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Exploring the co-evolution of air transport aviation and corporate networks

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Abstract

In this paper we aim to contribute to the literature on the empirical parallels between urban hierarchies and the transport networks supporting and/or reflecting these hierarchies. We adopt a stochastic actor-based modeling framework to analyze the co-evolution of the world city hierarchy and global air passenger networks between 2000 and 2010/2011. The data are drawn from an inventory of the location strategies of globalized service firms across world cities and the International Civil Aviation Organization (ICAO). Major findings include (1) exogenous effects, such as the impact of economic development and regionality; (2) endogenous micro-level effects producing macro-level patterns, such as preferential attachment processes; and (3) the two-way impact of both networks. (i.e., cities that are well connected in the aviation network tend to attract more major offices of globalized service firms, while the co-presence of major offices of globalized service firms in cities in turn stimulates the development of aviation connections between them).

Keywords

Urban hierarchies, transportation network, intercity corporate network, stochastic actor-based modeling

Highlights

- Exploring empirical parallels between urban hierarchies and the transport networks supporting and/or reflecting these hierarchies;
- Dynamics for individual intercity networks are driven by both endogenous and exogenous network effects;
- Aviation and APS networks co-evolve over time, with significant two-way impacts.

Introduction

Within transport geography, the geographical contours of transport systems are often explicitly set in the context of the wider urban system (e.g. Murayama, 1994; Malecki, 2002; Derudder and Witlox, 2008). One particular area of attention in this literature relates to the ways in which the *evolution* of transport geographies shapes/is shaped by the urban system in which these geographies are embedded (e.g., O'Connor, 2003; O'Connor and Fuellhart, 2012; Tranos, 2012). When narrowing the research context down to the global scale, for instance, there have been analyses of the development of rail systems (e.g., Niedzielski and Malecki, 2012), Internet and telecommunication networks (e.g., Malecki and Wei, 2009), and air transport networks (e.g. O'Connor, 2003) in the context of the 'world city' hierarchy.

The methodological tools adopted in this literature vary widely, and have resulted in different levels of analytical detail. Malecki (2002), for instance, restricts his analysis to a general *sketch* of the related geographies of Internet backbone networks and world cities, while O'Connor (2003) analyzes the shifting *concentration* of air transport connectivity across the world city hierarchy (see also Derudder and Witlox, 2009). Taylor et al. (2007), in turn, use *regression analysis* to reveal overall parallels and differences between the world city hierarchy and global air transport geographies, while Tranos (2012) recently proposed a more refined framework for assessing parallels between urban systems and transport networks: a regression analysis incorporating lagged explanatory variables allows him to disentangle the co-evolution of cities' hierarchical position and their involvement in Internet backbone networks in more detail. In particular, his framework allows evaluating whether urban-economic development is either driving or driven by the development of such infrastructures (see also Neal, 2011).

One element that has been lacking within the research dealing with the co-evolution of transport networks and the world city hierarchy, is a detailed appraisal of the *underlying network formation processes*: cities' centralities in the global urban hierarchy and the transport networks supporting and/or reflecting this hierarchy (however measured) are operationalized as homogenous macro-level variables, without consideration of the many different micro-level processes that may or may not feed the overall macro-level pattern. As a consequence, exactly *how* world cities and transport networks 'link up' over time remains unclear, as the focus tends to be firmly on macro-level parallels. In this paper, we aim to show that this literature may benefit from a more detailed consideration of the unfolding micro-level linkages between cities and transport systems.

To this end, this paper adopts a stochastic actor-based modeling framework to present a more comprehensive analysis of the co-evolution of global air passenger networks and the world city hierarchy. In particular, the methodological framework presented here allows linking comprehensive network-generation processes at the *micro* scale with the observed network parallels at the *macro* scale. The data used in our analysis are drawn from the International Civil Aviation Organization (ICAO) and the Globalization and World Cities (GaWC, <http://www.lboro.ac.uk/gawc>) research

network, respectively. The ICAO data detail the number of scheduled flights in a given time period between airports, while the GaWC data describe the location strategies of advanced producer service (APS) firms across world cities for different points in time. After transforming the ICAO and GaWC databases so that consistent datasets of inter-city flows are established for 2000 and 2010/2011, we link the shifts that have occurred in the APS-generated urban network with shifting geographies of global air transport networks. Our key purpose is thereby to trace the global co-evolutions in the urban and transport network back to a mix of exogenous (e.g., external impacts such as economic development and geographical location) and endogenous processes (e.g., the emergence of micro-level network-formation processes). Although our empirical focus is centered on world cities and air transport, the methodology outlined here can also be used at different scales, for different transport modes, and for different operationalizations of urban standing.

The remainder of this paper is organized as follows. In the next sections, we introduce our modeling framework and data sources, respectively. We then formally specify our model and provide an overview of the results, after which the paper is concluded with an overview of key implications and a discussion of some avenues for further research.

