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Codesharing network vulnerability of global airline alliances

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Abstract

Global airline alliances provide connectivity based on codesharing agreements between member airlines. An alliance member exit leads to the deletion of routes (if not operated by other members) which affects network connectivity. The paper measures the vulnerability of the codesharing network (CN) of Star Alliance, oneworld and SkyTeam, respectively, by applying the theory of complex networks. A normalized CN vulnerability metric is proposed. Using airline schedules data, a ranking of member airlines according to their share in the overall CN vulnerability is derived. The results for CNs are compared with the ones for the respective total network (TN) that includes routes with and without codesharing. The findings show that oneworld is the most vulnerable global airline alliance, SkyTeam ranks second followed by Star Alliance. The proposed graph theory approach might become a building block for a more comprehensive measurement of real world airline networks.

Keywords: Global airline alliances; codesharing; network vulnerability; complex networks

1. INTRODUCTION

The restructuring of airline activities into branded global alliances has been one of the major traits of this industry since Star Alliance was founded in 1997, followed by the formation of oneworld in 1999 and SkyTeam in 2000. Global alliances provide network connectivity based on codesharing agreements between member airlines. Codesharing is an interline partnership where one carrier sell tickets by placing its designator code on another carrier's flights. The airline selling seats is referred to as the marketing carrier and the airline providing the flight is referred to as the operating carrier. While codesharing dates back to the 1960s, it only became common in the early 1990s. The launch of the modern era of global airline alliances began with the large-scale codesharing agreement between Northwest Airlines and KLM in 1989. The aim is that the route network of a global alliance appears to be an extension of each partner's network. Codesharing in combination with coordinated flight schedules allows the provision of continuous services for passengers connecting between airlines. However, alliance members may take advantage of the route networks of partner airlines even without codesharing, e.g. due to interline agreements between individual airlines that cover connecting flights. A codeshare agreement usually requires an interline agreement.

At present, Star Alliance has 28 member airlines, SkyTeam 20, and oneworld 14 (cf. Appendix A) which together have a share of around 60% in worldwide air traffic. Extensive codesharing among global alliances allows airlines to offer routes without operating them which is cost-efficient. Avoiding overlapping operations also implies less competition. The drawback is a dependency on partner airlines. A member exit leads to the deletion of routes (if not operated by other alliance members) which affects network connectivity. In 2014, US Airways and TAM left Star Alliance after these two carriers merged with airlines from oneworld. oneworld on its part lost Malév after the financial collapse of this former Hungarian flag carrier in 2012. In early 2016, Qatar Airways threatened to withdraw from oneworld should fellow member American Airlines continue to push the US government to restrict market access for the Gulf carriers. An exit of partner airlines has negative consequences for global alliances, e.g. in the form of sunk costs due to alliance-specific investments or the risk that former alliance members use confidential information to their competitive advantage. Further, it implies a decrease in network coverage. The assessment of the (potential) damage to the codesharing network (CN) of global airline alliances is the subject matter of the present paper.

Not all member exits have the same impact because some airlines contribute more to the CN of a global alliance than others. Therefore, it is an important issue for the managing bodies of an alliance how to accurately assess the impact of an exit of a given member airline and similarly, how to develop a CN with appropriate partner selection. This paper studies the CN vulnerability of global alliances to member exits. We propose measures that can be instrumental in assessing the dependency of an alliance on a member's route network and can also serve to develop a more resilient CN. The results for CNs are compared with the ones for the respective total network (TN) that includes routes with and without codesharing.

Research on airline alliances and codesharing among airlines includes several studies on the effects of airline alliances on traffic volumes and airfares (Oum et al. 1996; Park, 1997; Park and Zhang, 1998; Brueckner, 2001; Brueckner et al., 2011; Zou et al., 2011). Kleymann and Seristö (2001) analyzed the trade-off between alliance benefits and risks. Douglas and Tan (2017) examined whether the formation of global airline alliances resulted in an increase in profitability for the founding members. Garg (2016) presented a model based approach to select strategic alliance partners. Different reasons for a company to leave an inter-firm co-operation are discussed by Sroka and Hittmár (2013). The welfare effects of codesharing agreements have been investigated by Hassin and Shy (2004) and, more recently, Adler and Hanany (2016).

There is an increasing and extensive literature of transport vulnerability studies. This paper measures the (potential) damage for the CNs of global airline alliances caused by member exits. Such alliances constitute an intermediate level of air transport networks between individual airline networks and the industry network (Lordan et al., 2014a). Mattsson and Jenelius (2015) provide an overview of recent research on vulnerability and resilience of transport systems. While they point out that there is no commonly agreed definition of transport system vulnerability, they conceptualize vulnerability as the susceptibility of transport systems to infrequent events that can result in considerable network degradations. In the context of the present paper, the infrequent event is a member exit having an adverse impact on the CN of a global airline alliance. The study of air transport networks includes the topological analysis of global (Guimerà and Amaral, 2004; Guimerà et al., 2005) and regional (Bagler, 2008; Zhang et al., 2010) route networks. Vulnerability is investigated for global (Lordan et al., 2014b), and regional (Chi and Cai, 2004; Du et al. 2016) networks. Lordan et al. (2015) examine the robustness of alliance airline route networks based on the assumption of unweighted networks only considering operating flights. Hence, the differing economic relevance of a given route operated by one member to other alliance members is disregarded. Weights could be based on the number of flight frequencies or seat capacities, and also by distinguishing between domestic, continental and intercontinental routes. The consideration of codesharing as an indicator of route relevance from the perspective of partner airlines represents a basic weighting scheme to enhance the practical meaning of the vulnerability measures. CNs are subsets of the respective TNs which consist only of operated routes that have a marketing flight number by at least one other carrier belonging to the same alliance. Our paper only looks at codesharing between member airlines of the same global alliance. In spite of this, the industry showcases other codesharing partnerships. There is codesharing between aligned and non-aligned airlines (e.g. Qantas and Emirates) and between carriers belonging to the same holding company (e.g. Lufthansa and Eurowings). Codesharing across global alliances is rather unusual. One example is Aeroflot and Finnair on the Helsinki-Moscow-route.

