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Invited Research Paper

Optimality of the hub-spoke system: A review of the literature, and directions for future research

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ABSTRACT

This paper reviews the relevant literature to answer the question if hub-spoke networks are optimal from an economic and environmental aspect. Hub-spoke networks are used to serve a large number of destinations with a high frequency. The concentration of flights and demand leads to positive economic effects: additional indirect effects come from the high number of destinations. Airlines may prefer indirect passengers over direct passengers, at the expense of local welfare, if the willingness-to-pay of the former is higher. Furthermore, indirect effects are a redistribution of the direct effect, and may lead to double counting.

Empirical evidence on environmental performance is mixed. Some case studies suggest hub-spoke networks are more harmful, given aircraft technologies and load factors. Proposed climate policies increase costs of operations, likely leading to a strengthening of the hub-spoke system. Further research into network development and the effect of climate policy on airline behaviour is necessary to support climate and aviation policy.

1. Introduction

Airport congestion is a problem at many (hub) airports. Eurocontrol (2013, 2018) and (2018) report a mismatch between future growth in demand and current and projected airport capacity in a number of countries. This is caused by i) growth in general demand; and ii) hubbing activities, which lead to a concentration of demand at specific airports. Since hub airports are more likely to face capacity limitations, and therefore need or want to grow, this paper discusses the literature on (positive) economic effects and negative environmental effects to determine if hubs should (be allowed to) grow further.

Two network structures are commonly used in the aviation sector: hub-spoke (HS) networks and point-to-point (P2P) networks. HS networks emerged after the deregulation of aviation markets in the late 1970s (Brueckner and Zhang, 2001; Nero, 1996), and the ensuing formation of airline alliances lead to further concentration of passengers on a relatively small number of airports. Already in 1997 Amsterdam Airport Schiphol had the expectation that only four major hubs would remain in Europe (Amsterdam Airport Schiphol, 1997). The expectation was that airlines would compete for transfer passengers, and airports and (local) governments would compete for a hub position, because the concentration of passengers at hubs would have positive economic effects. And indeed, we have seen studies confirming positive economic benefits of hubs (Bel and Fageda, 2008; Brueckner, 2003; Button et al., 1999), while increased competition from existing hubs but also from new hubs in e.g. the Middle East (O'Connell, 2011) may have led to the dehubbing of other airports due to the bankruptcy of their hub carrier (Wei et al., 2015; Redondi et al., 2012). Potential dehubbing of airports leads to the fear of loss of economic activity in the region surrounding the airport (Bilotkach et al. (2014)).

P2P networks are mainly used by low cost airlines. These airlines use distinctively different business models, and one of the differences with the business models of hub-spoke airlines is the use of secondary airports. This allows low-cost airlines to reduce turnaround times and therefore increase aircraft usage (see e.g. Doganis, 2006). For local authorities this may be attractive, because low-cost airlines link the region to the rest of the world. Therefore, some local authorities have used incentive schemes to attract low cost airlines to an airport[1]; see e.g. Laurino and Beria (2014) for a case study on Italian airports. However, Budd et al. (2014) report a 77% failure rate of low-cost airlines, and mention route choice and fleet (airline) size as important reasons: small airlines and/or airlines serving small destinations have a higher failure rate. Klophaus et al. (2012) and Daft and Albers (2015) report that a relatively large percentage of low-cost airlines adopted characteristics of

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[1] The literature mainly focuses on tourism effects of low cost airlines, see e.g. Alsumairi and Tsui (2017), Ferrer-Rosell et al. (2016), Farmaki and Papatheodorou (2015) and Chung and Whang (2011).

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full service airlines. For example, Air Berlin offered drinks and meals, and had a frequent flyer program. Ryanair nowadays offers services such as priority boarding and a ticket flexibility scheme, and included main hubs in its network. Dobruzkes et al. (2017) find that low-cost airlines are expanding their service to major airports, thus increasing demand for capacity at hubs.

Demand for capacity at hubs from both legacy carriers and low-cost carriers leads to congestion and/or competition for slots. Hub-spoke airlines want to grow to exploit density economies, low cost airlines need to fly to bigger airports when markets to local airports are saturated or unprofitable, while regional authorities look for the economic benefits of aviation services. While the airline services may be important to a local economy, they are also responsible for significant external effects such as congestion, noise and CO2 emissions. Several policy proposals were implemented to try to reduce external effects. For instance, in Europe, aviation CO2 emissions have been included in the emission trading system (ETS) since 2012, with a limitation to European flights since 2017. ICAO's "Carbon Offsetting and Reduction Scheme for International Aviation (Corsia)" has the objective to stabilize CO2 emissions at 2020 levels. To achieve this, airlines have to monitor and offset emissions by acquiring "eligible emission units generated by projects that reduce emissions in other sectors" (European Commission, n. d.).

From the discussion above we may conclude that there are conflicting interests in aviation policy. Hubs are good for the local economy, so demand may be stimulated, while aviation in general is bad for the environment, so demand may be reduced. One aspect that deserves particular attention is the environmental impact of hub-spoke networks. The impact on the environment remains unclear. Passengers take off twice in HS networks and take a detour, which is bad for the environment. However, airlines use bigger planes, which may be more fuel efficient per passenger at longer distances. The objective of this paper is therefore to discuss the optimality of hub-spoke networks, taking different types of market failure into account. Economies of density make hub-spoke networks optimal from a profit maximizing perspective, while environmental economies of scale, if they exist, may also make the hub-spoke network "optimal" (in the sense of: less polluting). Is the hub-spoke network preferable if we also include environmental and economic effects? In order to answer this question, this paper first discusses hub-spoke networks and economic effects from a purely economic perspective (Section 2 and 3). Then, environmental effects are discussed (Section 4). Finally, Section 5 combines economic and environmental effects. Section 6 concludes.

