Worldwide Multi-Level Networks of Cities Emerging From Air Traffic (2000)

Céline Rozenblat, University of Montpellier 3-UMR ESPACE (France), rozenblat@mgm.fr
Guy Mélançon, LIRMM UMR CNRS 5506 (France), Guy.Melancon@lirmm.fr
Magali Amiel, University of Montréal (Canada), magali.amiel@umontreal.ca
David Auber, University of Bordeaux I- Labri (France), david.auber@labri.fr
Carine Discazeaux, INSR-Montreal (Canada), cdiscazeaux@hotmail.com
Alain L'Hostis, INRETS-Lille (France), alain.lhostis@inrets.fr
Patrice Langlois, University of Rouen – MTG, patrice.langlois@univ-rouen.fr
Sébastien Larribe, University of Tours (France), sebastien.larribe@univ-tours.fr

Abstract. *The paper unveils « new reticular territories » implicitly defined in air transport networks. We describe an approach based on weighted graphs (induced from city to city air passenger traffic) from which we infer strongly connected components, themselves organized into sub-networks. The computation can be iterated within each component (or cluster) until each node or city appears as such in a component. The method leads to a multilevel presentation of the most connected cities in the world, underlining the necessary steps to go through when traveling worldwide, described as a path through the different levels and components. These components sometimes appear as being founded on spatial rules, but we also observed specialized subgroups emerging from economical or institutional logics such as partnership strategies. Our methods open new perspectives to study and represent networks or spatial interaction of cities systems at every level of geographical scale, from local to global.*

Key words : cities' networks, exchanges, air transport, small worlds, graphs

Networks linking cities worldwide are becoming denser and more complex at all levels of the geographical scale. Their analysis and their representation bring a challenge on three different aspect:

- producing readable visualizations of flows between cities, showing which cities play the most important role;
- identifying subgroups of closely interrelated and interdependent cities;
- helping the identification of organizational logic of urban territories at every geographical scale.

These three objectives depend on one another. Indeed, while representations of the network can help identify its logical organization, understanding the logic first can determine the most appropriate spatial configurations for their analysis.

We are developing new methods to exhibit reticular structures of spatial networks, based on the concept of "small worlds" or "scaling networks". Our approach is based on properties that can be measured: a high degree of connectivity between nodes and a small average distance between nodes characterize "small world networks" (Watts, 1999). However, these networks have an intrinsic complexity and each node of the network participate in its very own way to the dynamic of the global configuration.

This property has often been observed in spatial hierarchies and spatial anisotropies. Spatial networks analysis can be applied at every scale and from all perspectives concerned with cities, system of cities as well as local organization of cities. Therefore, this analysis can be performed on various types of large matrices such as transport systems, international flows of trade or international migrations; networks of transnational firms linking European or worldwide cities: daily migrations from a locality to another, around centres of employment, or displacements for access to services make it possible to delimit basins of life; systems of territorial actors exchanging information or sharing common interests.

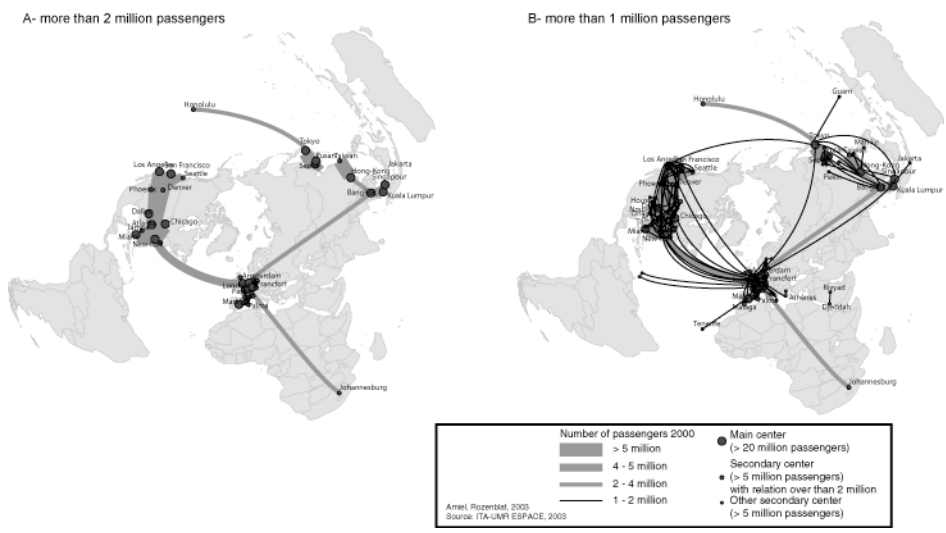
This network centered approach can indeed be applied in many different context. In this paper, we will show the potential of our method by applying it to the world air traffic network, keeping in mind that it can be applied more largely to any spatial interaction system, especially to urban systems.