In this paper, CN vulnerability of real world networks is analyzed building on the theory of complex networks (Estrada, 2011; Estrada and Knight, 2015). More specifically, CN vulnerability is measured using the concept of normalized average edge betweenness (Mishkovski et al., 2011). The proposed method to measure CN vulnerability relates to work using a graph theory approach to develop strategies to increase the resilience of air traffic networks to disruptive events, such as extreme weather events, strike action or terrorist threats (Dunn and Wilkinson, 2015). It might also be valuable for a more comprehensive study of route networks that include other network indicators such as hubness and size (Roucolle et al., 2017).

The proposed methodology provides a normalized measure of the vulnerability of a given CN to (potential) member exits. Data comes from the OAG airline schedules database. One result of applying this measure is that oneworld is the most vulnerable CN, SkyTeam ranks second and Star Alliance is the most robust CN. Further, the paper indicates a positive relation between network robustness and route overlaps among members of global airline alliances. We also rank member airlines according to their contribution to the overall CN vulnerability. Our paper shows that the size of a carrier's scheduled operation is not strictly related to the carrier's importance for the vulnerability of an airline alliance route network. Finally, a comparison with results for TNs as unweighted alliance route networks illustrates the importance of bringing out relevant routes in future analysis of airline route networks.

2. METHODOLOGY

A codesharing network (CN) contains airports (nodes) connected by codeshared routes (edges), i.e., two airports are linked if an alliance member is operating flights between them with a designator code of another carrier from the same alliance. The proposed metric to assess CN vulnerability extends the graph theory concept of average edge betweenness as introduced by Boccaletti et al. (2007) for the graph G:

$$b(G) = \frac{1}{|E|} \sum_{l \in E} b_l \tag{1}$$

where |E| is the number of edges and b_l is the edge betweenness of the edge l defined as

$$b_l = \sum_{i \neq j} \frac{n_{ij}(l)}{n_{ij}} \tag{2}$$

where $n_{ij}(l)$ is the number of geodesics (shortest paths) from node i to node j that contain the edge l, and n_{ij} is the total number of shortest paths between i and j. If N represent the number of nodes of a network, then the b(G) values for a complete graph and a path graph are

$$b(G_{complete}) = 1 \qquad \text{and} \qquad b(G_{path}) = \frac{N(N+1)}{6} \tag{3}$$

and, hence, $b(G_{complete}) \leq b(G) \leq b(G_{path})$. G is more robust than G', if b(G) < b(G'). The normalized average edge betweenness of a network is defined as (Mishkovski et al., 2011)

$$b_{nor}(G) = \frac{b(G) - b(G_{complete})}{b(G_{path}) - b(G_{complete})} = \frac{b(G) - 1}{\frac{N(N+1)}{6} - 1} \tag{4}$$

where $b_{nor}(G)$ ranges from 0 (i.e., the most robust network) to 1 (i.e., the most vulnerable network). Thus, $b_{nor}(G)$ is a normalized measure of network vulnerability. The contribution of a member airline to the overall vulnerability of a CN can then be calculated as the relative difference of the normalized average edge betweenness, that is

$$D_{member} = \frac{b_{nor}(G') - b_{nor}(G)}{b_{nor}(G)} \tag{5}$$

where G' is the graph obtained from G (i.e., the entire CN) after removing the edges of the exiting member airline which are not operated by any other member. A positive value of D_{member} implies that the CN becomes more vulnerable. The higher the value of D_{member} the more negatively affected is the CN by the exit of the respective airline. A negative value of D_{member} would mean that a member exit is actually decreasing the CN vulnerability, i.e., the alliance is more robust without this airline.

3. RESULTS

The vulnerability of the three global alliances is analyzed using OAG airline schedules data for the week ending September 11, 2016. In Figure 1 we rank member airlines of Star Alliance, SkyTeam and oneworld based on their contribution to the codesharing network (CN) of the respective alliance, i.e., according to their D_{member} value. ALL (with value 0) refers to the entire CN without any exit.

As D_{member} is calculated with the normalized average edge betweenness $b_{nor}(G)$ of a specific alliance, this metric measures the relative impact on network vulnerability caused by the removal of an airline from this alliance. As the value of $b_{nor}(G)$ can vary between alliances, the absolute impact on network vulnerability can be quite different across alliances for similar values of D_{member}. Taking this into account, the relative impact of American Airlines (AA) on oneworld's CN is comparatively larger than the one of United Airlines (UA) on Star Alliance and Delta Airlines (DL) on SkyTeam. This is illustrated in Figure 1 by the length of the bars representing UA, DL, and AA in relation to the bars of the other carriers of Star Alliance, SkyTeam, and oneworld, respectively.