2. The optimality of hub-spoke networks

This section discusses the optimality of hub-spoke networks. Section 2.1 discusses the most relevant academic papers on hub-spoke networks, while section 2.2 briefly discusses alliance formation. Section 2.3 discusses market concentration, and section 2.4 concludes.

2.1. Hub-spoke networks

Hub-spoke (HS) networks emerged in aviation after the deregulation of the aviation markets in the late 1970s (see e.g. Brueckner and Zhang, 2001; Nero, 1996).[2] Passengers that do not have the hub as a final destination travel via the hub, and this allows airlines to use bigger airplanes, which are cheaper per seat (Brueckner and Spiller, 1994). Concentrating passenger flows on links to and from the hub like this leads to high passenger densities on these links. This leads to relatively low average costs when economies of density are important, making the HS network the profit maximizing network (see e.g. Brueckner and Spiller (1991), Hendricks et al. (1995, 1999), Nero (1996), Wang (2016) and Zhang (1996)).

Part of the literature focuses on economies of density in the variable cost function, assuming a linear marginal cost function (see e.g. Brueckner and Spiller (1991), Nero (1996), Wang (2016) and Zhang (1996)). If fixed costs are included in the analysis, it becomes possible to explain why airlines with relatively high fixed costs (legacy airlines) opt for a HS network, while airlines with relatively low fixed costs (due to outsourcing) opt for point-to-point networks, even though in the latter case density economies (in the variable cost function) may still be important (Pels et al., 2000, 2001). The recently described trend of "network convergence" (Klophaus et al., 2012; Daft and Albers, 2015) may be an indication that low-cost airlines are adopting service characteristics of full-service airlines. If this increases fixed costs, a HS network, or at least a configuration that allows low-cost airlines to offer transfer traffic in its own or a partner's network, may become optimal.

Zhang (1996), using linear marginal cost functions, shows that airlines using HS networks (with different hubs) do not have an incentive to invade each other's local markets. Again, density economies are the main driver, since invasion of the local markets leads the "invaded" airline to increase output in indirect (competitive) markets served using the same links as the "invaded" local markets. In doing so, the "invaded" airline lowers it average cost on the links used to serve the local markets (where it lost market share), and at the same time captures market share from the invading airline on the indirect markets. This increases average costs on all links used in these markets by the invading airline, including the links in its "home network". Because economies of density are strong (see e.g. Brueckner and Spiller, 1994; Zuidberg, 2014), the increased costs in the "home network" likely outweigh the profits from the invaded markets.

2.2. Alliances and price effects of deregulation

Alliance formation is a logical continuation of the development of HS networks. Alliances allow airlines to increase the number of destinations in their network, without increasing the number of flights, and increase passenger density in its home network by channelling passengers from its alliance partner's home network through its hub, and vice versa. This increases load factors and reduces average costs for all alliance partners, again due to economies of density. Although there are obviously conveniences to passengers (more destinations, lower prices (Brueckner and Whalen, 2000)), possible collusion between carriers may also be a reason for concern because competition on routes between the hubs of alliance partners is reduced. For instance, in 1998 British Airways and American Airlines were allowed to form an alliance, provided that they would relinquish 267 slots at London Heathrow and London Gatwick (representing about 5% of the total weekly landings and take-offs (in 1998)). Competitors argued that at least 140 slots were needed to operate a (competitive) route between London and New York. The results of Brueckner and Whalen (2000) suggest that airline alliances and code sharing agreements are socially desirable in most cases. Fare increases in the market between hubs increases due to collusion are insignificant, while fares in interline markets (requiring a transfer and serviced by both airlines) decrease due to cooperative pricing. This increases demand, and due to economies of density, fares can decrease even further.

2.3. Market concentration

Due to the formation of HS networks and airline alliances, as described above, market concentration increased. Despite this concentration, fares have decreased in real terms within a relatively short

[2] Note that there are two networks that are centred around a "main airport": the hub-spoke network and the star network. When we discuss a hub-spoke network, we specifically assume that i) indirect tickets are offered, and ii) transfer times at the hub are minimized. Some low-cost airlines may use a star-like network, but do not offer indirect tickets and short turnaround times. Therefore we do not label them as hub-spoke airlines.

amount of time (Morrison and Winston, 1995). However, the competitive effects were distributed unevenly from a geographical perspective. On long haul, connecting flights, competition has intensified (Kahn, 1988; Grosche and Klophaus, 2015). But prices on spoke routes to the hubs are significantly higher than prices on other routes (Borenstein, 1989; Lijesen et al., 2001). This can be due to the lack of competition between hub-spoke airlines in local markets, as described above (Zhang, 1996). Another reason may be limited capacity at hubs,[3] so that capacity offered by airlines is also relatively scarce. Ticket prices could therefore be relatively high.

Empirical research provides evidence of relatively high prices on routes to and from hubs, and theoretical papers often assume Cournot competition to reflect that hub-spoke airlines have some degree of market power, at least in o-d markets, and are able to charge relatively high prices. More recent empirical research shows that the assumption of Cournot competition may no longer hold in many markets (Fageda, 2006). As explained above in section 2.1, airlines using HS networks are most likely to compete with each other in indirect markets, making such markets very competitive. Low-cost airlines are more-and-more operating markets to the hubs of full-service carriers, often adopting service characteristics of full-service airlines (see e.g. Gudmundsson, 2015).[4] Future research will have to show if this current trend of network convergence persists.

2.4. Conclusion

As described above, market concentration so far is the result of HS network and alliance formation. So ultimately market concentration results of economies of density, mostly due to the presence of fixed costs. Low-cost airlines have lower fixed costs, which allows them to use different, point-to-point strategies, allowing such airlines to compete with hub carriers on routes to and from hubs. Newer aircraft and strategy convergence may lead to a different cost picture for airlines currently using a HS network, but evidence from low-cost airlines shows that operations from secondary airports all too often are abandoned in favour of more profitable markets from larger airports. In doing so, low-cost airlines often adopt some characteristics from full-service airlines. Therefore, we conjecture that concentration of supply at hubs will remain, simply because these airports have enough demand to support a profitable level of aviation services. The next section will focus on the economic benefits of hubs.

