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World Cities of Scientific Knowledge: Systems, Networks and Potential Dynamics. An Analysis Based on Bibliometric Indicators

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Abstract

This paper is based on identification of the pattern of the upper level of the world city network of knowledge as published in a series of earlier papers. It is our aim to update the findings and relate to the general world city discussion. The structure of the world cities of knowledge network has changed over the past decade in favour of south-east Asian and south European cities and in disfavour of the traditional centres of North America and north-western Europe. The analysis is based on bibliometric data on the world's 100 largest cities measured in terms of research output. The level of co-authorship between researchers in different cities is an indicator of links and respect, and the number of citations of papers produced by researchers located in each city is an indicator of respect. Finally, one research discipline is selected for an experiment in forecasting future hot spots of research.

Introduction

This analysis is based on our research on the global system of knowledge centres defined as greater urban regions as documented in many papers—for example, Matthiessen and Schwarz, 1999; Matthiessen *et al.*, 2002a, 2002b, 2006. In the first of the papers mentioned, we identified the major European research centres and analysed the composition of research for each city by categorising total research output by disciplines. Using multivariate statistical methods, we found types of research cities. In the second and third papers, we analysed the changing performance of the major global research centres. We have identified the largest research centres of the world measured in general terms of research

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output and we have calculated growth rates. Co-operation between the large units in terms of co-authorship and citing patterns has been analysed and we have looked at two dimensions of co-operation links. One dimension is represented by the total of intercity relations, the other by the international parts of these links. We synthesised the analysis to a simple picture of the major global system and identified nodes of research. In the fourth of these papers, we summed up the pattern of global research centres and found winners and losers in terms of weight and nodality during the period 1996–2004.

The present paper relies on previous papers, but also presents new findings. We update the results of earlier papers by adding the time-period 2004–06, by incorporating cities not counted for before and by refreshing the delimitation of observation units. We also for the first time present results for the discipline of information and communication technology research. Also new is that, inspired by the GaWC group, we present a tentative categorisation of the world cities system of scientific knowledge centres; also new is that, by extrapolation, we identify future winners in the global system of major scientific knowledge centres. These are cities which have the potential to lift their position in terms of research strength and nodality. We relate to literature about concepts of cities as places of flows and about geographical proximity in bibliometric studies.

This paper is linked to the concept of world cities and to the concept of cities as places of flows (Friedmann, 1986; Sassen, 1991; Castells, 1996/2000). It is especially related to the GaWC group's work on the world cities concept (Taylor, 2004 and 2007; Taylor and Aranya, 2008; Taylor *et al.*, 2010; Derudder and Witlox, 2005; Smith and Timberlake, 2001). The concept of world cities is based upon the understanding that many cities are global service centres. Cities with world city status are metropolitan centres that have extensive transnational and global external links, and which assume a leading role in the organisation of series of significant networks. Not only are the world's great cities important nodes in the world economy, they are also command-and-control centres in a world-wide dominance hierarchy (Smith and Timberlake 2001).

Cities are almost always also centres for a hinterland, which they more or less dominate, but cities are no longer only dependent on their hinterlands in a Christaller-style understanding of the hierarchy of central places (Christaller, 1933). Taylor *et al.* (2010) find that central place thinking represents one of two complementary generic processes, the other being described as a central flow theory through an interlocking network model. Central place theory takes reasonable care of hierarchical relations, but is deficient for understanding complex non-hierarchical relations. In central place theory, Taylor *et al.* (2010) claim that centrality of location is the basic building-block upon which spaces of places are formally constructed. In contrast, in central flow theory, it is flows that come to play a central role as the building-blocks, generating a network: it is a space of flows that is formally constructed. In other words, it is a matter of what is important—'place' or 'flow'. The economic and social relations of cities are increasingly global; national flows and connections are extensive and important, but it is transnational flows that are notable and growing. The pattern of these transnational flows reflects the role of metropolitan centres as logistical and command centres in the global economy (Bayliss and Matthiessen, 2006).