Stochastic actor-based modeling

Stochastic actor-based models assume that actors making rational decisions on the forging of connections determine network changes, i.e. actors maximize a utility/objective function of network patterns (Snijders et al., 2010)¹. In this case, this implies that cities are treated as ‘actors’ that make ‘rational’ decisions regarding their connections with other cities in the aviation network as well as hosting globalized APS firms². The objective functions in stochastic actor-based models represent the local networking mechanisms that are linked with global network patterns (Snijders et al., 2010).

Similar to other generative models, stochastic actor-based models simulate network dynamics based on pre-defined model specifications and aim to generate simulated networks that maximally replicate the observed network (Warren, 2010). Network simulations are built upon utility-maximizing actors, and the objective functions are defined as the combinations of endogenous and/or exogenous network effects (Snijders et al. 2010). When a reasonable model specification is identified, the statistical significance of individual network effects can be directly tested (Snijders et al., 2010). Interestingly for our purposes, the modeling of the joint-dynamics of multiple networks can also include the effects of ‘exogenous networks’, i.e. a second

¹ Detailed descriptions about stochastic actor-based modeling can be found in Snijders et al. (2010) and Ripley et al. (2012). Utility and objective functions are used interchangeably in this paper.

² For most intercity network analyses, cities are treated as units of analyses. That is, the pairwise relationship between any two cities is used as a surrogate measurement for all interactions between individuals, firms, organizations, and institutions located within these cities. On the one hand, our treatment of cities as aggregated units of long-range interactions is thus similar to a one-mode network (e.g., the aviation network). On the other hand, our model explicitly acknowledges the importance of firms as the actual agents of intercity connectivity (e.g., firms in the intercity corporate network).

network that shares nodes with the focal network, and thereby may influence the evolution of the focal network. For instance, individual cities' positions in the world city hierarchy can be treated as exogenous effects when our focus is on modeling dynamics in aviation networks (and vice versa).

During a single simulation run, a randomly selected actor i changes one of its linkages, and the probability of this linkage change conditions on the objective function of potential network changes:

$$p_i(\beta, X) = \frac{\exp(f_i(\beta, X))}{\sum \exp(f_i(\beta, X'))}$$

Where X and X' represent networks that are generated by the focal connection change and other permissible changes by actor i , respectively; $\exp$ represents the exponential link function; $p_i(\beta, X)$ refers to the likelihood for the network to evolve into X by next run; $f_i(\beta, X)$ represents the actor i 's objective function; and β are parameters for the objective function. Note that stochastic actor-based models require binary networks as inputs, so that in the case of ratio, interval or ordinal measures, researchers need to decide on a dichotomization procedure (Ripley et al., 2012)

The objective function forms the core of stochastic actor-based models, implemented as a series of network *effects* (Snijders et al., 2010):

$$f_i(\beta, X) = \sum_k \beta_k s_{ki}(X)$$

The network effects $s_{ki}(X)$ summarize micro-level endogenous network topologies and/or exogenous attributes (e.g., nodal attributes and link properties) that are conjectured to be responsible for actors' networking behaviors. The effect parameters β_k capture the size, direction, and significance of corresponding network effects: a positive parameter indicates that the network evolves towards a position with a higher value for the corresponding effect, while a negative parameter implies that the network is prone to evolve towards a position status with a lower value for the corresponding effect. For instance, the so-called *4-cycle* effect among APS firms' locational strategies consists of two cities (A1 and A2) and two firms (B1 and B2), whereby both firms (B1 and B2) have major offices in both cities (A1 and A2). A positive and significant 4-cycle effect implies that individual firms have tended to follow other firms' locational strategies between t1 and t2 ($A1 \rightarrow B1$, $A1 \rightarrow B2$ and $A1 \rightarrow B2$ jointly imply $A2 \rightarrow B2$); a negative and significant 4-cycle effect indicates that individual firms have tended to avoid copying other firms' locational strategies between t1 and t2 (for example, $A1 \rightarrow B1$, $A1 \rightarrow B2$ and $A1 \rightarrow B2$ jointly imply not $A2 \rightarrow B2$); and a non-significant 4-cycle effect indicates that neither patterns is clearly visible between t1 and t2.

Our aim here is to include theoretically sound and empirically feasible/available network effects for our models, and the selected network effects will be elaborated for both networks after discussing our data.

Data collection

We model the co-evolution of aviation networks and the presence of globalized APS firms' in world cities based on abridged descriptions of both networks in 2000 (t1) and 2010 (t2).