3. Economic effects of hub-spoke networks

The previous section concluded that concentration of supply at hubs is likely to remain in the future. This section discusses the economic benefits of aviation, focussing on hubs. First, section 3.1. Discusses the most relevant academic papers, with a focus on hub-spoke networks. As mentioned above, the HS network means that demand is concentrated on specific airports (hubs), and, also as discussed above, we conjecture that this level of concentration will not decrease any time soon. Then, section 3.2 discusses some industry reports reporting indirect and other effects of aviation, and provides a theoretical perspective on the measurement of indirect effects. Section 3.3 concludes.

3.1. Effects on jobs and GDP: fear for economic effects of losing hub position

Using data for 1996 for the US and controlling for reversed causality, Brueckner (2003) finds that good airline services attract new firms to U. S. cities. Similarly, Bel and Fageda (2008), using European data, find that the availability of direct intercontinental flights is an important determinant of multinational headquarters' location. Brueckner (2003) reports a significant employment effect in the service sector, whereas airline services are less important for manufacturing firms. A similar effect is reported by Button and Taylor (2000): the availability of international air services from the US to the EU has a strong impact on economic activities in areas surrounding the airports, attracting or internally generating new economy employment. Both the number of destinations served and the frequency of service are important. This effect does not exist in cities without good air services. Furthermore, Button and Taylor (2000) report that the effect is not infinite: the benefits increase less than proportional with air services.

There are many more studies on the relation between aviation and the economy. Without going through them all, we summarize a lot of the research using a citation from Bell and Fageda (2008), who confirm the importance of international/intercontinental air services for "tacit information exchanges between cities for firm location".

Airlines using hub-spoke networks offer relatively high frequencies to/from the hub (Brueckner and Zhang, 2001), and relatively small airlines, operating out of relatively small cities, are only able to offer a large number of international/intercontinental destinations with high frequencies because the hub-spoke network allows them to exploit density economies. Alliance formation allows for further exploitation of density economies, while increased competition puts pressure on all airlines, and has caused bankruptcy of smaller hub-spoke airlines. These developments can lead to dehubbing (see e.g. Bilotkach et al., 2014), and the loss of a hub position would mean a loss of a large part of the intercontinental flights. The literature discussed above suggests this will have a big impact on the location decision of firms and jobs in the service sector/new economy. Redondi et al. (2012) report that dehubbing is likely to be irreversible, although airports may recover to some extent when low cost carriers replace hub carriers. Redondi et al. (2012) also report that dehubbing has a stronger effect on the number of seats than the number of destinations. Bilotkach (2015) reports that in the U.S., the number of destinations is a more important determinant of local employment and business establishments than traffic volume. So, although dehubbing likely has negative effects, the effects may be less severe if the effect of dehubbing on the number of seats is stronger than the effect on the number of destinations.

3.2. Indirect, induced and catalytic effects

Industry outlets also emphasize the importance of the aviation sector to the global economy. The effects described above are often divided into direct, indirect, induced and catalytic impacts (see e.g. ATAG, 2018), and these impacts are also used in academic papers, see e.g. Donzelli (2010). Direct effects refer to employment effects within the air transport industry itself, whereas indirect effects refer to employment effects in the industries supplying to the air transport industry (ATAG, 2018). Induced impacts cover spending "by those directly or indirectly employed in the air transport sector" ATAG (2018), while catalytic effects measure the effects on other industries. The general idea is that direct, indirect and induced effects originate from aviation industry revenues, whereas catalytic effects are effects elsewhere in the economy. The catalytic effects are mentioned by ATAG (2012) to be the "most far reaching economic contribution", although these effects are difficult to measure. Table 1 provides numbers for the global GDP impact of aviation in 2016, derived from ICAO (2019).

While both the academic literature and industry outlets emphasize the importance of aviation for the economy, the use of indirect, induced

[3] Eurocontrol reported in 2013 that by 2035 12% of air travel demand cannot accommodated due to a lack of capacity at hub (major transfer) airports (Eurocontrol, 2013, 2018). Since 2013, demand has grown further, while airport capacity still is scarce. Eurocontrol (2013) finds that there still is a mismatch between capacity and expected demand, especially in Turkey, Germany, France and UK.

[4] Most low-cost airlines use point-to-point networks, and can therefore enter "local" markets without the repercussions in any indirect markets as discussed in Section 2.1 for airlines using HS networks.

Table 1
Global GDP impact of aviation, 2016.

	billion US$	%	index, direct = 100
catalytic	896.9	33	127
induced	454.0	17	64
indirect	673.8	25	96
direct	704.4	26	100
total	2729.1	100	387

Source: ICAO, 2019.

and catalytic effects may be problematic for various reasons. Firstly, and as mentioned above, direct, indirect, induced and catalytic effects are all related to the revenues of the aviation industry (ATAG, 2005). It is the spending of a benefit that leads to a benefit elsewhere in the economy. If only benefits are counted, and not costs (expenditures), there is the risk of double counting. Rouwendal (2012) makes a distinction between direct effects (effects for the direct user) and indirect effects (effects elsewhere in the economy through the spending of the direct effect, so including induced and catalytic effects). If the spending of the direct effect leads to effects elsewhere that exceed the direct effect, it is the difference between these effects, the *additional* indirect effect, that must be included in the project evaluation. Secondly, if this difference is not equal to zero, this is an indication that there is some form of market failure. Rouwendal (2012) argues that in a full competition, an increase in profits or benefits for e.g. an airline, resulting from an input price change[5], has to be passed on to the final consumer: the direct effect equals the indirect effect. If this does not occur, there is market failure, and the direct effect will be different from the indirect effect. This is e.g. the case for a monopoly market or when there are scale (density) economies.