Before developing the methodology itself and show its great advantages, we will begin by describing the main intervening factors of world air network organization.

1. Complex logics of world air network organization

The characteristics of the organization of the world air network are perceptible through its topology (graph, and weight of the exchanges) which is produced itself by economic actors or policies which largely evolved for ten years.

Figure 1: Main worldwilde air passenger traffics



1.1 Main routes of the world air network

The strongest links in term of annual passenger traffic (fig.1 (A)) is concentrated within a restricted number of dominant cities. The 49 connections of more than 2 million passengers per year (in 2000) connect only 41 cities (including 23 cities of the United States). Paradoxically, the connections which add up the strongest passenger traffic are the shortest ones in average distances. The most attended connections are Pusan - Seoul (more than 6 million passengers), Fort Lauderdale - New York, Hong Kong - Taipei, Chicago - New York, New York - Orlando, Los Angeles - New York and Boston - New York (having all more than 5 million passengers). The first European connection, Dublin - London, arrives at the 13th rank with 4.1 million passengers, followed by Barcelona - Madrid (3.9 million, sitting at the 15th rank). On the whole, among the 49 connections of more than 2 million passengers, 32 connections connect cities of the United States, 10 connections concern European cities and 6 concern Asian cities.

London - New York constitutes the only transcontinental major connection, sitting at the 12th rank with 4.2 million passengers.

The connections of more than 1 million passengers, moderately extend the network in terms of how many cities are covered. On the contrary, they increase the density of the already well served zones (fig.1 (B)). In particular, no city of South America appears in this world major sub-network. The first connection of the South American continent is Buenos Aires - Santiago of Chile (850 000 passengers per year), followed by Buenos Aires - Sao Paulo (725 000).

1.2 Deregulation effects on the network topology

One could make the assumption that this world concentration is the result of gravitating logics where the richest and most populated cities of the planet would have greater exchange as they are geographically close to one another. However, the application of this gravitational model to the air exchanges shows only one weak traditional effect of Euclidean or time distance (Amiel, 2003). The current organization of the world traffic is the result of various processes of liberalization that took place in air transport. Since the deregulation of air transport, started in 1978 with the United States and which is spreading over the world since 1993, the routes followed by planes do not depend solely any more on the capacities of the places to exchange, nor to the "technological" limits of the apparatuses.

Other logics participate to structure the organization of air exchanges:

- Economical logics of competition between the companies or partnership inside "alliances" of which most known are Sky TEAM, Star Alliance and One World. These alliances organize the division of air networks between various companies, and offer larger destinations for the passengers. The economical logic of these alliances develop consumer loyalty by various programs proposing specific advantages (guaranteed reservation, choice of the seats, precede miles);
- Logics of governorship inside each company to centre the activity on the air courses and on the higher added values activity sectors. Another type of governorship is emerging from merges between companies which consist in creating groups of international scale able to maintain a strong position on a greater number of markets;
- Airport logics, through agreements between companies and airports, define hubs and spokes, where shorter or average routes are concentrated in order to feed connections of long distance flights more regularly. The major factors of the companies to choose airports are dedicated piers, reserved departure gates, number of takeoffs and increased landings.