It is generally acknowledged that world city status is obtained by relational data on what flows through cities (people, goods, information, knowledge and money) rather than on what is contained in them (Derudder and Witlox, 2005). With air passenger and telecommunication flows analysis as notable exceptions (Pirie, this issue; Mahutga *et al.*, this

issue; Córdoba Ordóñez and Gago García, this issue; Vinciguerra *et al.*, this issue), Devriendt *et al.* (2008) identify a lack of appropriate data on urban networks, especially on transnational flows. Their study presents an overview of the dominant approaches for understanding intercity networks through analysis of actual connections such as fibre cables and their interconnections, and they find, by studying the cyberspace immaterial flows such as Internet traffic, that the Web is dominated by north-west European cities. Taylor (2004 and 2007) and the GaWC group consider cities in relational terms, as the product of networking activities. Their analyses of interurban flows and connectivity focus on cities as the organising 'hubs' of globalisation and interpret cities as global service centres. They analyse data on multinational financial and business services co-operation across 315 cities world-wide by the use of standard multivariate statistical methods. The GaWC group identifies a hierarchy of world cities based on the connectivity of business service networks. They state that it is the myriad of flows between offices in different metropolitan centres that forms the world city network. Through an analysis of leading global service firms in terms of their overall network connectivity, they classify the network of world cities and, in a later paper (Derudder *et al.*, this issue), they measure connectivity changes 2000–08 and identify an exceptional decrease in the connectivity of US cities (with the exception of New York) and a rise for Chinese cities. Overall, however, they find a high degree of inertia and an overall stability over time in intercity relations. In contradiction, Alderson *et al.* (this issue) indicate that the world city system is in the midst of a restructuring in such a way as to concentrate power in a small number of cities, and Mahutga *et al.* (this issue) find, using airline passenger data, a substantial changing pattern with certain semi-peripheral and/or Asian cities tending towards dominant positions.

Our study of the knowledge cities of the world is related to this research. We consider the system as not merely a sub-system of the world cities system, but as a combination of such a sub-system and a system in its own right. Knowledge production and distribution constitute a significant network. Interaction between scientists is often an untraded relation in the way Storper (1997) has described it and the benefits are of a qualitative nature. Creativity flourishes in the co-operation between researchers, why else should they co-operate?

We isolate one type of immaterial flow (co-authorship), which, however, reflects material flows of the persons involved. They meet, talk with each other, work together and go on the Internet. Subsequently, they produce a result in the form of a qualified research paper. Their actual interaction pattern is the consequence of a well-established and often long-lasting interaction network and it demonstrates how cities are involved in the knowledge-producing parts of the world economy. The linking of cities in this respect indicates that some cities house high-quality value-adding processes for the knowledge economy global system. Research connectivity is an important feature for the status of a given city. The way in which the flows of ideas are structured and link the world cities of knowledge reflects patterns of interaction and dominance. We analyse the overall patterns of the top-level global research system 1996–2006 in terms of structure, growth and nodality, and combine this with an attempt to answer the research question: can the next generation of winners and losers (cities) be predicted within narrow fields of research disciplines? Our claim is that cities with a higher than average growth in output of one discipline of research, and with higher than average growth in the number of citations per paper, are likely to be the hot spots of future research of that discipline. We isolate one discipline, information and communication technology, and consider which

cities will be the future winners and losers in the world of research within that discipline.

The Data: The Science Citation Index Registered on Functional Urban Units

The data source is the Science Citation Index which comprises papers from leading international research journals and reports of natural science, medicine and technical science. Papers are registered in the database with some delay and, due to our use of citings to papers in the present analysis, we cannot include the latest registering and have decided the time limit for inclusion to be 31 December 2006. The Science Citation Index database is produced by the Institute for Scientific Information (ISI, Philadelphia, PA) along with a number of related products. It records, for over 5000 journals leading in their field and for a large number of conference proceedings and other research publications, all contributions with full bibliographic description, all authors with affiliations, subject codes for journals and all references (citations) to the research literature, and it categorises papers according to research disciplines. When using the Science Citation Index for registered papers in science, medicine and engineering, all the biases and problems inherent in this type of data are carried into the analysis. The international bibliographic databases are useful tools for study of many aspects of the international research system, but the data are not unproblematic, due, *inter alia*, to various biases of coverage and due to different publication patterns in different disciplines. The measure exhibits an Anglophone bias and it presents technical intricacies, like subject classification of articles and handling of multiple authorship. Some analysts find it impossible to evaluate scientific productivity. We obviously do not share such an opinion. Our conclusion is that analyses based on bibliographic data can give indications (but indications only), of a quantitative nature and interpretations must be seen in the light of the biases and limitations inherent in the data.