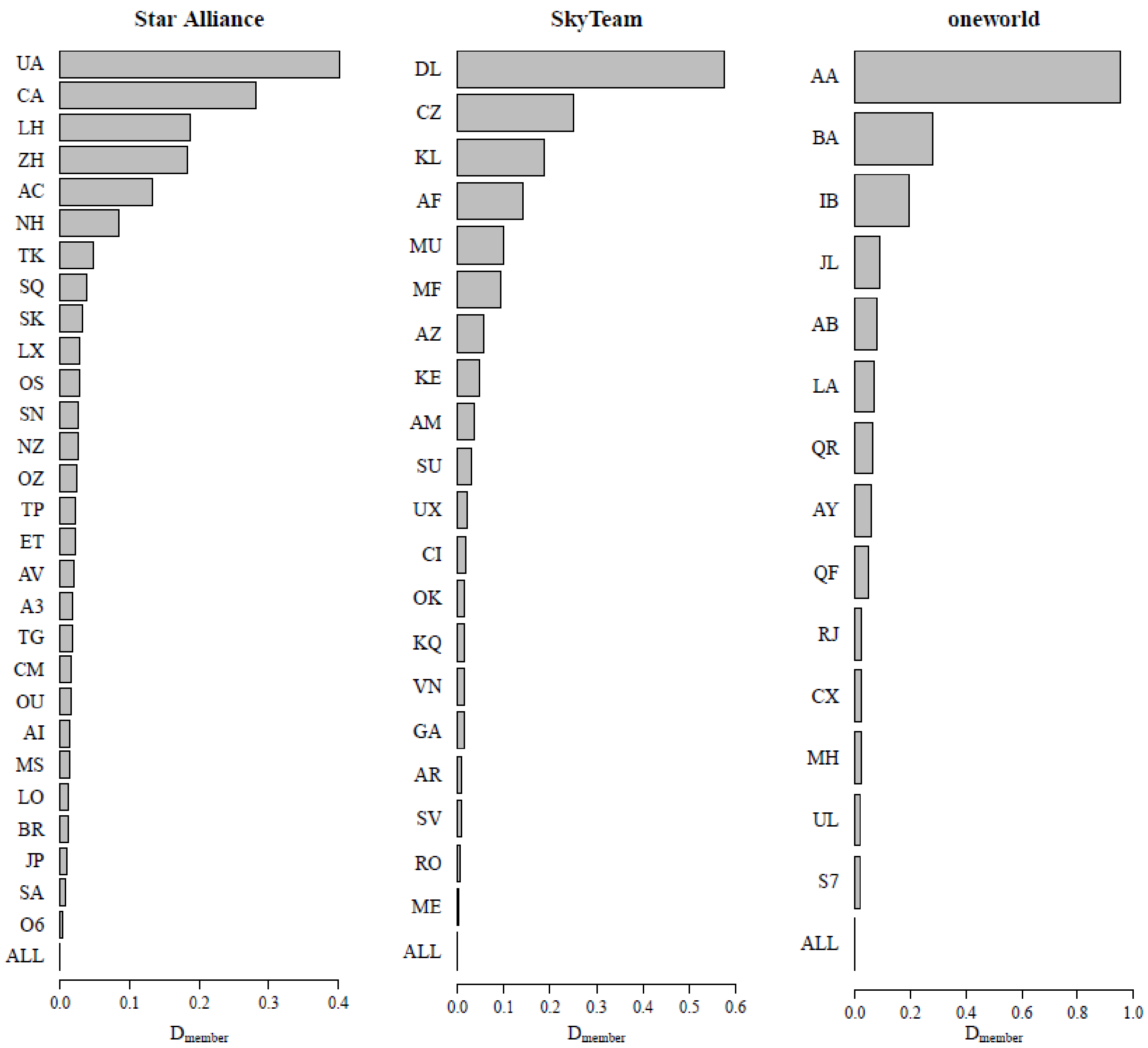

Fig. 1. Vulnerability of CNs of global airline alliances to member exits ranked by D_{member}.

Table 1 provides the values of the average edge betweenness b(G'), the normalized average edge betweenness b_{nor}(G'), and relative difference of the normalized average edge betweenness D_{member} for each member airline. For ALL, b(G') and b_{nor}(G') equal b(G) and b_{nor}(G), respectively, as ALL stands for the CN without any member removal. The b_{nor}(G) value ALL = 0.0724 for oneworld's entire CN is larger than the respective values for SkyTeam and Star Alliance which makes it the most vulnerable among the three CNs. While the values of D_{member} and b_{nor}(G') represent a one-to-one mapping, i.e., a higher (lower) value of D_{member} is strictly related to a higher (lower) value of b_{nor}(G'), this is not the case for the relation between D_{member} and b(G'). For example, the b_{nor}(G') of the Star Alliance members United Airlines (UA) and Air China (CA) are 0.00508 and 0.00464, respectively, while the values for b(G') have a reverse order (277.7 and 312.6). The average edge betweenness does not account for the change in the number of airport nodes of a CN resulting from a member exit. This is the reason why D_{member} is computed as the relative difference of the normalized average edge betweenness of a CN with and without a given member airline.

Table 1. Vulnerability measures of CNs ranked by D_{member}.