Rouwendal (2012) assumes a monopolist (or a firm operating under monopolistic competition) produces a single good and is able to set the price to maximize profits. A change in the input price leads to change in the area under the firm's demand curve for the input: the direct effect. In full competition these cost savings are passed on to the final consumer. But under other market conditions, a change in the input price leads to change in demand for the input and a change in the output price. Therefore, the total welfare effect of the input price change, labelled as the total indirect effect by Rouwendal (2012), is the change in consumer surplus (ΔCS) plus the change in profits. The additional indirect effect is the total indirect effect minus the direct effect, and Rouwendal (2012) shows this additional indirect effect is nonnegative when the output price differs from the marginal cost: a lower input price results in a lower output price and increased output, as would a subsidy to increase output and welfare. Furthermore, the additional indirect effect equals the change in consumer surplus with linear demand and constant marginal cost, and is related to consumer surplus in more general cases. Table 2 gives the specific result on the additional indirect effect derived by Rouwendal (2012) for specific cases.

If demand is linear and marginal costs are constant, the additional indirect effect is 50% of the direct effect. This stands to reason, because the output price change is determined from the inverse demand function, while the input price change (and thus change in marginal costs) leads to a different monopoly output, determined by the equality of marginal costs and marginal revenues, which is twice as steep as inverse demand. If scale effects exist, the additional indirect effect is smaller due to the effect of fixed costs.

With log linear demand, the size of the additional indirect effect depends on the price elasticity of demand of the final good. If the price elasticity is larger than 1, but close to 1, the indirect effect can be relatively large. But for larger values the indirect effect quickly

Table 2
Additional indirect effect under different assumptions.[a] ε is the absolute value of the price elasticity of demand.

Market structure	Demand function	Cost function	Additional indirect effect
Monopoly	Linear	No scale effects	50% of direct effect
Monopoly	Linear	Linear with fixed costs	up to 50% of direct effect
Monopoly	Log linear	Linear with fixed costs	ε/(ε-1)*direct effect
Monopolistic competition	Symmetric aggregate demand	Linear with fixed costs	< ΣCS, and positive (demand downward sloping in all prices) or negative (demand downward sloping only in own price)

[a] Both in monopoly and monopolistic competition the demand function is downward sloping in the (own) price, and there is a mark-up over marginal costs. In monopolistic competition the number of firms is given.
Source: Rouwendal (2012).

approaches the direct effect in size. A back-of-the-envelope calculation shows that the catalytic, induced and indirect together (from Table 1) are 2.87 times as large as the direct effect. This would correspond to a price elasticity of about 1.534, which is a bit higher than the average point elasticity of 1.21 reported by Brons et al. (2002). Note that this by no means a validation of the ICAO-results provided in Table 1. Rouwendal (2012) assumes firm specific demand functions derived from consumer surplus by taking the derivative with respect to the firm's price, and then the indirect effect is positive only if demand is decreasing in all firm's prices. So additional empirical research is necessary to confirm: i) the elasticity of demand for the markets under consideration; and ii) the demand structure. Only then can the results in Table 1 be validated. If demand is more elastic, or if demand is better characterized by linear demand or monopolistic competition, then the estimates in Table 1 may very well be too high, given the theoretical findings in Table 2. In fact, the indirect effect may even be negative. For this to occur markets are in monopolistic competition, and the demand curve of a specific firm is not downward sloping for all price changes of all firms simultaneously.

3.3. Conclusion

There is plenty of evidence that aviation contributes to economic prosperity in terms of e.g. the number of high-tech jobs created. In order to evaluate the contribution to the economy and the result on the necessary investment, project appraisal is used. However, the use of indirect effects (and other effects resulting from indirect effects) may result in double counting if only benefits and not costs are counted. In fact, from a theoretical perspective there are good arguments to support an upper boundary to the indirect effects. Only for the case of log linear demand and demand elasticities close to 1 (in absolute value) can we expect high indirect effects. In all other cases, values are reported by industry outlets seem to be on the high side.

Finally, Button and Taylor (2000) report decreasing marginal benefits of international services. This suggests there may be a natural limit to growth, and for sure smaller hubs benefit more from additional services than larger hubs.

4. Negative effects of aviation

Section 2 discussed the optimality of hub-spoke networks, focussing on airline operations, and Section 3 discussed the positive economic effects. This Section discusses negative effects of aviation, again with a focus on hub-spoke networks. Section 4.1 discusses airport congestion, while Section 4.2 discusses environmental effects of aviation. Section 4.3 concludes.

[5] In the example of Rouwendal (2012) an investment makes an input cheaper. E.g. an investment in airport capacity makes airport capacity less scarce.

4.1. Airport congestion

Airport congestion is a problem at many (hub) airports, see e.g. Santos and Robin (2010), and Eurocontrol (2013, 2018) for an evaluation of airport capacity in Europe. As mentioned above, future growth in demand can hardly be accommodated with current and projected airport capacity in Europe. Other parts of the world show higher (expected) growth numbers.

Hubs usually are located at primary airports that generate a relatively large amount of o-d traffic.[6] In hub-spoke networks, frequencies are relatively high (Brueckner and Zhang, 2001), and for competitive reasons, airlines want to schedule flights close together (Givoni and Rietveld, 2009).

As greater numbers of (hub) airports encounter capacity constraints (physical or environmental), allocation of scarce capacity becomes an important issue. Congested airports usually have slot controls and/or peak charges to deal with congestion.[7] Doganis (2006) mentions a few advantages of slot controls. It is internationally integrated and accepted by most carriers. The system is not disruptive and there are no sudden changes from year to year because of grandfather rights airlines can "invest" in a network. New entrants can obtain slots at no cost, if available. Finally, there is some flexibility in the system as one-for-one trading of slots is permissible. But these advantages mostly seem to be advantageous for the incumbent airlines. Other allocation mechanisms may also be "stable" in that there may not be sudden changes year to year. Holding onto the current system because it is not disruptive may therefore be a weak argument. In the U.S., there are only a few airports with slot controls. Most airports have "free access", and for these airports congestion pricing is proposed.