Search methods applied to the index are combined with a spatial urban delimitation in order to elaborate a reasonably significant list of important research centres, measured by research output related to the address of the institution of authors. The only global system of delimiting urban units is the outdated United Nations system of urban areas. This is purely physical and based on minimum distance between buildings. It does not allow for registering the limits of modern functional urban regions. So we have delimited our observation units as 'greater' urban agglomerations by a uniform logic where it has been the object to identify 'functional' units—that is, city and daily hinterland (labour market area). We have done so manually by using topographical maps in combination with statistical observations on density and commuting, and we have looked into already-existing delimitation systems like the metropolitan statistical areas (SMAs) of the US and the nomenclature of territorial units for statistics (NUTS) observation system of the European Union. When in doubt we have overbounded the functional urban region. We have further combined neighbouring cities if the distance between the cities is less than 45 minutes of surface transport. We have tested more than 100 city-regions world-wide in order to identify the largest centres and we are confident that our top 30 and top 40 lists really represent the 30 or 40 largest cities of the world in this respect. We also present data analysis concerning a selection of 74 regions, but must then state that we cannot be certain that this selection is the 74 largest in this respect, even if it comes close. We have then constructed a system (file of postal numbers or other identifications like city names) whereby addresses of authors' institution or company can be allocated manually to the urban units, in a time-consuming process. We have used the latest (2006) delimitation as the basic observation unit for all time-series. The

method is presented in detail in Matthiessen *et al.*, (2002a).

Structure and Change of the General System of World Cities of Knowledge

Research output is dominated by OECD countries with the US first and the UK second, and it is a general observation that scientific output is highly concentrated due to agglomeration advantages. Yet spatial concentration in a selection of centres is extreme, which is confirmed by our findings. Frenken *et al.* (2009) list three reasons for this. First, serendipitous encounters are more likely when two actors are in close vicinity. Secondly, the needed face-to-face interaction comes at a cost related to distance. Thirdly, the rules of the game in the form of funding, labour market regimes, intellectual property rights and languages constrain interaction, in particular between nation-states. We would add a fourth reason—namely, the history of the initial location of universities and the subsequent inertia.

Globally, research (medicine, science, technical) produced 2 792 459 papers in 1996–98, 922 888 in the 30 largest centres, and 3 571 213 papers in 2004–06 of which 1 238 131 were produced in the 30 largest centres. Total growth has been 28 per cent and growth in the top 30 cities has been 34 per cent, which demonstrates a concentration process. Of the total research output, 35 per cent was produced by the 30 largest cities in 2004–06. Figure 1 presents the top 30 list of research cities in the world for the two periods of time. The true giants of knowledge production are London and Tokyo–Yokohama. These two urban regions are in a league of their own. They were so in 1996–98 and they are so in 2004–06—the two periods of time we use in this paper. Yet their rank has shifted in favour of Tokyo–Yokohama. The two leaders are followed in rank by a series of eight cities, which comprise the second level of knowledge-producing cities. The second levels are almost identical for the two time-periods. The group comprises the San Francisco Bay Area, Paris, Osaka–Kobe and Boston together with New York, the Amsterdam region (Amsterdam–Hague–Rotterdam–Utrecht) and Los Angeles. In 1996–98, Moscow was a member of the group, but this city has suffered a dramatic decrease in the output of research papers and has fallen from rank 6 to 11. The new member of this group is Beijing, which was not even in the top 30 list for 1996–98, but is now a prominent number 4. In 1996–98, the top 10 consists of four US cities, four European centres and two Japanese regions. In 2004–06, the top 10 list includes four US regions, three European cities, two Japanese and one Chinese region. The level of cities ranking 11–30 included 10 North American and 10 European centres in 1996–98, and changed in 2004–06 to nine European, eight North American and three Asian centres. Although a high degree of inertia can be observed in the two top 30 lists there are shifts, and some cities like Beijing, Seoul and Toronto show dramatic advances in rank, while Moscow, Washington DC, Edinburgh–Glasgow, Cambridge and Oxford–Reading likewise suffer dramatic falls in rank. Very few studies can be used to mirror our findings. One exception is Taylor (2005) who, on the basis of data published by Matthiessen *et al.* (2000), calculates high nodality for the same five cities that top our list for 1996–98.