The exchanges are thus organized in a reticular logic where airports stages are charged by companies with passengers redistributing according to partnerships agreements between companies and between airports and companies. From any place in the world, passengers go through stages to join the dominating network, which lead to other stages to finally reach the desired place. Thus, many airports intervene like successive relays between every cities of the planet and the great intercontinental exchanges, which does nothing but reinforce the dominated network.

The network structure, which was hitherto subjected to the will of the States, is founded under the supervision of airline companies, following their strategy. As most airline companies are private companies, they organize their network to optimize profit neglecting the development of a territorial homogeneous service road. Companies being less and less national (even if the national history of the companies still appears in their current structure [Amiel, 2004]), the routes followed by companies exceed national borders and create new transnational structure of equivalent territories (i.e. connected to the same focal point or hub). Thus territorial logics which prevailed before the deregulation are becoming obsolete and new territorialities emerge.
The objective of our approach is to help the identification of these "new reticular territories", defined by inter-connected overhead grids which divide the world in various levels of road service through obliged steps through hubs. The spangled form of the networks, inherited in the deregulation of air industry, supports the emergence of a system made up of multiple air platforms. The dynamic space of center-periphery type are reinforced there. Already strong centers often became more powerful through this new organization (New York, London, Chicago, Paris), while it helped secondary centers to emerge (Seoul, Fort Lauderdale) (Amiel, 2005).

1.3 "Small world" form of the air network
So, the world air network has specific properties of "small world". It is necessary, for example, to borrow 15 different flights to go from Mount Pleasant (in the Falkland Islands) to Wasu (New Guinea): this is the longest shortest path of the world air network (Guimera and al., 2005). We can see now the “small world” form of this networks. In fact, there is a high degree of connectivity between some selected airports and short ways to reach any airport to another, but in another hand, some numerous peripheral airports are very far from the entire network.

2. Hierarchical network analysis and visualization

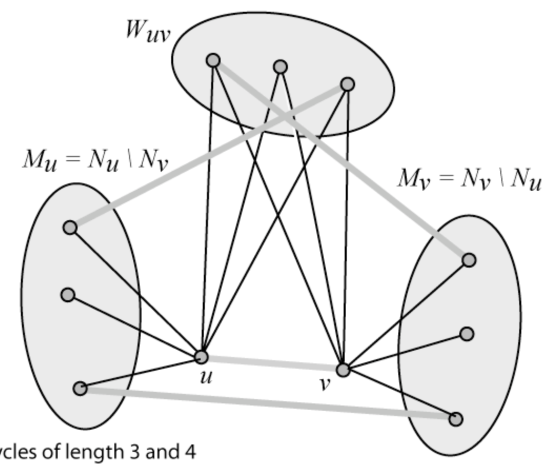
Making visible the emergence of these new configurations is difficult using "traditional" charts of flow. We thus planned to apply to geographical networks a methodology developed by D. Auber *et al.* in 2003, which allows to treat networks on a hierarchical basis according to the dominant interconnections. The algorithms which they developed on non-valuated graphs were adapted to valuated graphs.

2.1 Bursting of the network topology
The whole network can be broken up into related sub-graphs inside the general graph. These sub-graphs correspond to airports exchanging more passengers, directly or indirectly (i.e. with stopovers). Several "communities" of inter-connected airport cities coexist in this complex system (Guimera and al., 2005). The methodology developed by Auber *et al.* (2003) proceeds by filtering edges of a graph in order to break it up into sub-graphs. These sub-graphs correspond to the related components of the graph, highlighted by removing the edges which play a minor role in local connectivity. The procedure can be repeated on each sub-graph and thus reveals a hierarchy of nested sub-graphs.