The literature on airport congestion pricing is quite extensive. An important result is that the way airlines deal with airport congestion crucially depends on the market structure. In general airlines internalize congestion if they have market power. The degree to which congestion is internalized depends on the degree of market power. In monopoly, all congestion is internalized, in oligopoly only the congestion caused to an airline's own passengers is internalized. If airlines do not have market power, because, for instance, there is a fringe competitor, congestion is not internalized (Brueckner and Van Dender, 2008). See e.g. Zhang and Czerny (2012) for a more extensive review. Zhang and Zhang (2006) extend the literature by including airports in the analysis, and find that private or public airports operating under a budget constraint overinvest in airport capacity if airlines have market power.

These results are relevant for various reasons. Firstly, many airlines use hub-spoke networks, and such networks lead to peak demand at airports. As mentioned above, hub-spoke airlines have little incentive to compete with each other in spoke markets. Secondly, if airlines internalize congestion, demand is relatively low. From a welfare perspective this may be desirable (externalities are included), although the additional indirect effects discussed above likely are lower. In this case airports may invest too much in capacity. Finally, if airlines are competitive, congestion is not internalized and congestion pricing is necessary to maximize welfare, as explained above. The additional indirect effect will likely be absent. While the literature suggests that airline markets in general may be more competitive, the results on congestion pricing depend on the specific competitive effects in specific the markets under consideration.

4.2. Environmental effects

Wolfe et al. (2014) conclude that aviation-induced climate change is more important than aviation noise and effects on air quality together. The costs of noise are incurred locally, Wolfe et al. (2014) report that people living close to the airport (up to 5 km) bear the brunt of the associated noise costs, and the cost of air quality degradation approaches local noise costs if traffic increases at the airport. The cost of climate change is a global problem, and although the impact on local residents and the local economy may be smaller per person compared to noise and air quality costs, Wolfe et al. (2014) conclude that the aggregated cost climate change exceeds the "local" external costs of aviation.[8]

Noise effects are usually countered with airport night flying restrictions and/or noise surcharges, although Morrell and Lu (2000) conclude that the noise surcharges at Amsterdam Airport Schiphol are lower than the social cost of noise. Since 2000 noise surcharges and noise emissions per flight movement may have changed, so new calculations would be necessary to see if this conclusion still holds, but nowadays there is also more emphasis on climate change. In Europe CO2 emissions from the aviation sector have been included in the emission trading system (ETS) since 2012, with a limitation to European flights since 2017. For now, the current European scheme is in place until 2023, allowing for the implementation of a world-wide scheme, starting in 2021. This scheme, ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (Corsia), aims to compensate the growth in CO2 emissions from international flights compared to the base year 2019–2020.

In order to evaluate the usefulness of compensation schemes, or any other way to reduce climate change costs, it is necessary to understand where these costs come from. As mentioned already above, local costs of noise and air quality increase in traffic levels, and traffic levels are particularly large at hub airports. The choice of network type largely depends on economic factors (density economies), as described above, and technical factors (Peeters et al., 2001). But the network choice also has an impact on the environmental impact of the airline. In general, emissions take place in the landing and take-off phase (LTO) phase and in the cruise phase.[9] Fuel burn is relatively high during the take-off phase.[10] In a hub-spoke network, passengers need to take-off twice to reach their final destination. From that perspective, fuel burn per passenger mile is relatively high in a hub-spoke network. However, larger planes are used in hub-spoke networks because of the concentration of passengers on a few links (Brueckner and Zhang, 2001). Givoni and Rietveld (2009) find that aircraft size may be relatively low because airlines tend to increase frequency rather than aircraft size in the face of competition. While hub-spoke airlines may not invade each other's local markets, low-cost airlines are tough competitors, as discussed above. Furthermore, Givoni and Rietveld (2009) find that aircraft size largely depends on route characteristics. Large aircraft are used on large distances, given everything else. Even though total fuel burn may be higher for larger aircraft, the fuel burn per passenger or seat (mile) may be relatively low due to environmental economies of scale. The literature does not yet agree on the existence of environmental economies of scale. If environmental economies of scale are significant, a hub-spoke network, with relatively large aircraft, has a lower environmental

[6] If a hub would be located in a secondary or tertiary airport, the hub-spoke airline would be primarily transporting indirect travellers with a relatively low willingness-to-pay.

[7] Slot controls mean that airlines need a landing or take off slot in order to be able to offer a flight.

[8] There are many other studies on the climate and noise costs of aviation. These will not be discussed in the current paper. Instead, after a short introduction, this section will focus on the environmental effect of hub-spoke networks, rather than climate effects in general.

[9] The LTO phase includes taxiing, take-off, and climbing or approach landing below 3000 feet. The cruise phase includes all operations above 3000 feet.

[10] The amount of fuel needed is proportional to the drag. During the take-off phase the drag is relatively high. At higher altitudes the drag, and thus also the fuel burn, is lower.

impact than a point-to-point network. Peeters et al. (2001) argue that technological improvements to increase fuel efficiency were mainly focused on small body short range aircrafts, and the conclusion was that environmental economies of scale did not exist when hub-spoke networks and low-cost airlines emerged in the last two decades of the 20th century. The introduction of new wide body aircraft like the Boeing 787 and the Airbus A350 may have changed this conclusion. Table 1 summarizes some papers that confirm the existence of environmental economies of scale.

Even though environmental economies of scale may be present (see Table 3), this does not automatically imply that hub-spoke networks are also the preferable option form an environmental point-of-view. Various papers point out that point-to-point networks are preferable; see Table 4 for an overview of a few relevant studies.