Growth percentages are further demonstrated in Figure 2. It is clear that some 10 cities advance highly in this respect, but also that a few centres are in a losing mode. St Petersburg and Moscow are in decline. The 10 most advancing cities comprise six Asian cities, three centres from Latin America plus one Australian region. A new pattern of the knowledge world city system is evolving rapidly. Clearly, the position of European and North American research is under challenge from new high-producing centres outside these continents.

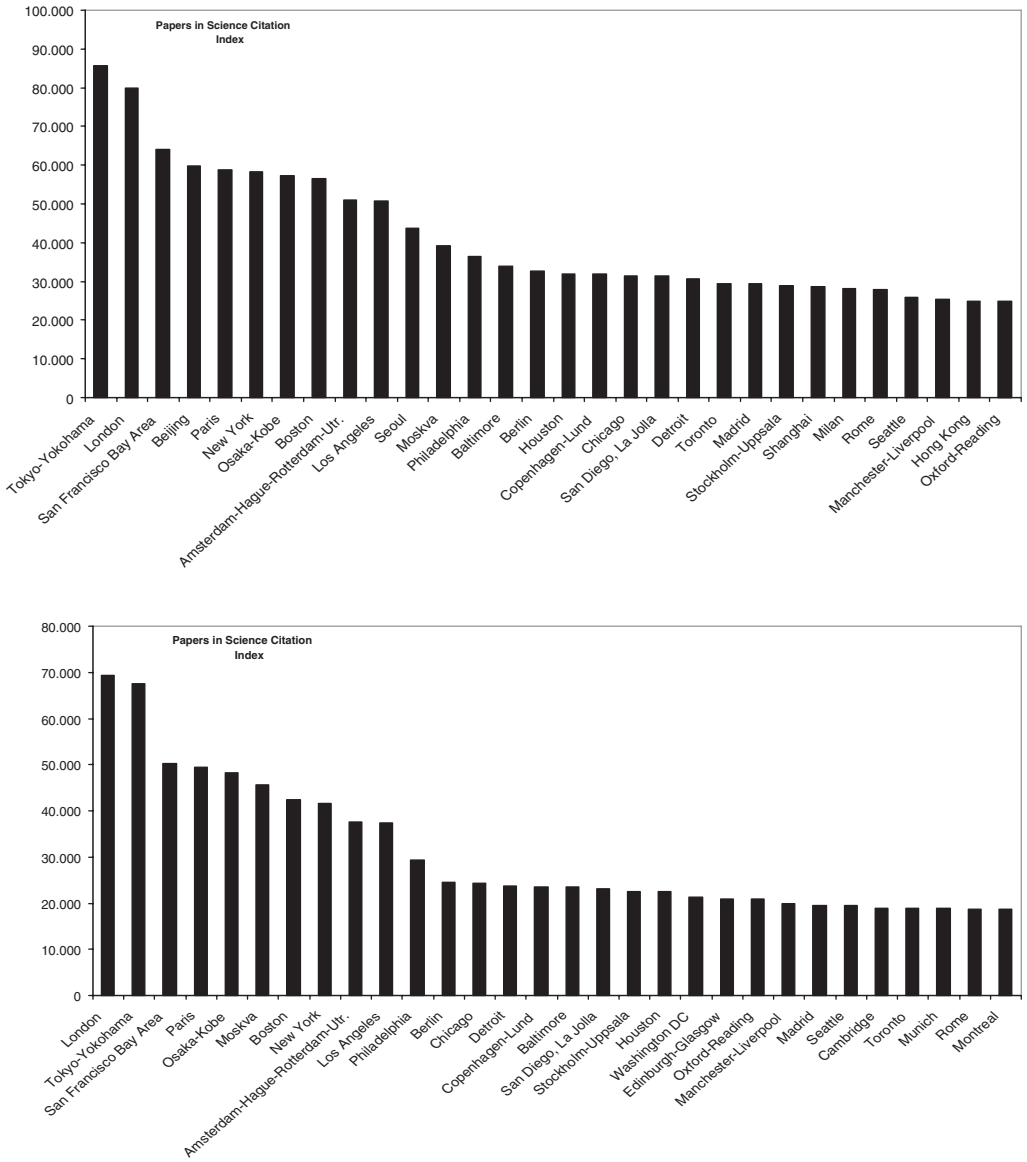

Figure 1. Ranking of the 30 largest world cities of knowledge, 1996–98 (lower graph) and 2004–06 (upper graph): all research (in medicine, science and technology).

Space in Bibliometric Studies

Dealing with space in scientometric studies is a complicated matter due to factors related to definitions. Frenken *et al.