Star Alliance	b(G')	b_{nor}(G')	D_{member}	**SkyTeam**	b(G')	b_{nor}(G')	D_{member}	**oneworld**	b(G')	b_{nor}(G')	D_{member}
UA	277.7	0.00508	0.403	DL	310.2	0.00696	0.575	AA	301.0	0.01416	0.956
CA	312.6	0.00464	0.282	CZ	390.1	0.00552	0.249	BA	315.0	0.00928	0.282
LH	328.8	0.00430	0.186	KL	377.3	0.00524	0.186	IB	284.9	0.00866	0.196
ZH	323.1	0.00429	0.183	AF	373.8	0.00504	0.140	JL	299.1	0.00788	0.088
AC	325.9	0.00410	0.132	MU	387.2	0.00486	0.100	AB	338.6	0.00780	0.078
NH	326.9	0.00393	0.084	MF	424.6	0.00483	0.093	LA	290.1	0.00774	0.069
TK	314.1	0.00380	0.047	AZ	399.6	0.00467	0.058	QR	298.0	0.00769	0.062
SQ	322.7	0.00376	0.038	KE	403.2	0.00462	0.047	AY	327.0	0.00765	0.057
SK	316.5	0.00374	0.032	AM	370.4	0.00457	0.034	QF	330.5	0.00759	0.048
LX	340.8	0.00373	0.029	SU	372.5	0.00454	0.028	RJ	336.4	0.00743	0.026
OS	333.4	0.00373	0.029	UX	396.8	0.00451	0.021	CX	336.0	0.00742	0.025
SN	330.8	0.00372	0.026	CI	397.1	0.00449	0.017	MH	330.0	0.00740	0.022
NZ	315.5	0.00372	0.026	OK	401.1	0.00449	0.016	UL	337.0	0.00738	0.020
OZ	329.4	0.00371	0.025	KQ	385.9	0.00449	0.016	S7	292.3	0.00738	0.020
TP	334.3	0.00371	0.023	VN	403.0	0.00448	0.015	**ALL**	**330.4**	**0.00724**	**0**
ET	323.0	0.00370	0.022	GA	396.3	0.00448	0.014				
AV	324.2	0.00369	0.019	AR	394.3	0.00446	0.009				
A3	331.7	0.00369	0.018	SV	400.5	0.00446	0.009				
TG	330.6	0.00369	0.017	RO	391.8	0.00444	0.006				
CM	321.3	0.00368	0.016	ME	401.9	0.00443	0.004				
OU	332.8	0.00368	0.016	**ALL**	**400.3**	**0.00442**	**0**				
AI	331.3	0.00367	0.014								
MS	330.1	0.00367	0.013								
LO	335.8	0.00366	0.011								
BR	334.0	0.00366	0.011								
JP	331.5	0.00366	0.009								
SA	328.5	0.00365	0.008								
O6	322.1	0.00364	0.005								
ALL	**332.2**	**0.00362**	**0**								

CNs contain only routes operated by one member airline of a global airline alliance network that also has codesharing (i.e. a marketing flight number) by at least another carrier from the respective alliance. Codesharing is an indicator for relevance of a given alliance route. This can also be seen as a basic weighting scheme assigning the weight “1” to all codeshared routes and “0” to all non-codeshared routes. The results for CNs are now related to the respective total network (TN) that includes routes with and without codesharing.

Table 2 provides the values for nodes N, edges E, shared nodes S_N, and shared edges S_E of each airline belonging to one of the three TNs. S_N and S_E stand for the number of airport and route duplicates in a TN with other member airlines out of the total alliance nodes and edges. All non-shared nodes and edges of an airline, i.e., all airports and routes not operated by any other alliance member, disappear from the TN if this airline leaves the alliance. For ALL, S_N and S_E stand for all duplicates among its members out of the total alliance nodes and edges. 39.0% of all 1,207 weekly scheduled airports operated by Star Alliance in September 2016 are duplicates, 33.4% out of 1,058 at SkyTeam and only 27.3% out of 942 at oneworld. oneworld has the lowest S_E percentage with 2.6%, while S_E percentages for Star Alliance and SkyTeam are 5.8% and 9.0%, respectively. S_N and S_E for ALL are the lowest for oneworld which are network properties that contribute to the higher vulnerability of oneworld measured by D_{member} in comparison to the more robust alliance networks. Similarly, the total TN edge-to-node ratio of oneworld is 2.9 (2,734 edges divided by 942 nodes) which is considerably below the ratio of 3.7 and 3.6 for the two other global airline alliances.

Table 2. Member properties of TNs ranked by D_{member} (N: Nodes; E: Edges; S_N: Shared nodes; S_E: Shared edges).

Star Alliance	N	E	S_N %	S_E %	**SkyTeam**	N	E	S_N %	S_E %	**oneworld**	N	E	S_N %	S_E %
UA	337	845	43.6	5.4	DL	328	833	31.4	2.4	AA	340	932	29.1	2.8
TK	277	423	71.1	4.0	CZ	196	646	79.6	34.1	AB	103	281	75.7	1.1
CA	180	405	68.9	17.3	MU	206	633	74.8	31.1	BA	213	267	83.6	8.2
AC	189	327	66.1	6.4	SU	143	235	59.4	5.5	QR	150	151	74.7	3.3
LH	200	297	94.0	17.2	AF	165	194	79.4	10.8	IB	125	174	81.6	9.8
ZH	75	236	86.7	16.1	KL	146	153	84.9	15.7	LA	134	271	26.9	7.7
SK	103	193	72.8	10.4	SV	80	185	58.8	3.8	AY	94	94	73.4	3.2
NH	95	187	65.3	14.4	MF	76	211	97.4	44.5	JL	74	124	47.3	8.9
A3	82	140	95.1	12.1	AZ	91	129	78.0	10.9	S7	100	134	34.0	0.7
AI	87	163	50.6	6.7	KE	114	140	92.1	27.9	QF	79	135	31.6	6.7
OS	112	123	86.6	12.2	AM	84	128	56.0	3.1	CX	56	62	96.4	21.0
LX	99	119	96.0	16.8	VN	51	101	70.6	10.9	MH	69	103	50.7	4.9
AV	83	149	65.1	9.4	UX	53	92	71.7	4.3	RJ	49	50	93.9	10.0
ET	100	120	79.0	13.3	CI	68	84	92.6	23.8	UL	29	29	93.1	13.8
SN	92	98	89.1	13.3	KQ	54	74	64.8	9.5	**ALL**	**942**	**2,734**	**27.3**	**2.6**
TP	81	93	81.5	8.6	OK	47	51	87.2	13.7					
OZ	85	96	85.9	20.8	RO	40	45	80.0	8.9					
CM	74	87	87.8	16.1	GA	79	144	25.3	8.3					
MS	68	80	89.7	10.0	ME	32	33	84.4	12.1					
SA	72	105	50.0	6.7	AR	59	109	30.5	3.7					
LO	63	63	96.8	15.9	**ALL**	**1,058**	**3,839**	**33.4**	**9.0**					
BR	52	59	96.2	16.9										
TG	61	64	95.1	25.0										
SQ	60	61	98.3	32.8										
OU	35	56	94.3	19.6										
JP	37	46	91.9	8.7										
NZ	50	85	40.0	3.5										
O6	24	54	37.5	0.0										
ALL	**1,207**	**4,507**	**39.0**	**5.8**										