The rationale behind the GaWC approach towards mapping the world city hierarchy is that globalized APS firms serve as key network agents among world cities (Sassen, 2001; Taylor, 2004). As a consequence, in the GaWC approach the empirical focus is on mapping the evolving presence of globalized APS firms' in world cities. Here we use information from the GaWC datasets for 2000 and 2010³. The original GaWC datasets characterize the geographic distribution of 100 firms in 315 cities for 2000 and 175 firms in 526 cities for 2010, detailing the relative importance of individual branches within firms' office network through a 6-point ratio scale ranging from 0 (no presence) to 5 (global headquarters). However, for reasons of consistency and computational ease, our analysis is restricted to (1) the 57 firms that have remained leading APS providers during the period 2000-2010; (2) major offices in the office networks, revealing the command and control structures of globalized APS firms (i.e. global and regional headquarters that score 4 or 5 in the GaWC data); and (3) the 91 cities that hosted at least one major office of the 57 firms in 2000 or 2010⁴.

Two two-mode adjacency matrices are the result of this data transformation. These binary two-mode networks capture the geographic distribution of 57 globalized APS firms in 91 cities in 2000 and 2010 (Table 1), with a value of 1 and 0 indicating the presence and absence of a major branch, respectively. Unlike more conventional one-mode networks that feature connections between actors of the same type (such as airline networks), a two-mode network represents the relationships between two disjoint sets of actors (Liu and Derudder, 2012). In our case, the two-mode intercity corporate network characterizes firms' presence in cities: the *Outdegree* connectivity in this intercity corporate network thus gauges the number of firms in individual cities, while the *Indegree* connectivity counts the number of cities in which individual firms have presence (Table 2a).

In general, the APS firm network expanded between 2000 and 2010: there are 232 major offices in 2000, and 333 in 2010 (Table 1). However, this overall rise obscures broader changes, as only 93 major offices remained in place and 139 and 240 major offices were closed/downgraded or opened/upgraded, respectively (for more details on change in the world city hierarchy, see Derudder et al., 2010). However, these changes have not implied a major overhaul in the Outdegree ranking, as a lot of changes in either direction are concentrated in the same set of cities, with London, New York and Hong Kong leading in Outdegree (i.e. hosting the most major offices of globalized APS firms).

³ Detailed descriptions about the GaWC datasets in 2000 and 2010 can be found in Taylor (2001) and Taylor et al. (2013), respectively.

⁴ Two cities (Palo Alto and Utrecht) that host major APS offices but do not have a major airport are added into neighboring major metropolis (San Francisco and Amsterdam, respectively).

[TABLE 1 ABOUT HERE]

Our second dataset describes the evolving geographies of inter-city aviation networks. The initial data represent a more conventional one-mode network, wherein nodes represent the 91 selected cities, and linkages represent the total number of direct flights between these cities (as given in ICAO data for 2000 and 2011). To derive a meaningful binary dataset that reflects the relevance of individual connections as succinctly as possible, we adopted the following truncation procedure: the importance of city A in city B's aviation network is calculated as the ratio of flights between A and B over B's total flights. If flights are distributed randomly between cities, any city A should account for approximately 1.1% (1/90) of city B's connections. A connection is regarded as significant and set to 1 if its importance is greater than 1.1%, and 0 otherwise. For example, there are 17 flights monthly connecting Abidjan and Amsterdam for 2000. These 17 flights are deemed significant for Abidjan (accounting for 9.7% of Abidjan's total number of flights), but not significant for Amsterdam (accounting for 0.2% of Amsterdam's total number flights). Meanwhile, the 1364 flights between New York (4.8% of the total 27987 flights) and Los Angeles (9.3% of the total 14631 flights) are important for both cities.

The end product of this data transformation is two asymmetric 91-by-91 binary matrices summarizing the relative importance of individual inter-city aviation connections in 2000 and 2011 (for other procedures to reveal nodes' significant linkages in air transport networks, see Van Nuffel et al. 2009 and Fuellhart and O'Connor 2012). A directional linkage from city A to city B reflects that the connection between A and B is significant for A. The *Outdegree* connectivity of a city therefore simply reflects how many cities the focal city has significant linkages to. Similarly, *Indegree* connectivity summarizes from how many cities the focal city receives significant linkages (Table 2b).

[TABLE 2 ABOUT HERE]

The number of significant air transport linkages rose from 1595 to 1698 between 2000 and 2011. During this study period, 1403 significant linkages remained unchanged, while 192 and 295 linkages were eliminated/downgraded or developed/upgraded, respectively. Overall, this points to stability, if not inertia in air transport networks (see Fuellhart and O'Connor, 2012). London, New York, Paris, Frankfurt, Amsterdam, Los Angeles boast the largest *Indegree* values in our transformed network, and are constantly ranked as the most popular cities in both years. Frankfurt, Istanbul, and London, in turn, had the most significant outgoing linkages in 2000, with Dubai rapidly rising to the top in this *Outdegree* ranking by 2011 (see Vespermann et al., 2008). Overall, there is less inequality amongst cities' connectivity in the aviation network than in the APS-generated network.