2.2 Edge Filtering
A filtering is carried out on the basis of an associated value with each edge. This value reflects the cohesion brought by the edge within its vicinity. The “strength” of an edge is a generalization of the clustering index for nodes introduced by Watts and Strogatz

(Watts, Strogatz, 1998; Watts, 1999) and is close to ideas introduced by Granovetter (Granovetter, 1973). The strength of edges is obtained by calculating the ratio between the number of effective links between nodes incident to the edge and the maximum number of links which could be observed (fig.2).

Figure 2 : Edges filtering method



look at cycles of length 3 and 4

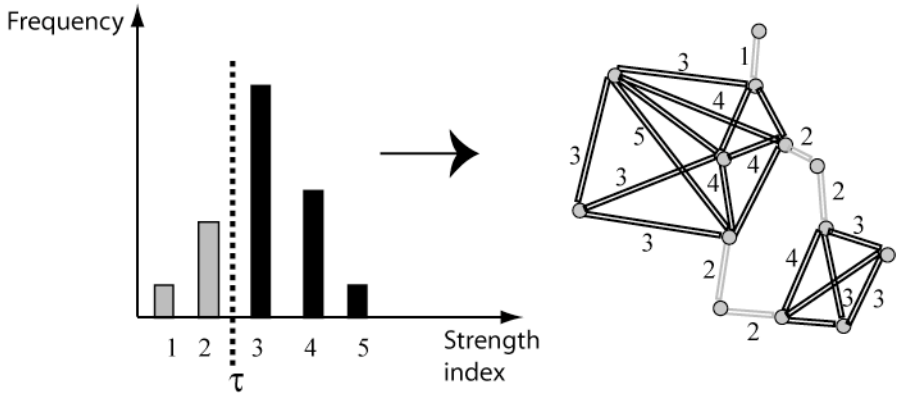
$$\gamma_3(e) = \frac{|W_{uv}|}{|M_u| + |M_u| + |W_{uv}|}$$

$$\gamma_4(e) = s(M_u, W_{uv}) + s(M_v, W_{uv}) + s(M_u, M_v) + s(W_{uv}, W_{uv})$$

Strength measure : $\Sigma(e) = \gamma_3(e) + \gamma_4(e)$

Among the neighbors of the two nodes *u*, *v* incident to the edge, it is necessary to distinguish their common neighbors (the *Wuv* unit on the figure) and those which are neighbor to only *u* or *v*. The importance of the number of common neighbors compared to those which are not common will determine if the edge is maintained or not. For example, on figure 3, only the edges whose nodes have more (or as much) common neighbors that non common neighbors are maintained (in black). The filtering process partly relies on the distribution of edge strength (fig.3). All edges with a value below a fixed threshold are filtered out. This threshold *t* is selected according to an quality index MQ(*t*) borrowed from Mancoridis (1998), which is similar with many optimization criteria proposed in literature (Alpert, Kahng, 1995; Berkhin, 2002, Chiricota *et al.*, 2002).

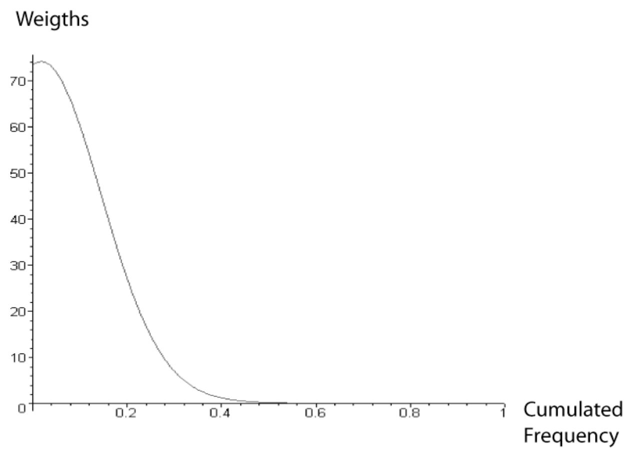
Figure 3 : Edge strength distribution



2.3 Taking passenger traffic into account

To obtain a relevant partition of the network based on passenger traffic, it was necessary to adapt the methodology of Auber *et al.* (2003), in order to take into account weight of edges representing passenger traffic. These exchanges distribute according to a "scalefree" distribution which correspond to a strong hierarchy of inter-connected world overhead networks (fig.4). In order to hold account of these weights, we multiply the strength of an edge by its weight. Taking into account of the weights produces a more relevant network partition.