The exit of the respective US member airline would have the biggest impact on the TN of all three alliances, because many routes offered by the US carriers are not operated by any other alliance member. For example, Delta Air Lines (DL) only operates S_E=2.4% overlapping routes and a relatively small percentage S_N=31.4% of airport duplicates with other member airlines from SkyTeam. Clearly, this is due to the large domestic network offered by the US carriers.

Codesharing enhances the commercial significance of airports and scheduled routes in global airline alliance networks. Table 3 allows for a comparison of member properties between CNs and TNs. It contains the rank difference of each carrier's contribution to the network vulnerability measured by D_{member} between the respective TN and CN, a positive (negative) value for the difference TN minus CN indicating that a carrier's contribution is higher (lower) for CN than TN. Table 3 also shows the number of nodes N and edges E linked with codesharing for each carrier and for ALL as well as the node and edge ratio between CN and TN.

Table 3. Member properties of CNs ranked by D_{member}
(Rank Δ: Rank difference to TN; N: Nodes; E: Edges; CN_N: Node ratio to TN; CN_E: Edge ratio to TN).

Star Alliance	Rank Δ	N	E	CN_N %	CN_E %	Sky Team	Rank Δ	N	E	CN_N %	CN_E %	oneworld	Rank Δ	N	E	CN_N %	CN_E %
UA	0	233	594	69.1	70.3	DL	0	263	667	80.2	80.1	AA	0	223	477	65.6	51.2
CA	1	143	333	79.4	82.2	CZ	0	128	351	65.3	54.3	BA	1	153	180	71.8	67.4
LH	2	170	248	85.0	83.5	KL	3	135	139	92.5	90.8	IB	2	103	113	82.4	64.9
ZH	2	72	216	96.0	91.5	AF	1	149	167	90.3	86.1	JL	4	59	74	79.7	59.7
AC	-1	117	192	61.9	58.7	MU	-2	103	233	50.0	36.8	AB	-3	40	69	38.8	24.6
NH	2	68	106	71.6	56.7	MF	2	66	187	86.8	88.6	LA	0	68	93	50.7	34.3
TK	-5	88	89	31.8	21.0	AZ	2	71	89	78.0	69.0	QR	-3	54	53	36.0	35.1
SQ	16	50	51	83.3	83.6	KE	2	70	74	61.4	52.9	AY	-1	55	55	58.5	58.5
SK	-2	54	81	52.4	42.0	AM	2	68	87	81.0	68.0	QF	1	27	44	34.2	32.6
LX	2	62	73	62.6	61.3	SU	-6	60	67	42.0	28.5	RJ	3	19	19	38.8	38.0
OS	0	64	69	57.1	56.1	UX	2	28	30	52.8	32.6	CX	0	34	37	60.7	59.7
SN	3	68	73	73.9	74.5	CI	2	32	34	47.1	40.5	MH	0	26	26	37.7	25.2
NZ	14	42	64	84.0	75.3	OK	3	32	32	68.1	62.7	UL	1	10	9	34.5	31.0
OZ	3	51	55	60.0	57.3	KQ	1	38	52	70.4	70.3	S7	-5	38	37	38.0	27.6
TP	1	28	32	34.6	34.4	VN	-3	19	30	37.3	29.7	**ALL**	**0**	**522**	**1,234**	**55.4**	**45.1**
ET	-2	52	58	52.0	48.3	GA	2	23	31	29.1	21.5						
AV	-4	44	57	53.0	38.3	AR	3	16	22	27.1	20.2						
A3	-9	28	33	34.1	23.6	SV	-11	12	16	15.0	8.6						
TG	4	40	40	65.6	62.5	RO	-2	22	23	55.0	51.1						
CM	-2	35	36	47.3	41.4	ME	-1	8	7	25.0	21.2						
OU	4	21	33	60.0	58.9	**ALL**	**0**	**736**	**2,086**	**69.6**	**54.3**						
AI	-12	24	35	27.6	21.5												
MS	-4	29	29	42.6	36.3												
LO	-3	29	28	46.0	44.4												
BR	-3	22	24	42.3	40.7												
JP	0	18	20	48.6	43.5												
SA	-7	20	20	27.8	19.0												
O6	0	16	17	66.7	31.5												
ALL	**0**	**740**	**2,508**	**61.3**	**55.6**												

Table 3 contains some pronounced rank differences between CN and TN. In the Star Alliance network, notable upward movers are Singapore Airline (SQ) and Air New Zealand (NZ). In contrast, Turkish Airlines (TK), South African Airways (SA), Aegean Airlines (A3), and Air India (AI) lose ranks. Considering the smaller total number of 20 member airlines of Skyteam in comparison to the 28 members of Star Alliance, the rank losses of Aeroflot (SU) and in particular Saudi Arabian Airlines (SV) are striking. In the oneworld network, S7 Airlines (S7) forfeits many ranks. The mentioned airlines with rank losses tend to be more recent accessions to the respective alliances.