In addition to the data on the unfolding APS and airline networks between 2000 and 2010/2011, city-related data are also collected as exogenous variables: gross domestic product (*GDP*) and population size (*POP*) for 2010, as well as regionality

through three dummy variables (*PAC*, *EUR* and *NAM*), indicating cities' affiliations among the world's three most urbanized regions: Pacific Asia, Europe, and North America.

Although we believe that the data used here are amongst the best available, there are obviously some data issues as well. First, there is the extreme simplification of the airline and APS data because of the binary data requirement of the modeling framework. In the case of the GaWC data, however, it is worthwhile to note that our focus on global and regional headquarters actually tends to iron out some of the subjectivity in the GaWC data gathering (Liu and Taylor, 2011). In addition, above all this simplification serves our goal of acquiring a better understanding of how transport networks and APS networks link up over time. Second, *t2* (2000 versus 2011) is slightly different for both networks. Third, rather than including *evolution* in population size or GDP, these variables are treated static background dummy variables for a single point in time (2010 for most cities). In addition, no firm-specific exogenous effects are included in the model, as the relevant data is extremely hard to assemble. And finally, the ICAO data features the individual legs of trips rather than the complete origin-destination routes, which is a widely acknowledged caveat in analyses of urban systems based on airline data (Derudder and Witlox, 2008).

Now that we have introduced the potential of stochastic actor-based modeling and the data used to map the co-evolution of both networks, we are in a position to provide a formal model specification. Effectively, this implies elaborating on the potential endogenous network structures at play in the unfolding of the networks between *t1* and *t2*.

Model specification

Modeling the evolution of the world city network

The APS firms' networks part of our model involves four effects for both endogenous and exogenous networking mechanisms (Table 3)⁵.

A positive *Density* parameter implies that individual firms deploy many major offices (e.g., a global or regional headquarter in each major world region), whereas a negative estimate corresponds to the case that most firms have a limited number of headquarters (e.g., only a global headquarter). The *Outdegree activity* and *Indegree popularity* effects indicate preferential attachment processes (Snijders et al., 2010), which give rise to the global hierarchies of cities and firms (Neal, 2008). More specifically, the *Outdegree (city) activity* effect captures the trend that cities with many offices at *t1* tend to accumulate more offices over time. Likewise, a positive *Indegree popularity (firm)* effect indicates that firms with many branches are prone to pursue expansive locational strategies. The so-called *4-cycle* effect was discussed earlier as an example of the modeling framework: a positive effect indicates that

⁵ Our current analysis controls for a set of basic endogenous network effects (Snijders et al., 2010; Ma and Timberlake 2012), which are fundamental to the formation of most networks. Meanwhile, other complex endogenous effects can be implemented in RSiena to test more specific hypotheses.

individual firms that are co-located in a city at t1 have further mimicked each other's location strategies by t2. Only four city-related *Ego* exogenous effects are included⁶.

[TABLE 3 ABOUT HERE]

Modeling the evolution of the aviation network

The aviation network part of our model hypothesizes the network generation as a function of six endogenous (network-based) effects and twelve exogenous (attribute-based) covariates (Table 4).

Similar to intercepts in conventional regression analyses, the *Density* effect benchmarks the overall tendency for cities to make aviation linkages. A positive *Indegree popularity/Outdegree activity effect* implies that cities receive/send more aviation linkages are more likely to gain additional connections, with negative effects suggesting the opposite trends.

The model also includes three effects that account for the interdependence among aviation connections: the *reciprocity* effect measures the tendency towards mutuality in aviation connections. A positive *reciprocity* effect suggests that a flow between city A and B would become significant for both A and B. Transitivity effects (*triplets* and *3-cycle*) reflects the tendency of two cities A and B to become linked if both cities share a neighbor (city C) in the network. A positive *triplets* effect supports a local hierarchical mechanism ($C \rightarrow A$ and $C \rightarrow B$ jointly imply $A \rightarrow B$), and a positive *3-cycle* effect indicates a triadic closure process and counters local hierarchical ordering ($C \rightarrow A$ and $A \rightarrow B$ jointly imply $B \rightarrow C$).

We include three exogenous effects for each of the four covariates (GDP, population, Pacific-Asian cities, and European cities)⁷: the effect of *sender's* covariates on linkage change (the *ego* effect); the effect of *receiver's* covariates (the *alter* effect); and the effect of both *sender* and *receiver's* covariates (the *similar* effect). For example, a positive *Population ego* effect and a positive *Population alter* effect suggest that more populous cities would send and receive more aviation linkages, respectively; moreover, a positive *similar Population* effect implies that cities tend to link with other cities of similar population sizes; negative parameters would suggest that patterns are unfolding the opposite way.