Figure 4: Edge weights distribution (air traffics)



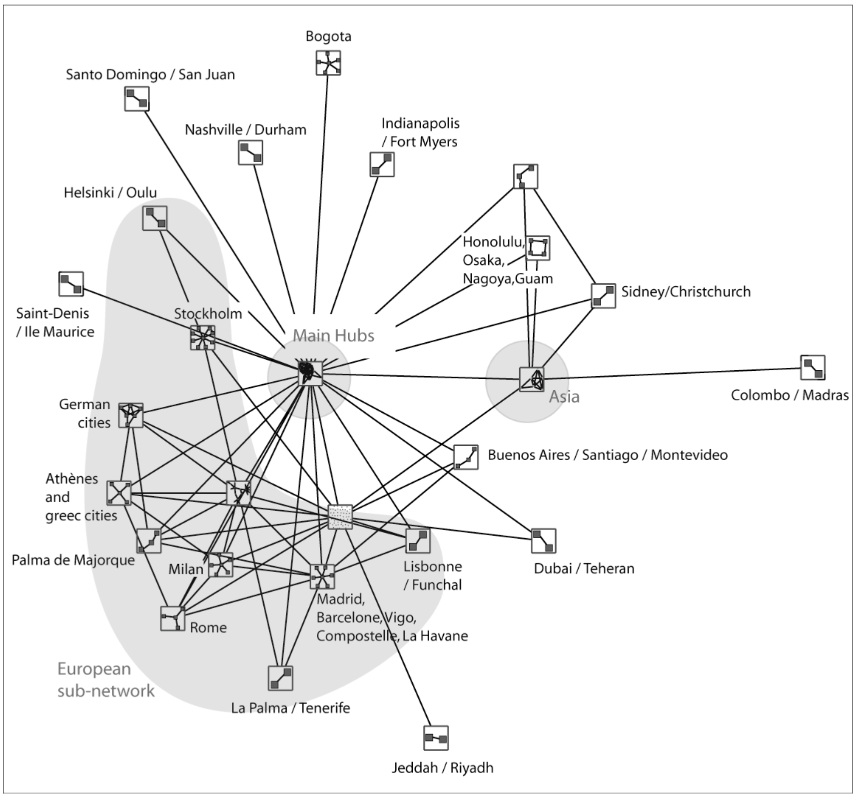
3. "Small worlds" in the world air network

A decomposition of the world air network could be carried out according to this adapted methodology from D. Auber *et al.* 2003. This new method makes it possible to treat on a hierarchical basis the network in nested sub-networks, according to the locally dominant interconnections. This method underlines the more interrelated groups of cities which thus form "small worlds". The step is reiterated inside each group in order to define even more interrelated sub-groups of cities. This step of hierarchical downward classification is performed repeatedly. It results in a number of different levels according to parts of the graph defining differentiated "depths". The depths of these levels are as stronger as the level of dependence and complexity increase inside the formed groups.

Thus, the method makes it possible to visualize, at various levels of the graphs which it would be impossible to represent in an understandable way on a single level. The matrix we considered consisted of the 1 000 connections having generated traffics higher than 300 000 passengers in 2000. These inter-connections relate to 250 cities of the world.

At the highest level of the world air traffic (fig.5), the network is organized around a central component, which we named "principal worldwide hubs". Around this component, a star topology spreads, emphasizing the role of the intercontinental hubs. On the same level, small cores are strongly inter-connected with this central component. Among those, sub-networks with continental logic appear, as it is the case in Europe and Asia. While descending the levels from the graph, one can specify this general organization. The algorithm of decomposition, applied to each component makes it possible to isolate in an iterative way of the levels from connectivity forming, starting from the most general level, and going to the sub-graphs nested at level 2, 3, etc.