The exclusion of non-codeshared routes brings down the size of CNs compared to TNs. This also holds for the number of airports as some are served without codesharing. The ALL values for CN_N and CN_E of oneworld are considerably below the respective values of the other two alliances. The different percentages of codeshared airports and routes among global airline alliances essentially result from varying member strategies on virtual network extension by codesharing. Within Star Alliance, CN_N and CN_E values of three carriers exceed 80%, i.e. more than 4 out of 5 airports and routes operated have at least one codesharing arrangement. Besides Lufthansa (LH) and Singapore Airlines (SQ), Shenzhen Airlines (SZ) is also highly active in promoting their operations with codesharing. Actually, SZ features the highest overall CN to TN ratios (CN_N = 96.0%, CN_E = 91.5%). Skyteam has the largest gap between the most and the least active operating carrier allowing for codesharing with at least one other alliance partner; KLM-Royal Dutch Airlines (KL) with CN_N = 92.5% and CN_E = 90.8 in contrast to Saudi Arabian Airlines (SV) with CN_N = 15.0% and CN_E = 8.6%.

4. DISCUSSION

The normalized average edge betweenness for the CN of oneworld is larger than the respective ALL-values for SkyTeam and Star Alliance. Hence, oneworld's CN is more vulnerable to member exits than the other two CNs. This is reflected by the average D_{member} values (Star Alliance 0.061, SkyTeam 0.082, and 0.139 for oneworld) and also the maximum D_{member} values (Star Alliance 0.403, SkyTeam 0.575, and 0.956 for oneworld). Intuitively, one might ascribe this difference in vulnerability to the different percentages of shared nodes S_N among all nodes. For TN, 39.0% of all 1,207 weekly scheduled airports operated by Star Alliance in September 2016 are duplicates, 33.4% out of 1,058 at SkyTeam and only 27.3% out of 942 at oneworld (see Table 2). This suggests higher average D_{member} values for oneworld. Likewise, low percentages of shared edges S_E increase D_{member} indicating higher vulnerability. oneworld has the lowest S_E percentage with 2.6%, while S_E percentages for Star Alliance and SkyTeam are 5.8% and 9.0% respectively.

The total number of airports and routes offered by a member airline also affects its share in the network vulnerability. Alliance members operating larger networks with many routes and airports tend to also have higher D_{member} values which is intuitively plausible. However, there is no one-to-one relation between the total number of nodes or edges and D_{member} values. Table 3 shows the rank difference of each carrier as an alliance member between the respective CN and TN. A positive (negative) value of the difference TN minus CN indicates that a carrier's contribution to network vulnerability is higher (lower) for CN than for TN. For example, Rank $\Delta = 3$ for Air Berlin (AB) indicates that AB is lesser important for the vulnerability of oneworld's CN than TN. Looking at the TN only might lead to wrong conclusions about the potential impact of an exit of a carrier like AB on the airline grouping. AB operates many routes that seem to have little commercial relevance for other oneworld members as three out of four routes operated by AB are without codesharing. Hence, the exit of AB which actually ceased operations on October 28, 2017 after filing for bankruptcy is less relevant for oneworld considering codesharing routes instead of operated routes.

For all three alliances the exit of the US member airline (UA, DL, or AA) would have the biggest impact on the TN and the CN. This is illustrated in Figure 2 showing the CN of oneworld with and without AA. An exit of AA would drastically reduce the number of codeshared airports and routes of oneworld in the US. Due to the loss of international routes operated by AA with codesharing by at least another alliance member, the CN of oneworld would also become thinner between the US and other parts of the world, for example, across the North Atlantic.

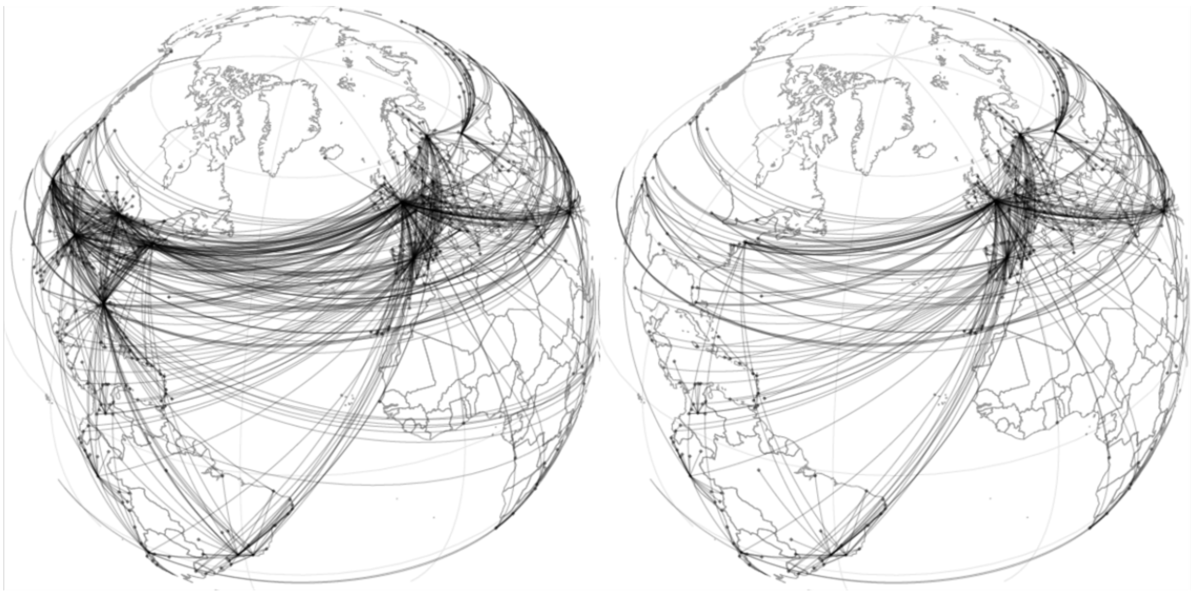

Fig. 2. CN of oneworld with and without AA.