[TABLE 4 ABOUT HERE]

Co-evolution of the two networks

The final part of our modeling exercise lies in its potential to look at interaction effects between both previously specified networks: four interaction effects

⁶⁻⁷ Regional effects for North American are not statistically significant and thus excluded.

measures the interdependence among cities' positions in different networks (Table 5, see also Tranos, 2012). A positive *Aviation outdegree to GaWC activity* effect supports the trends for cities with more air transport connections to host more globalized APS firms. Furthermore, a positive *Aviation agreement to GaWC* effect suggests that two cities significantly connected by air transport at t1 result in them co-hosting more major offices of firms at t2. The *GaWC outdegree to Aviation activity* effect tests whether the number of firms a city host at t1 is correlated with its connectivity in the aviation network at t2, while the *GaWC agreement to Aviation* effect captures the tendency for two cities co-hosting major offices of the same APS firms at t1 to be significantly connected in the aviation network at t2.

[TABLE 5 ABOUT HERE]

To sum up, by modeling endogenous and exogenous network mechanisms and accounting for interactions between networks, the co-evolution of air transport and globalized APS networks is directly tested with our stochastic actor-based model. Models are implemented with the RSiena package (Ripley et al. 2012; Conaldi et al. 2012). The goodness-of-fit measurements for our SABMs can be found in Appendix 1.

Results

Macro-level parallels

By way of introduction to the modeling results, we begin with a straightforward macro-level description of the (evolving) parallels between the APS-produced world city hierarchy and air transport networks. Table 6 presents a correlation matrix based on Spearman's rank-order correlations for cities' position in the different connectivity rankings for both t1 and t2. Overall, the level of change seems limited, as the correlations between *Aviation Indegree* and *Aviation Outdegree* on the one hand and *GaWC Outdegree* on the other hand remains largely stable between 2000 and 2010. In line with previous research, these associations are statistically significant, but far-from-perfect (see Taylor et al., 2007).

However, it is unclear whether this is due to an overall stability in the relation, or rather a near-zero-sum outcome of different tendencies in the linking processes between both networks. Or, put differently: such a correlation analysis only provides a general appraisal of the evolving association between cities' positions within different networks, while our modeling results allow revealing how the connections between both networks have emerged or dissolved over time.

[TABLE 6 ABOUT HERE]

Table 7 presents an overview of the parameter estimates. In the event, forward model selection, Wald tests, and score-type tests are employed to exclude network effects that do not improve model fits (Snijders et al., 2010). The effect parameters capture the size, direction, and significance of individual network effects. The

remainder of this section focuses on the modeling results and the linking processes these reveal.

[TABLE 7 ABOUT HERE]

Evolution of the intercity corporate network

In addition to the endogenous hierarchical processes (*Density*, *Outdegree activity* and *Indegree popularity*), exogenous socio-economic status (GDP and population), and exogenous geographic disparities (Pacific Asian and European effects), the dynamics of the intercity corporate network also shows the interdependence among firms' locational strategies (*4-Cycle*),

The negative *Density* effect confirms that most APS firms have a limited number of headquarters. The positive *Outdegree (city) activity* effect suggests that newly entered firms prefer to locate in cities with many existing firms, i.e., a preferential attachment process. Preferential attachment processes in the intercity corporate network are often driven by agglomeration (or external) economies of scales, as the clustering of different producer services may benefit from labor-pooling, supporting infrastructures, and innovation/information spillovers (Neal, 2008; Drennan and Kelly, 2011). Similar to a "snowballing" scenario, a positive *Indegree (firm) popularity* effect indicates that firms with many branches are prone to continue their expansive locational strategies. The significant *4-cycle* effect reflects interdependence among firms' locational strategies (Head et al., 1995; Taylor, 2004), while the clustering of globalized APS firms in rich cities (Pereira and Derudder, 2010) are confirmed by the positive *GDP* effect. As suggested by the negative *Population* effect, large populations do not offer advantage in attracting major offices. For example, many of the major cities in developing countries are also the world's most populous cities, whereas they host relatively few globalized APS firms. There is a negative effect for European cities and another positive effect for Pacific Asian cities, revealing the increasing importance of Pacific Asian cities found in other studies (Derudder et al., 2010).

Evolution of the intercity aviation network

The formation of the intercity aviation network for the period of 2000-2011 is mainly driven by endogenous hierarchical processes (*transitive triplets*, *3-Cycle*, *Outdegree activity*, and *Indegree popularity*), as well as exogenous socio-economic and geographic effects (*GDP*, Pacific Asian and European effects).