* (2009) have published an overview of the literature on spatial scientometrics and have identified a series of methodological problems. They have extracted collaboration, citation and mobility as the main research topics in the literature and they identify common findings of extreme spatial concentration of scientific activity and of the high impact of physical proximity in scientific co-operation. The use

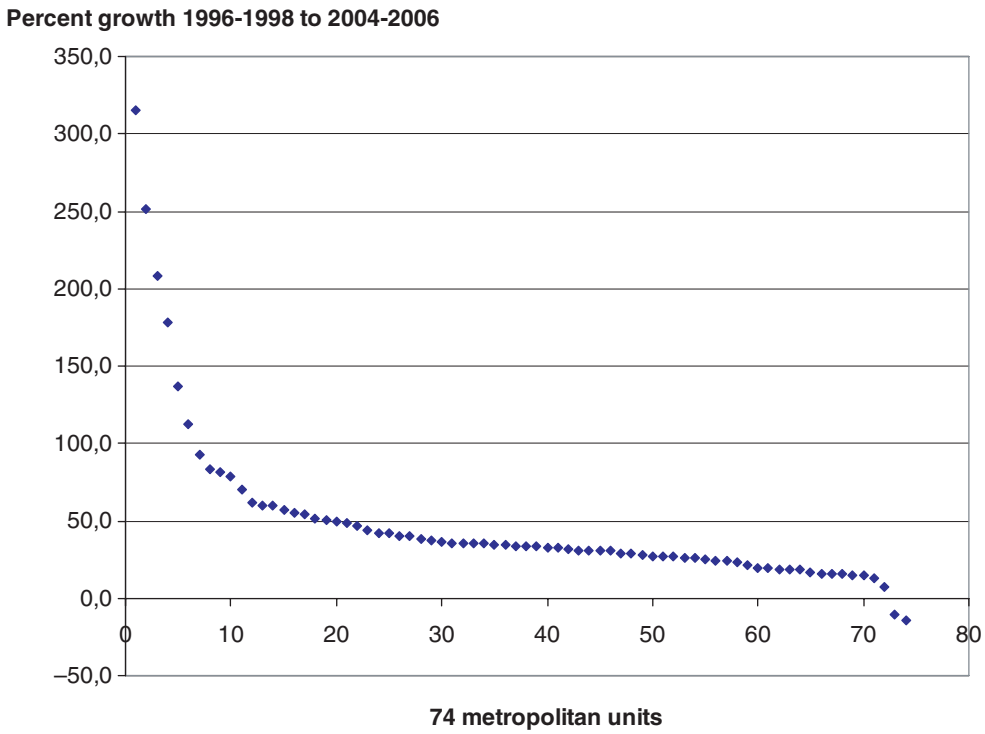

Figure 2. Growth in output: total research (medicine, science and technology) for 74 world cities of knowledge, 1996–98 to 2004–06.

of publication data is both promising and challenging. Promising because of the vast information related to the single bibliometric unit and challenging due to the question of the spatial unit and the use of an address to allocate a paper to this unit. The review makes clear that spatial analyses of science generally are one-dimensional and do not account for other dimensions of interaction such as cognitive, social or organisational proximity.