Figure 5 : Air passenger traffic worldwide network (Level 1)

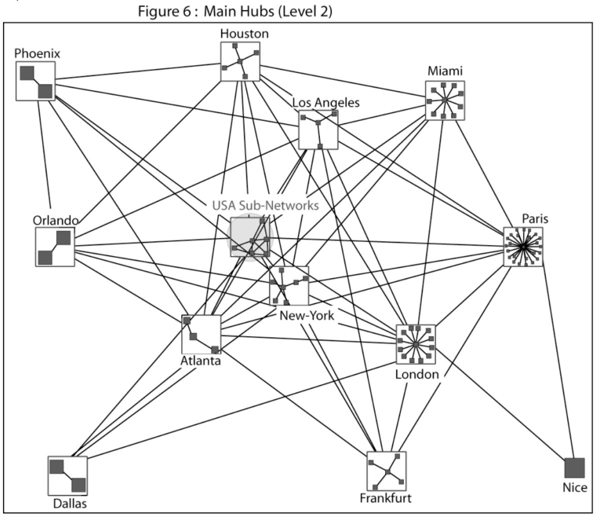


3.1 Most central cities

The cities which form the group of the "principal worldwide hubs" are American and European (fig.6). The examination on this second finer level of this area of the graph, reveals certain European hubs like Paris, London or Frankfurt, as well as principal American hubs like New York, Los Angeles, Houston or Miami. These American hubs are those which are dissociated for two principal reasons:

- initially, they are the continental entrance doors for the connections arriving from Europe;
- additionally, they were in majority chosen to constitute hubs for large American companies, like Delta Airlines in Miami or American Airlines in New York (Vowles, 2000).

Figure 6 : Main Hubs (Level 2)



An American sub-network is dissociated in the center, which one can specify on a third level (fig.7). The extent of the American territory imposes in fact, an air organization more complex than in Europe. Indeed, the use of the plane is the fastest and effective means of transport in the United States. If this unit is mainly made up of American cities, three European cities appear particularly related to these cities: Amsterdam, Dublin and Manchester. The justification of this presence is explained by the bilateral agreements and alliances between companies, in particular Continental Airlines which is present in the three airports.

The central component of this graph of third level can also be broken up again on two lower levels, that is to say on a fifth level (fig.8). This fifth level puts forward the local organization of the center and western North American area. They are secondary, very dependent between them and at the same time they are very "embedded" in the American hubs system (levels 3 and 2) which themselves are dominating on a world level (level 1). The strong connections between the American secondary cities and the world level rise from an organizational characteristic of the American airspace which has been arranged hierarchically very early, according to 3 main categories of hubs:

- traditional "gateways" (Los Angeles, Chicago, Boston, San Francisco);
- principal hubs (Philadelphia, Atlanta, Strait, Houston, Dallas);
- secondary hubs (Minneapolis, Denver, Phoenix, Cincinnati, St Louis, Tampa, Las Vegas) (Weber, Williams, 2001, O' Connor, 2003).

This hierarchical organization makes possible the American secondary cities to be particularly well integrated in the world air network.