The US member airlines are also the largest carriers within each alliance based on available seat kilometres (ASKs). However, the size of a carrier's scheduled operation measured by ASKs is not strictly related to the carrier's importance for the network robustness. For example, measured by D_{member} for TN, Air Berlin (AB) is more important than British Airways (BA) for oneworld. When it comes to the number of operated routes, AB operates 281 routes, BA 267 routes. Obviously, comparing just these two numbers can be misleading as they do not account for essential capacity parameters such as frequencies and aircraft sizes. However, that AB operates 278 of its routes exclusively, i.e., without route overlaps with other oneworld members, while the number of non-shared routes of BA is only 245 partially explains the higher D_{member} for TN of AB in comparison with BA. Similarly, D_{member} values for China Eastern (MU) and China Southern Airlines (CZ) for Skyteam's route network are larger than the value for Air France (AF) despite of lower ASKs.

In general, airlines adding additional airport duplicates and route overlaps reduce global airline alliance network vulnerability and, hence, strengthen network robustness. For instance, scheduled services operated by Aegean Airlines (A3) include slightly less nodes and edges than Avianca (AV) but more alliance duplicates and overlaps leading to a higher D_{member} of A3 in the TN of Star Alliance. However, there is a reversal in the D_{member} ranking for the CN as the codesharing node and edge ratios of A3 are below the ones of AV. As a result, AV is more important for the CN vulnerability of Star Alliance. The opposite D_{member} rankings of A3 and AV despite of similar number of served airports and operated routes exemplify the complexity of analysing global airline alliance networks.

Table 4 shows how Star Alliance, SkyTeam and oneworld cover different region groups as distinguished in the OAG airline schedules database, Australia and New Zealand belonging to the Southwest Pacific (SW) region. A regional network is defined by domestic routes and cross-border routes within a given region. Interregional refer to routes between two regions. Adding airports and routes across regions leads to the global network (ALL).

Table 4. Regional and interregional sub-networks of global airline alliances.

Region	**Star Alliance**				**SkyTeam**				**oneworld**			
	N	E	S_N %	S_E %	N	E	S_N %	S_E %	N	E	S_N %	S_E %
Africa (AF)	135	222	40.0	5.4	64	74	46.9	4.1	38	14	28.9	7.1
Asia (AS)	289	1,006	41.2	8.7	367	1,548	42.5	17.6	173	285	22.0	3.9
Europe (EU)	288	1,189	51.4	5.7	206	546	41.3	3.8	225	674	48.4	1.8
Latin America (LA)	142	233	43.0	5.6	141	206	24.8	1.0	180	247	23.9	1.2
Middle East (ME)	31	4	61.3	0.0	39	101	33.3	3.0	31	45	61.3	4.4
North Atlantic (NA)	275	840	21.8	1.5	230	652	11.3	0.0	231	730	12.6	0.3
Southwest Pacific (SW)	47	83	21.3	0.0	11	2	72.7	0.0	64	110	12.5	1.8
Interregional	--	930	--	7.1	--	710	--	6.1	--	629	--	6.2
ALL	**1,207**	**4,507**	**39.0**	**5.8**	**1,058**	**3,839**	**33.4**	**9.0**	**942**	**2,734**	**27.3**	**2.6**

All three alliance networks are thinner in the southern hemisphere than in the northern hemisphere. Star Alliance has a relatively large African network due to its members Ethiopian Airlines (ET) and South African Airways (SA). The loss of one of these two carriers would be difficult to replace for Star Alliance. The same would be true for Avianca (AV) and Copa Airlines (CM) in Latin America, and even more for Air New Zealand (NZ) in the Southwest Pacific region.

D_{member} values are normalized against the average edge betweenness b(G) of the graph G, i.e., the entire network and not the most important airline of a network or of all three networks. The average D_{member} values for Star Alliance and SkyTeam are smaller than for oneworld because oneworld has a more balanced membership, i.e., relatively less dominant airlines with many routes offered by no other member airline and also fewer small airlines relative to the largest airline in the alliance. Furthermore, all else equal the larger the number of member airlines the smaller is the average D_{member} value of an alliance. Hence, it is not surprising that oneworld with the smallest number of members is more vulnerable to member exits than Star Alliance and SkyTeam. Similarly, this also contributes to AA's D_{member} being larger than UA's despite AA being smaller than UA when the carrier size is measured by ASKs.

CNs are sub-networks of TNs, but they are also multilayer networks consisting of individual airline networks with route overlaps. A removal of route overlaps reduces the structural redundancy of the different layers and a CN becomes more vulnerable. A member airline having many route overlaps with other members reduces the overall network vulnerability but also increases intra-alliance competition which might lead to negative consequences such as lower average fare levels. This is also a crucial issue for airline alliances when selecting new members. De Domenico et al. (2015) introduced a method based on quantum theory to identify redundant layers. An empirical application to unimodal transportation networks having functionally similar interaction layers did not substantially reduce the original structure as these networks purposely avoid layer redundancy (De Domenico et al., 2015). This in accordance with Lordan et al. (2014a) that member selection of global airline alliances is influenced by the route potential, i.e., preferred new partners offer complementary routes not operated by an alliance before.

Comparing CN with TN leads to variations in the individual carrier D_{member} ranking. The CNs considered in the present paper consist of scheduled services with at least one codesharing agreement giving the weight “1” to all codeshared routes and “0” to all non-codeshared routes. In practice, multiple codesharing is quite common. For example, UA operates scheduled services between Chicago (ORD) and Los Angeles (LAX) codesharing with five member airlines (CA, LH, AC, NH, SK) of Star Alliance but also with non-aligned Aer Lingus (EI). Routes with multiple codesharing might be considered more important for an airline alliance than routes with single codesharing and, hence, might also get bigger weightings in CNs.