One thing these studies have in common is the use of actual aircraft types, routes and emissions in the analysis. O'Kelly (2012) concludes that a fuel-efficient network may require a large number of smaller regional jets, while Baumeister (2017) concludes that regional jets are considerably less fuel efficient than other aircraft (narrow body, wide body or turboprop). Peeters et al. (2001) point out that long haul aircraft had a relatively strong environmental impact because technological development in the preceding decades focused on short to medium haul aircraft. Again, more recent technological progress in long haul aircraft may lead to a different conclusion.[11] It thus seems that in any analysis, the choice of aircraft type and also load factors[12] are major determinants of the results. O'Kelly (2012) already mentions that: "a common complaint about much research in this area is that the evaluation is based on an extracted set of flows or OD pairs".

O'Kelly (2012) also points out that hub-spoke networks are necessary for some airlines due to, amongst other reasons, consolidation. The most efficient aircraft are assigned to the thickest routes, and if this is also a long route, the efficient aircraft cannot be used again in the same day to serve another route. At least in the short run, less efficient aircraft will therefore still be used. Thus, even though the papers mentioned in Table 4 conclude that point-to-point networks are better for the environment than hub-spoke networks, economic motivations may lead to the use of hub-spoke, and also the use of less efficient aircraft.

4.3. Conclusion

This section discussed the external effects of aviation, and hub-spoke networks in general. Many hub airports are congested, due to the fact that the dominant airlines at these airports use hub-spoke networks. The use of hub-spoke networks also means that local pollution is relatively high. Frequencies may be higher and/or larger aircraft may be used to exploit density economies, but as a result, emissions of noise and other pollutants per aircraft movement are relatively high. Consolidation of passengers in large aircraft on long haul routes could give rise to environmental economies of scale and less global pollution per passenger. However, empirical evidence is mixed. The choice of routes and aircraft types in the analysis is important drivers of the result on environmental economies of scale. Therefore, this issue needs to be studied on a case-by-case basis if there is no global policy in place that gives airlines the proper incentives to use the most efficient aircraft in any market.

5. Discussion

5.1. Hub-spoke strategy vs. low cost strategy

HS networks emerged after the deregulation of aviation markets in the late 1970s and allow airlines to exploit density economies. In order to offer relatively high frequencies in a relatively large number of markets to and from the hub, passengers travelling indirectly via the hub (and not to the hub as a destination) are necessary to fill empty seats, or in general, to reduce (fixed) costs per passenger. This argument has been used many times in the literature to explain the use of HS networks. And even though cities in markets served indirectly may be relatively small compared to the hubs (although not necessarily so), such markets may still have passengers with a relatively high willingness-to-pay. For the airline these passengers are interesting for two reasons: they help to bring down average costs, and they may have a higher willingness-to-pay than some of the passengers that have the hub as an origin or destination. Hub-spoke airlines thus are able, but also have to offer a relatively large number of destinations. The high-end of the market is targeted first in each market, and cheaper tickets are offered to fill remaining capacity. This allows the airline to use relatively large aircraft with a low cost per passenger or seat, as discussed in Section 2. For competitive reasons, high frequencies are offered, and this may lead to the use of relatively small aircraft (Givoni and Rietveld, 2009).

For the airport and city accommodating the hub, this system clearly has economic benefits; there is plenty of evidence on the positive effects of having a hub; see Section 3, although the indirect, induced and catalytic effects often reported may be an overestimation of the economic effect (also see Section 3). On a basic, theoretical level, the benefit for the local economy is derived from direct markets: the number of destinations is important. There is the direct effect to the users, and the indirect effect through the spending of the direct effect. The latter may be larger than the former, and this additional indirect effect can be derived from the consumer surplus in each market. If e.g. a capacity increase means that more destinations can be offered, or capacity in each market can be increased, this means that consumer surplus increases, and this may give rise to additional indirect effects. If the increase in consumer surplus form a new market exceeds the increase in consumer surplus in an existing market following a capacity increase, adding the new market may result in a higher positive additional indirect effect.[13],[14] However, the airline may allocate part of the additional capacity to indirect markets, serving passengers with a high willingness-to-pay there. If such passengers do not exist in the new markets, the airline can still choose to reserve part of the additional capacity for indirect passengers with a low willingness-to-pay, rather than accepting more passengers from the markets to and from the hub at lower fares.[15] The only effect that these indirect passengers have on direct markets to/from the hub is that they lower average costs, and as such they may contribute more to airline profits than to consumer surplus in direct markets. This network effect may thus lead to an increase in consumer surplus (and thus additional indirect effects) in direct markets that may be lower than expected. This "problem" is caused by the profit maximizing behaviour of international airlines and the need for concentration: without indirect travellers, many hub-spoke airlines would likely cease to exist. The bankruptcies and mergers we have seen in the last few decades are a strong indication that hub-spoke airlines that have small home markets and find it hard to compete in indirect markets will fail or become part of a larger alliance.

[11] Note that Baumeister (2017) has examples of older aircraft being more efficient, depending on seat configuration. So age is not the only determinant of efficiency.

[12] Francis et al. (2007) report that low cost airlines, using mainly point-to-point networks, on average have higher load factors than airlines using hub-spoke networks.

[13] Given the assumptions/conditions outlined in section 3.

[14] Bilotkach (2015) reports that in the U.S., the number of destinations is a more important determinant of local employment and business establishments than traffic volume.

[15] Some of the passengers that are willing to pay the high fares may find the restrictions on reduced fare tickets acceptable, and go for the lower fares. This lowers profits for the airline, and is undesirable from this perspective.

Table 3
Details on environmental economies of scale (EES) from various studies.

Paper	EES climate costs	EES local costs	EES total costs	Data/location	Method
Grampella et al. (2016)	yes	no		1453 aircraft-engine combinations for 2013, 500 nm flight	OLS, double log, environmental cost as dependent variable
Givoni and Rietveld (2010)	yes	yes (noise) no (pollution)	yes	From aircraft manufacturers; various sources on environmental cost.	calculations; results sensitive to assumptions
Loo et al. (2014)	yes	no (CO2)		Greek airspace, Hong Kong/Sanya airspace, 2010	calculations
Schipper (2004)			yes	156 aircraft types in 36 European interstate markets, 1990	calculations

Table 4
Key studies reporting that hub-spoke networks are more damaging to the environment than point-to-point.