As indicated by the negative *Density* effect, cities have on average not established new significant aviation connections. The positive *Reciprocity* effect indicates the tendency for mutuality in aviation connections, i.e., individual airline flows become important for cities on both ends. For example, a pair of reciprocal ties often signifies intensified social and economic linkages, and is often associated with convergence within urban systems (Ma and Timberlake, 2012). *Indegree popularity* effect reflects the *Mathew Effects* or preferential attachment process underlying the

formation of aviation connections (Barabási and Albert, 1999; see also Vinciguerra et al., 2010), whereby cities with large number of aviation linkages are more likely to gain additional aviation connections. Conditioning on other effects (e.g., population and GDP), this preferential attachment process is mostly consistently with the hub-and-spoke strategies employed by individual airline carriers, which are designed to employ the (internal) economy of scale (Horner and O’Kelly, 2001; Campbell and O’Kelly, 2012). The negative *Outdegree activity* effect suggests that cities sending fewer linkages in 2000, i.e. ‘peripheries’ in the aviation network, are more likely to initiate new connections in 2011. The joint interpretation of *Density*, *Outdegree activity*, and *Indegree popularity* effects indicates that most new connections during our study period emerge between ‘core’ and ‘peripheral’ cities. The preferential attachment process gives rise to global hierarchies in the intercity aviation network, which are in turn reinforced by hierarchical processes at local level (the positive *Transitive triplets* and negative *3-Cycle* effects).

We also find exogenous GDP and regionalization effects in the intercity aviation network. The positive *GDP alter* effects indicates that richer cities have on average acquired more aviation connections, and the positive *GDP similarity* effect indicates that cities tend to connect with cities with similar economic capacities. As suggested by the positive *PAC same* and *EUR same* effects, cities from the same region have better chances to be linked in the aviation network. The positive *PAC ego* and *PAC alter* effects indicate that Pacific Asian cities are more likely to gain aviation connections, and the negative *EUR alter* effects implies that European cities tend to receive less linkages. Although improving the overall model fit, population-related effects are not statistically significant.

Interactions between intercity aviation and corporate networks

A joint interpretation of the four interaction effects suggests that the aviation network have more influence on the APS-firm network than the other way around, as both aviation-originated interaction effects are statistically significant (*Aviation outdegree to GaWC activity* and *Aviation agreement to GaWC*). The positive *Aviation outdegree to GaWC* effect suggests that globalized APS firms are prone to deploy major offices in cities with many aviation connections, while the positive *Aviation agreement to GaWC* indicates that firms are increasingly co-located in cities that are well-connected by air transport (see also Neal, 2011).

Both agreement effects (*Aviation agreement to GaWC* and *GaWC agreement to Aviation*) are positive, implying a reciprocal process in the evolution of both networks: well-connected cities in the aviation network are more likely to attract more APS firms, which in turn stimulate more aviation connections between them. In other words, the aviation network seems to facilitate the daily operation of APS-firms as the supporting infrastructure, while the co-location of multinational APS firms equally seems to be motivating new developments in aviation transport.

Finally, log odds ratios between likelihood of different network scenarios can be computed with the estimated parameters (Snijders, 2001; Snijders et al., 2010). For

example, suppose city A and B are identical in terms of their attributes and positions in both networks, except that city A has one more firm. All other effects being equal, the chance for city A, rather than city B, to gain an additional firm is 59% ($\exp(0.3686)/(\exp(0.3686)+1)$)⁸. Conditional on all other effects, the odds for a new aviation connection between two Pacific Asian cities against a new connection between a Pacific Asian city and any other city is 2.78 ($\exp(1.0227)$), *ceteris paribus*, i.e., the binary probability of a Pacific Asian city to establish an aviation linkage with another Pacific Asian city is 74% (the *PAC same* effect in the aviation network). Calculations for more complex scenarios can be performed in a similar fashion, however with less straightforward interpretations.

Discussion and conclusions

In general terms, the purpose of this paper has been to present a methodological framework that allows revealing the *network formation processes* between cities' centrality in an urban system and the transport networks supporting and/or reflecting this system. Although our empirical focus was highly specific in that it dealt with world cities and global air transport networks (with the further complication of the former being specified as a two-mode network), this methodological framework can also be used at different scales, for different transport modes, and for different operationalizations of urban standing.

Given the specificity of our time intervals and data sources, as well as the impact of the different data transformations, we emphasize that our results are indicative rather than definitive. Nonetheless, our analytical framework allows identifying a number of patterns in the (co-)evolution of both networks, i.e.: (1) exogenous effects, such as the impact of GDP and regionality; (2) endogenous micro-level effects producing macro-level patterns within both networks, such as different preferential attachment processes; and (3) the way in which networks are impacting each other, such as the observation that cities that are well connected in the aviation network tend to attract more major offices of globalized APS firms, while the co-presence of major offices of globalized APS firms in turn stimulates the development of aviation connections between them. In addition, the way in which the model is specified allows plugging the estimated parameters into the objective function to calculate the log odds ratios between different network changes. Still, our analysis is concerned with association rather than causality between the two networks, as the latter requires data of longer periods and exclusion of confounding factors.

The limitations of our analysis also point to a number of avenues for further research. These could include sensitivity analyses through focusing on the impact of the dichotomization procedures employed here, as well as paying attention to the influence of the time interval. In addition, specifying and using other endogenous network effects may result in more comprehensive appraisals of how micro-level connections between urban hierarchies and transport systems co-evolve.