While our paper focuses on the (potential) damage to the CN of a global airline alliance due to a member exit, our findings may also contribute to a better risk assessment of the short-term impact on a CN if a member airline is temporarily grounded (e.g. the BA shutdown due to a major IT systems failure on May 27, 2017) which also implies a decrease in CN coverage. In this respect, there is a link with the research of Voltes-Dorta et al. (2017) who measured the vulnerability of European air transport to major airport closures.

A member exit removes nonstop services from a global airline alliance network. However, our anal-ysis of CN vulnerability is primarily concerned with lost offline connections between airlines at connecting points based on codesharing agreements. From the perspective of the other alli-ance members, the commercial problem of a member exit is the elimination of offline con-necting services from the CN. This raises the question of the extent to which compensation is possible with other offline connections and also online connections. That an airline may be forced to rethink connecting points due to an alliance member exit relates our work to research on competition for connecting traffic (e.g. Lieshout et al. (2016), Grosche et al. (2017)) which evaluates travel alternatives according to their quality considering total travel time.

5. CONCLUSIONS

How to assess the impact of a (potential) exit of a member airline is a critical issue for the managing bodies of global airline alliances. We proposed to study the vulnerability of global alliance with a graph theory approach based on topological network properties.

Applying the vulnerability measure to the flight schedules of Star Alliance, SkyTeam and oneworld shows that oneworld is the most vulnerable global alliance, followed by SkyTeam and then Star Alliance. Further, the size of a carrier’s scheduled operation is not strictly related to the carrier’s importance for the network robustness. However, the exit of the large US carriers United Airlines (UA), Delta Air Lines (DL) and American Airlines (AA) would have the biggest impact on of the respective airline grouping as there are many routes offered by these American carriers not operated by any other alliance member. In early 2016, Qatar Airways questioned the company's oneworld alliance membership as a consequence of the dispute between US and Gulf carriers over government subsidies. Based on our analysis such a move by the carrier would have a limited negative impact on oneworld’s network as Qatar Airways has only the seventh largest member share of all 14 members in the overall codesharing network (CN) vulnerability of this alliance. Similarly, the recent exit of Air Berlin (AB) which ceased operations after filing for bankruptcy becomes less relevant for oneworld considering codesharing routes instead of operated routes.

A CN consist of all routes operated by one member airline of a global alliance that also has codesharing (i.e. a marketing flight number) by another carrier from the respective alliance. Our paper related the findings for CNs with the total network (TN), i.e. the unweighted alliance network of all operated routes. Codesharing as an indicator for route relevance from the perspective of partner airlines immediately translates into a basic weighting scheme which assigns the weight “1” to all codeshared routes and “0” to all non-codeshared routes. A refinement of the weighting scheme considering frequency, seat capacity or distance might be a way to further increase the practical meaning of the proposed vulnerability measures. It could also be interesting to assess the reverse of a member exit: What happens in terms of reduced network vulnerability if a given airline joins an alliance? Future work might investigate the optimal robustness of an airline alliance route network, i.e., the trade-off between network vulnerability and overlapping networks, which should be of interest to airline managers. Similarly, it might be valuable to combine the proposed vulnerability analysis of airline alliance networks in a more comprehensive approach with related concepts such as hubness. The vulnerability analysis might also be expanded to consider connecting flights in addition to non-stop flights which requires a methodology for connection building with parameters such as minimum or maximum connecting times. A related problem to measuring vulnerability is how to build a robust route network with appropriate partner selection. This paper did not measure a new member’s contribution to the robustness of an alliance route network. In practical terms, optimization of alliance composition should be assessed with available candidates.

Appendix A. Alliances and member airlines

ALL	Star Alliance	ALL	SkyTeam	ALL	Oneworld
A3	Aegean Airlines	AF	Air France	AA	American Airlines
AC	Air Canada	AM	Aeromexico	AB	Air Berlin
AI	Air India	AR	Aerolineas Argentinas	AY	Finnair
AV	Avianca	AZ	Alitalia	BA	British Airways
BR	EVA Airways	CI	China Airlines	CX	Cathay Pacific Airways
CA	Air China	CZ	China Southern Airlines	IB	Iberia
CM	Copa Airlines	DL	Delta Air Lines	JL	Japan Airlines
ET	Ethiopian Airlines	GA	Garuda Indonesia	LA	LATAM Airlines
JP	Adria Airways	KE	Korean Air	MH	Malaysia Airlines
LH	Lufthansa German Airlines	KL	KLM-Royal Dutch Airlines	QF	Qantas Airways
LO	LOT - Polish Airlines	KQ	Kenya Airways	QR	Qatar Airways
LX	Swiss	ME	Middle East Airlines	RJ	Royal Jordanian
MS	Egyptair	MF	Xiamen Airlines Company	S7	S7 Airlines
NH	All Nippon Airways	MU	China Eastern Airlines	UL	Srilankan Airlines
NZ	Air New Zealand	OK	Czech Airlines		
O6	Avianca Brazil	RO	Tarom		
OS	Austrian Airlines	SU	Aeroflot Russian Airlines		
OU	Croatia Airlines	SV	Saudi Arabian Airlines		
OZ	Asiana Airlines	UX	Air Europa		
SA	South African Airways	VN	Vietnam Airlines		
SK	SAS Scandinavian Airlines				
SN	Brussels Airlines				
SQ	Singapore Airlines				
TG	Thai Airways International				
TK	Turkish Airlines				
TP	TAP Portugal				
UA	United Airlines				
ZH	Shenzhen Airlines				

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