Paper	Result	Method
Morrell and -Y Lu (2000)	Hub by-pass routes are more environmentally friendly compared to hub-spoke operations	Scenario analysis; e.g. market Heathrow to/from San Diego uses B767-300 (direct), or B747-400 to Chicago and A321-200 to San Diego
O'Kelly (2012)	Network with a high degree of connectivity has lowest fuel cost; pure single assignment hub network has the highest fuel cost. Airline may use smaller number of larger planes (and this increase fuel costs) to avoid congestion and noise costs.	minimize fuel burn, given the number of passengers and flight distance, various network configurations
Peeters et al. (2001)	Point-to-point networks have smaller global impact than hub-spoke networks, hub airport has big local impact compared to non-hub airport.	Data used may be biased against larger aircraft, because technological advances were mainly focussed on small to medium sized aircraft at that time. Since 2001, new large aircraft were introduced.
Jamin et al. (2004)	Lower fuel burn (and thus emissions) if connecting flights are replaced by direct flights	Gravity model to predict future U.S. passenger flows; simulation using different scenarios

This leads to concentration of passengers and additional indirect effects on a relatively small number of hubs.

The "new" low cost airlines are able to offer services without relying on indirect travellers. The "spoilage effect" mentioned above therefore is a smaller problem. Additional capacity is not allocated to indirect passengers by the airline, unless the airline acts as a feeder for another airline. For "de-hubbed airports", low cost airlines may be a way to recover because such airlines offer mostly point-to-point traffic to destinations with sufficient demand to sustain operations. Note that Fu et al. (2019), in a case study on Southwest Airlines' network effects, conclude a point-to-point network offers benefits similar to those offered by a HS network. Although the scientific debate on the viability of a long-haul low-cost strategy, which could replace a hub carrier in the intercontinental market if the hub carrier fails, is still on-going, this model is already applied in practice.[16] If long-haul low-cost airlines can be successful without offering transfer traffic, the "spoilage effect" mentioned above will not be an issue.

To summarize the discussion so far, there are positive effects derived from a large number of destinations offered at an airport. But these positive effects may be overestimated if we focus too much on catalytic and induced effects. Furthermore, hub-spoke airlines have an incentive to use the capacity where it generates the highest profits. This means passengers that contribute little the local economy of the hub (other than lowering average cost) may be accommodated. Low cost airlines do not need indirect travellers, and further research (and practical experience) will need to show if the long-haul low-cost strategy is viable and if the hybridization of airline business models will continue. For now, a lot of airlines simply need indirect passengers in order to stay in business.

5.2. Environmental effects

The concentration of flights and passengers at hubs has local negative environmental effects and causes congestion. Furthermore, global environmental effects may exist because indirect travellers take a detour, although the concentration of passengers in long distance markets in large aircraft could also give rise to environmental economies of scale. The empirical evidence is mixed, and largely dependent on the case at hand. Further research, using aircraft with the lowest emissions per passenger or passenger mile and different hubs, will have to show if hub-spoke networks lead to overall lower emissions per passenger. Although the case studies mentioned in Section 4.2 show that this is not always the case, further research, focussing on different network and fleet configurations, is necessary.

From an economic perspective, any external cost should be internalized to maximize welfare. The degree to which congestion is internalized depends on the degree of market power, as discussed in 4.1. Pricing congestion means that passengers with a low willingness-to-pay will no longer fly, thus reducing congestion cost. Pricing environmental damage is necessary to reduce demand and maximize welfare. In both cases, the price for the externality should equal the marginal external costs.

In practice, different approaches are chosen. For instance, Corsia aims to stabilize CO2 emissions at 2019–2020 levels by means of compensation. We will not enter the debate on the optimality of 2019–2020 emission levels, but note that compensation means airlines need to make costs that are likely passed on to passengers. An optimal compensation effort is necessary, and airlines with efficient aircraft will find it easier to compensate. Future research is necessary to determine the optimal compensation effort, and this again includes research in to network configuration and fleet allocation. One important aspect is the take-off vs. cruise phase. Emissions are high during take-off, so compensation needs to be high. But during the cruise phase emissions are relatively low.

5.3. Conclusion

The key difference between the hub-spoke and low-cost business model lies in the way customers are targeted. The original low-cost

[16] We could take the failure of some long-haul low-cost carriers as an indication that the model is not viable. But many low-cost airlines failed over the last two decades, while the economic success of the low-cost model in general is not a topic for discussion.

model offers a single fare, which may change over time, while the hub-spoke model offers different fares to different travel classes. The hub-spoke model offers high frequencies together with e.g. ticket flexibility to attract business travellers. However, fixed costs are relatively high,[17] while Mason (2006) finds that in short haul markets, low-cost carriers offer cheaper ticket flexibility and Mason (2000) reports that travel budgets for business travellers may be under pressure. Increased competition therefore prompted hub-spoke airlines to adopt service characteristics from low-cost airlines, and vice versa. Low cost airlines nowadays have an increased focus on primary airports (Dobruzkes et al., 2017), leading again to concentration at primary airports, especially if low cost airlines also serve as feeders to intercontinental networks (e.g. easyJet offers intercontinental flights in conjunction with Norwegian). Even without a pure hub-spoke airline, a relatively large number of destinations can still be offered in this way, and this is important for the local economy. But then also the low-cost airline needs to focus services on the (primary) airport.

Hub-spoke networks are profitable if fixed costs are relatively high. Pricing or compensation of CO2 emissions lead to an additional fixed cost per flight for take-off, so from that perspective it helps to concentrate as many passengers as possible on each flight. Frequencies are relatively high in hub-spoke networks (Brueckner and Zhang, 2001), and are an important competitive tool (Givoni and Rietveld, 2009). Further research is necessary to determine the effect of environmental policy on competition levels and frequency of service, because if it only perceived as an additional cost it may not give airlines a proper incentive to reduce the number of flights or allocate more efficient aircraft to the route.