Figure 7 : USA Subnetworks (level 3)

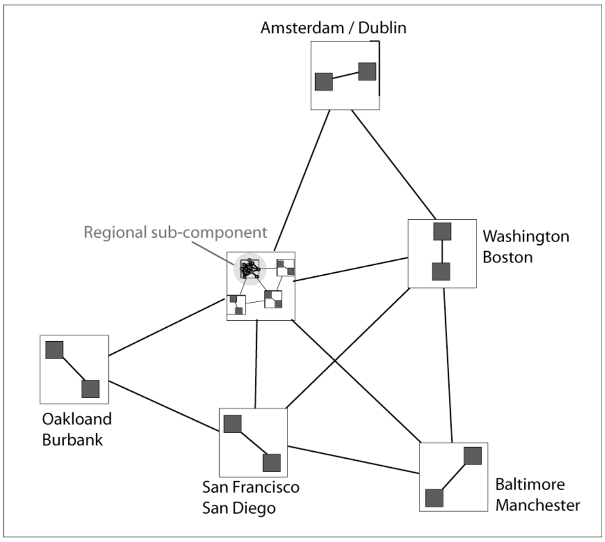
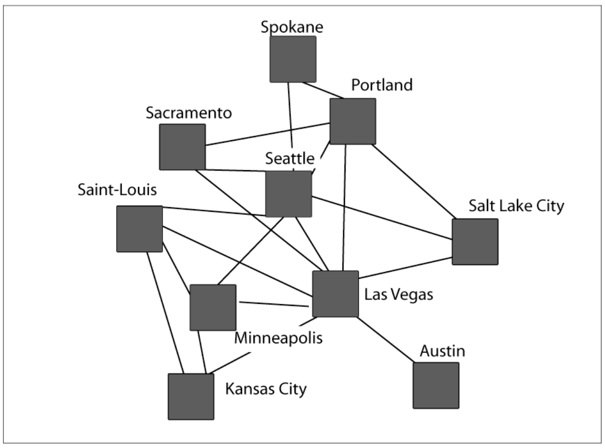


Figure 8 : Regional sub-component (Level 5)



The position of the whole of these cities is thus in the air world traffic core. The encased shape of these graphs shows a very integrated system, primarily on parts of the United States territory.

3.2 Continental groups
In opposition to the North-American system, the Asian and European systems seem less integrated into the world system. However, if the European cities not integrated in the system of hubs seem burst enough in various groups, the Asian system is very connected and forms a group with whole share (fig.5).

The Asian system can be broken up on a second level (fig.9). This system is organized in particular around two poles, Hong-Kong and Tokyo. The decomposition on a third level around the pole of Tokyo shows an international system strongly integrated around the Japanese capital, system going of Jakarta with Pusan, while passing by Shanghai (fig.10). Insularity in the Asian area partly justifies the strong integration of the regional network. Moreover, the potential and the demand for air transport in Asia involve an increasingly strong competitiveness between the airports and between the cities (Park, 2003).

Figure 9 : Asian network (level 2)

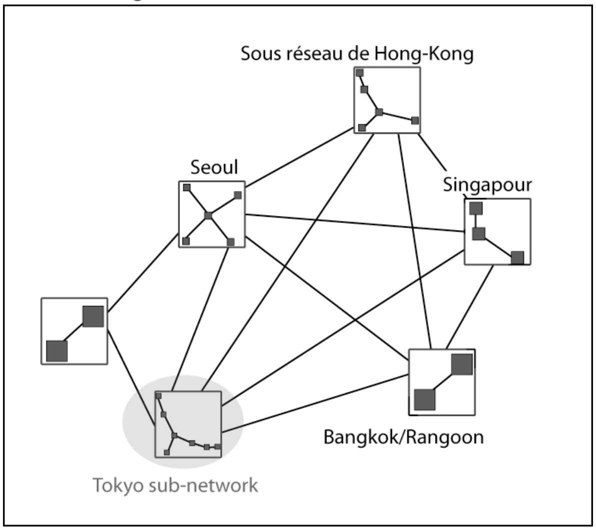
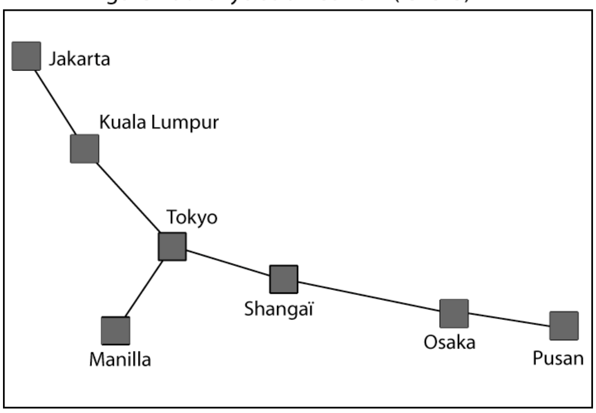