⁸ Note that this calculation only accounts for first-order impact, and does not consider impacts beyond second-order (e.g., aviation->corporate->aviation).

Tables

Table 1. Descriptive network statistics

Table 2. Cities' connectivity rankings in the intercity aviation and corporate networks

Table 3. Network effects for intercity aviation network

Table 4. Network effects for intercity corporate network

Table 5. Joint dynamics of intercity aviation and corporate networks

Table 6. Spearman's rank-order correlations between cities' rankings

Table 7. Determinants of network formation

Table 1 Descriptive network statistics

Statistics	GaWC 2000	GaWC 2010	Aviation 2000	Aviation 2011
Nodes	91 cities and 59 firms		91 cities	
Density	0.043	0.062	0.195	0.207
Average degree	2.549	3.659	17.527	18.659
Existing ties	232	333	1595	1698
Total potential ties	5369	5369	8190	
Jaccard index	0.197		0.742	
0→0	4897		6300	
0→1	240		295	
1→0	139		192	
1→1	93		1403	

The Jaccard Index measures the proportion of unchanged linkages during 2000 and 2010/2011, and networks with Jaccard Index greater are suitable to be analyzed by stochastic actor-based models (Snijders et al., 2010)

Table 2. Cities' connectivity rankings in the intercity aviation and corporate networks

(a) Top-ranked cities in the intercity corporate network

Rank	GaWC 2000		GaWC 2010	
	Cities	Outdegree	Cities	Outdegree
1	New York	38	London	39
2	London	35	New York	31
3	Hong Kong	13	Singapore	17
4	Chicago	12	Hong Kong	16
5	Tokyo	11	Paris	14
6	Frankfurt	9	Chicago	11
7	Washington	8	Tokyo	9
8	Los Angeles	7	Dubai	9
9	Miami	7	Sydney	8
10	Singapore	7	Washington	6

(b) Top-ranked cities in the intercity aviation network

Rank	Aviation 2000		Aviation 2000		Aviation 2011		Aviation 2011	
	Cities	Outdegree	Cities	Indegree	Cities	Outdegree	Cities	Indegree
1	Frankfurt	32	London	67	Dubai	37	London	66
2	Istanbul	29	New York	60	London	33	New York	59
3	London	27	Paris	52	Amsterdam	29	Paris	53
4	Zurich	27	Frankfurt	50	Paris	29	Frankfurt	49
5	Paris	26	Amsterdam	48	Zurich	29	Amsterdam	43
6	Amsterdam	26	Los Angeles	42	Athens	27	Los Angeles	36
7	Brussels	26	Zurich	39	Brussels	27	Rome	35
8	Moscow	26	Milan	35	Frankfurt	27	Barcelona	34
9	Tel Aviv	26	Brussels	34	Istanbul	27	Madrid	34
10	Vienna	25	Chicago	31	Munich	27	Milan	34

Table 3. Network effects for intercity corporate network

ID	Effects	Time 1 (t1)	Time 2 (t2)
Positive effects		➔	
Negative effects		➔	
Endogenous network effects			
1	Density
2	4-Cycle
3	Outdegree activity
4	Indegree popularity
Exogenous covariates effects			
5	Ego

1. Cities and firms are represented as white and grey circles, respectively. A label "c" marks cities with particular exogenous variables.

2. Dash and solid lines represent yet-to-exist and existing network ties at t1, respectively.

3. We only illustrate the cases for positive network effects. For the case of negative effects, local network structures are more likely to evolve from those in t2 to those in t1.

Table 4. Network effects for intercity aviation network

ID	Effects	Time 1 (t1)	Time 2 (t2)
Endogenous network effects			
1	Density
2	Reciprocity
3	Triplets
4	3-Cycle
5	Outdegree activity
6	Indegree popularity
Exogenous covariates effects			
7	Ego
8	Alter
9	Similar

1. Cities are represented as circles, with the label "c" marking particular exogenous variables.

2. Dash and solid lines represent yet-to-exist and existing network ties at t1, respectively.

3. We only illustrate the cases for positive network effects. For the case of negative effects, local network structures are more likely to evolve from those in t2 to those in t1.

Table 5. Joint dynamics of intercity aviation and corporate networks

ID	Effects	Time 1 (t1)	Time 2 (t2)
	Positive effects		→
	Negative effects		←
From aviation to corporate			
1	Aviation outdegree to GaWC activity		
2	Aviation agreement to GaWC		
From corporate to aviation			
3	GaWC outdegree to Aviation activity		
4	GaWC agreement to Aviation		

1. Cities and firms are represented as white and grey circles, respectively.
2. Network connections in both intercity aviation and corporate networks (two bounding rectangles in dash lines) are depicted. The overlapping area represents the interaction between two networks.
3. Dash and solid black lines represent yet-to-exist and existing network ties at t1, respectively.
4. We only illustrate the cases for positive network effects. For the case of negative effects, local network structures are more likely to evolve from those in t2 to those in t1.