New aircraft can have lower economic cost and/or environmental cost per seat or passenger,[18] and hybridization may lead to lower fixed costs, reducing the necessity to use indirect passengers to reduce average costs. For the local economy this will hardly matter, but the airline may loose profits from indirect travellers with a relatively high willingness-to-pay.

6. Conclusion

This paper reviews the relevant literature on hub-spoke networks to answer the question if hub-spoke networks are preferable if we also include economic and environmental effects.

The first conclusion from the literature is that economies of density, and fixed costs specifically, are the main driver of the optimality of hub-spoke networks. This is of course already well known. But the recent discussion on hybridization, changing passenger preferences and new aircraft technology may cause airlines to move to strategies that involve lower fixed costs, e.g. due to different cost of capital, different schedules, different service levels etc. Further research is necessary to determine the impact on network structures. Although it is not likely that fixed costs will disappear completely, the number of indirect passengers necessary to be able to run the network could be reduced. And even if a hub-spoke airline still is dependent on indirect passengers, other airlines may use new aircraft to offer direct routes between cities that were previously only connected via a hub. This also causes a loss in indirect travellers and the need to rethink the hub-spoke strategy.

The second conclusion is that any additional indirect effects[19] of aviation are the result of market failure, and likely come from a relatively high number of destinations. Hub-spoke networks lead to concentration and a high number of destinations served from the hub. This type of network is used by airlines to maximize profits, and not necessarily (local) welfare. Should small destinations be offered if there is not enough demand to sustain these destinations by themselves? There is empirical evidence a local economy benefits from a relatively large number of destinations, and due to density effects, small destinations can still be offered. So, both the airline and a local economy can benefit from the large number of destinations. For a single market it is obvious that, absent any externalities, any abuse of market power leads to welfare loss because the output is too low. But if there are multiple markets and limited capacity, capacity must be allocated to where it yields the highest local benefit. And then the decision can be to limit output in markets, to capture as many passengers with a high willingness to pay from each market via the consumer surplus in each market to and from the hub. But on top of that, an increase in (hub airport) capacity can be used by the airline to generate additional profits from passengers with a high willingness to pay travelling indirectly via the hub. Such passengers contribute little to the local economy other than reduced average costs for the airline. This "spoilage" of capacity benefits the airline, but means less o-d passengers are accommodated. Further research has to show to what extent this spoilage is relevant. Two final remarks about economic effects. Since (additional) indirect effects largely depend on the spending of the direct effect, there is considerable risk of double counting if benefits are counted, and not expenditures. Furthermore, note there is an additional indirect effect only if there is market failure. Rouwendal (2012) mentions that in the case of market power (other market failures are considered below), an increase in capacity has a similar effect as a subsidy to a monopolist: output is increased, and this leads to positive economic benefits. A good understanding of the nature of the additional indirect effect is necessary to determine if capacity expansion is the appropriate policy to get the desired economic effect.

Hub-spoke networks lead to a local concentration of demand and flights. This causes congestion and local environmental damage. While it has been suggested that, due to environmental economies of scale, hub-spoke networks could cause less environmental damage than point-to-point networks, empirical evidence is mixed, but case studies show that hub-bypassing may have a lower environmental impact. If an airline needs to compensate emissions, this leads to necessary and unavoidable costs. And depending on the aircraft type, aircraft configuration and flight distance, the cost for compensating emissions during the take-off and landing phase and the emissions during the flight phase should be analysed. Further research will have to show if proposed measures to mitigate environmental effects will i) be enough; and ii) lead to network changes, and therefore different emission patterns.

Based on the literature review, this paper puts forward that the number of destinations is important to the local economy, and not the number of indirect passengers. The latter are only a means used by (some) airlines to operate the network, while others manage without. From an environmental perspective, the evidence on the environmental performance of the hub-spoke network is mixed, although case studies suggest that hub-bypassing has a lower environmental impact. Proposed mitigation measures lead to additional (fixed) costs, which could lead to a preference for the hub-spoke network. And even though a hub-spoke network may be undesirable if it has larger environmental effects than other networks (as concluded by some case studies), some airlines need this structure in order to be able to be profitable. This leads to the final conclusion that, due to economies of density, airline concentration will continue, because legacy carriers remain will remain dependent on indirect passengers to a certain extent and low-cost airlines move towards primary airports. This does not necessarily imply that hub-spoke networks are optimal in the broadest welfare sense. Airlines look for the most profitable markets, which often are also large markets. If these airlines use a hub-spoke network, frequency of service is relatively high, and remaining capacity is used to accommodate passengers from competitive indirect markets. Smaller hubs (with relatively small home

[17] This is a result of offering e.g. high quality and transfer opportunities. In general, a point-to-point network is more likely to be optimal if fixed costs are very low or absent (Pels et al., 2000, 2001).

[18] Note that Peeters et al. (2016) question the environmental effect of many proposed technical solutions.

[19] As discussed in 3.2, with this we mean the difference between the total indirect effect and the direct effect.

markets) may have a larger positive welfare effect if the indirect passengers are priced according to their environmental impact. Indeed, this means some markets can no longer be served, and some markets will be served with lower frequency, but the loss in profit and consumer surplus needs to be balanced against lower environmental impact because indirect passengers that mainly contribute to additional economic effects elsewhere are no longer accommodated. Eurocontrol (2013) and (2018) report a mismatch between future growth in demand and current and projected airport capacity in a number of countries. Further research into i) the environmental performance of various network configurations; and ii) the effect of proposed climate policy on airline behaviour is necessary to support policies to deal with this mismatch.

CRediT authorship contribution statement

Eric Pels: Conceptualization, Writing - original draft, Writing - review & editing.

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