Figure 10 : Tokyo sub-network (level 3)



The European system appears, at the opposite, less integrated from Stockholm to Lisbon, undoubtedly because of the pregnant heritage of an airspace burst structure. Indeed, the national companies, under the pressure of the States, had organized hubs on each large European capital. It was necessary to await the deregulation of the European air sky in 1993 so that the transfer of competences in the management of the air routes of the European states takes place towards the private airline companies (Burghouwt, Hakfoort, Ritsema van Eck, 2003). In spite of the European Community efforts to build a coherent airspace, it still remains of great competitions between principal European hubs, as London, Paris, Frankfurt and Amsterdam (Graham, 1998).

3.3 Cities strongly dependent to the central network

Some cities are, although strongly dependent on the major hubs or the two unintermitting systems, little connected between them. It is the case of towns of Latin America like Bogota, Buenos-Surfaces, Santiago of Chile, or cities of Middle-East like Dubai, Teheran, Jeddah, or Riyadh. The relations between large South American capitals and the central network are intense because the exchanges towards the international one are done in great majority in an exclusive way starting from the large capitals. These capitals reproduced the movement resulting from the neo-liberal policies of airspace opening, which leads to the constitution of star distribution system formed around the hub and spokes system (Lipovich, 2002).

4. Emerging multilevel reticular territories

The organization of the air transport network, thus represented, is revealing of an interesting process of spatial integration. Indeed, the networks are articulated around a central core made up by principal hubs where the organization of the "reticular territories" distinguishes the three organizing zonal sets from the world economy: The United States, Europe and Asia. In the United States, the structures are treated on a hierarchical basis and the relations with the various territories are perfectly integrated. The example of Europe shows an airspace organization very little organized and little treated on a hierarchical basis: there is a multitude of airports and relations of the same level without single organization as for the United States. With the new European transport policy, one can suppose that this phenomenon will attenuate during next years (in particular by the application of the White Paper on the "European transport policy by 2010: the hour of choices "[European Commission, 2001]).

The weight of the Asian area is to be considered with attention. Indeed, Asia is the area which currently knows the greatest growth in term of air transport. It will be necessary to follow closely its evolution, because there one can suppose that the principal worldwide hubs group will integrate soon airports like Tokyo, Hong-Kong or Singapore.

The role of economies, markets and airline companies internal reorganizations are factors which supplement the explanation of these tendencies. The power transfer from states towards private companies, returns the airspace less and less partitioned and thus more turned towards competitiveness logics. Thus the private strategies are from now on large organizing "reticular territories" air. The only regulating authorities of this system are the international air organizations (IATA, ICAO). Air transport being one of the most competing sectors in world (Spinetta et al. 2003), one must expect a constant evolution of the networks and an increasingly complex organization of its reticular territories.

Conclusion

The integration of the properties of "small worlds" in the analysis, led to the identification of subgroups or "communities" of cities constituting the main world air network. A hierarchy was made visible, more complex than a simple hierarchy of traffics, because multiple.

The original information underlined by this type of representation is the structure in two "small worlds" of the overhead network: one is Western and the other is the Eastern one. "Forsaken" cities of these small worlds are positioned in periphery of air transport, less accessible from the planet than the others. The deepening of the study of these small worlds and their dynamic approach will allow, in next studies, to better evaluate the impact of the strategies of the companies on the structuring of the world air exchanges. This dynamic could have strong effects on the globalization by multinational companies and on the international division of labor. This way of research has to be explore deeply, comparing exchanges matrices, to build a real geography of world cities.

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