Table 6 Spearman's rank-order correlations between cities' rankings

	Aviation 2000 Outdegree	Aviation 2000 Indegree	Aviation 2011 Outdegree	Aviation 2011 Indegree	GaWC 2000	GaWC 2010
Aviation 2000 Outdegree		0.754**	0.846**	0.740**	0.375**	0.390**
Aviation 2000 Indegree			0.769**	0.939**	0.555**	0.464**
Aviation 2011 Outdegree				0.786**	0.364**	0.316**
Aviation 2011 Indegree					0.454**	0.453**
GaWC 2000						0.474**
GaWC 2010						

** correlation significant at the 0.01 level

Table 7 Determinants of network formation

Network effects	Effects parameters	
Intercity corporate network		
Rate		
Change rate	23.5508*	3.3568
Endogenous network effects		
Density	-4.011*	0.2644
4-Cycle	-0.0162*	0.0097
Indegree popularity	0.4542*	0.1082
Outdegree activity	0.3686*	0.0511
Exogenous covariates effects		
Population ego	-0.8446*	0.3383
GDP ego	0.8283*	0.3285
PAC ego	0.2415*	0.116
EUR ego	-0.3104*	0.1128
Intercity Aviation network		
Rate	Estimate	S.D.
Change rate	9.5853*	0.6574
Endogenous network effects		
Density	-2.4663*	0.553
Reciprocity	2.3517*	0.1715
Transitive triplets	0.1595*	0.0115
3-Cycles	-0.1443*	0.0191
Indegree Popularity	0.1134*	0.0551
Outdegree Activity	-0.3214*	0.0588
Exogenous covariates effects		
Population alter	-0.3887	0.4167
Population ego	0.5762	0.4345
Population similarity	0.3184	0.3727
GDP alter	1.5383*	0.5232
GDP ego	1.0998	0.7068
GDP similarity	0.9196*	0.4508
PAC alter	1.1422*	0.2299
PAC ego	1.0233*	0.2561
PAC same	1.0227*	0.2292
EUR alter	-0.2865*	0.1249
EUR ego	0.5064*	0.1567
EUR same	0.3068*	0.1159
Joint dynamics between networks		
Aviation outdegree → GaWC activity	0.2473*	0.1001
Aviation agreement → GaWC	0.0944*	0.0513
GaWC outdegree → Aviation activity	-0.1891	0.1513
GaWC agreement → Aviation	0.2201*	0.1229

*Estimates are significant at 0.1 level

Appendix 1. Goodness-of-fit measurements for SABMs

The validity of stochastic actor-based models can be assessed by comparing observed networks with networks that are simulated from the proposed model, i.e., measuring goodness-of-fit (Snijders et al., 2009; Conaldi et al., 2012). Smaller divergences between the observed and simulated networks suggest that the specified models (i.e., network effects) are more likely to capture the true underlying network mechanism, and vice versa. The properties of simulated networks are obtained by averaging over two thousand simulations based on SABMs specified in Table 7. The boxplots (Figure A1) represent degree distributions of the two thousand simulated networks, whereas the solid blue lines represent the observed degree distribution. For most degree values, the observed distribution falls within two standard deviations of the means of simulated distributions, implying a reasonably well goodness-of-fit. In addition, Table A1 summarises the differences between networks statistics of observed and simulated networks. All deviations between observed and simulated networks, except for skewness, are less than 10%.

Table A1. Goodness of fit measure based on 2000 simulations

Aviation	Simulated	Observed	Difference (%)
<u>Outdegree</u>			
Degree	18.70	18.66	-0.20
Standard deviation	6.83	6.86	0.57
Skewness	-0.48	-0.36	-32.54
<u>Indegree</u>			
Degree	18.70	18.66	-0.20
Standard deviation	12.85	13.21	2.76
Skewness	0.81	1.03	21.33
GaWC			
<u>Cities</u>			
Degree	3.70	3.66	-1.24
Standard deviation	6.38	6.44	0.90
Skewness	4.41	4.32	-2.18
<u>Firms</u>			
Degree	5.71	5.64	-1.23
Standard deviation	5.11	5.63	9.24
Skewness	2.54	4.50	43.46

Figure A1. Goodness of fit measured based on 2000 simulations

Degree distributions of (1) outgoing (outdegree) and incoming (indegree) ties in the aviation network; and (2) sending (cities) and receiving (firms) ties in the corporate network. The X- and Y-axes represent degrees and number of cities/firms with corresponding degrees, respectively. The box plots represent simulated degree distributions based on two thousand simulations, and the solid blue lines represent observed distributions. The empirically derived distributions may provide a reasonably well fit to the observed distribution, if the solid blue lines fall within boxplots for most degree values.

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