (2019). Efficiency and robustness of weighted air transport networks. Transportation Research Part E: Logistics and Transportation Review, 122, 14–26. https://doi.org/10.1016/j.tre.2018.11.008

Zhu, Z., Zhang, A., & Zhang, Y. (2018). Connectivity of intercity passenger transportation in China: A multi-modal and network approach. Journal of Transport Geography, 71, 263–276. https://doi.org/10.1016/j.jtrangeo.2017.05.009