At a local scale, Segal, Quince,Wicksteed (1985) identified the Cambridge phenomenon, which had to do with the distance-related spillover of research activity at universities to local companies. Distance played a major role with respect to the Cambridge phenomenon and distance is also important for understanding more global patterns. In pre-Internet studies, Luukkonen *et al.* (1992) and Luukkonen *et al.* (1993) identified, using 1970–90 data, that the distance between scientists represented a strong motivation to collaborate, while Katz (1994) concluded that geographical distance played a significant role in scientific collaboration using 1981–90 data for Canada, Australia and the UK. In the Internet period, it has been a persistent assumption that electronic communication has diminished the role of distance for interaction patterns and that in recent years geographical proximity has become less important for research collaboration. When this is tested relative to other possible factors, such as language and culture—as, for example, done by Havemann *et al.*, (2006) using German immunological institutes' collaboration data for 1992–2002—it is found that the Internet did not change much the collaboration pattern. No matter the

time-period studied, geographical distance between co-authors of papers is found to be one of the most important factors affecting research collaboration. This has been concluded by Liang and Zhu (2002) using 1998–99 Chinese regional data; and, when Hoekman *et al.*, (2009) addressed the role of proximity (in combination with the role of élite structures) for interregional scientific collaboration between 1316 European Union regions plus Norway and Switzerland for the period 1981–2004 at the NUTS-3 level, they found a powerful relation to proximity of regions (they also found the existence of élite structures between regions of excellence and between capital regions).

Recently a number of scholars (Malmberg and Maskell, 2002; Torre and Rallet, 2005; Boschma, 2005) have criticised the view on the role of geographical proximity as being oversimplified and have found that the precise role of geographical proximity for knowledge exchange and collaboration still remains unclear. Ponds, van Oort and Frenken (2007) took up the challenge. They used 1988–2004 data on the spatial pattern of the Netherlands NUTS-3 regional collaboration and tested, with positive results, the hypothesis that the collaboration between different kinds of organisations is more geographically localised than collaboration between organisations that are similar due to institutional proximity. In conclusion, they found that geographical proximity plays a significant role in collaboration, especially when it comes to overcoming institutional differences.

Research Quality: Co-operation Patterns

Size of research output does not necessarily indicate quality of output. With bibliometric methods, it is, however, possible to find strong indications of research quality, because the way researchers publish together indicates respect, as does the way they cite each other. Researchers work with colleagues if their own research is expected to benefit. However, the way researchers work together takes many paths and reflects co-operation on different levels and of different types. The interaction pattern of researchers mirrors the flows of ideas and reflects attraction patterns and traditions of co-operation. It is influenced by similarities and differences of many types and is also the consequence of different kinds of barriers to contacts. The pattern of co-operation reflects underlying structures like distance, language, nationality, religion, culture, economic blocks, migration (expatriates), teacher–student relations and even friendship. A tradition of co-operation is of great importance and traditions differ from discipline to discipline, from university to university and between the university world and other producers of research results, like private enterprises and public institutions and organisations. Research co-operation contributes to the status of a given city and, when added up, it demonstrates the nodal position of the centres in question.

Research is also—by definition—an innovative and creative activity, and thus in itself a driver of urban growth. Interaction between researchers in different cities further indicates creativity as researchers work together to improve their performance. Co-authorship thus represents connectivity of high quality and well-connected cities are likely to be important cities in the global knowledge network.

In our analysis, observed co-authorship is linked to expected level of co-authorship between scientists of two cities estimated from statistical averages across all intercity links and decided by number of papers produced by the smaller of two cities in a city pair. Figure 3 identifies the 4 per cent strongest links of all possible links between the 40 largest centres within science, medicine and technical research. The diagram of total intercity co-authorship gives national patterns in the US a very clear and distinct

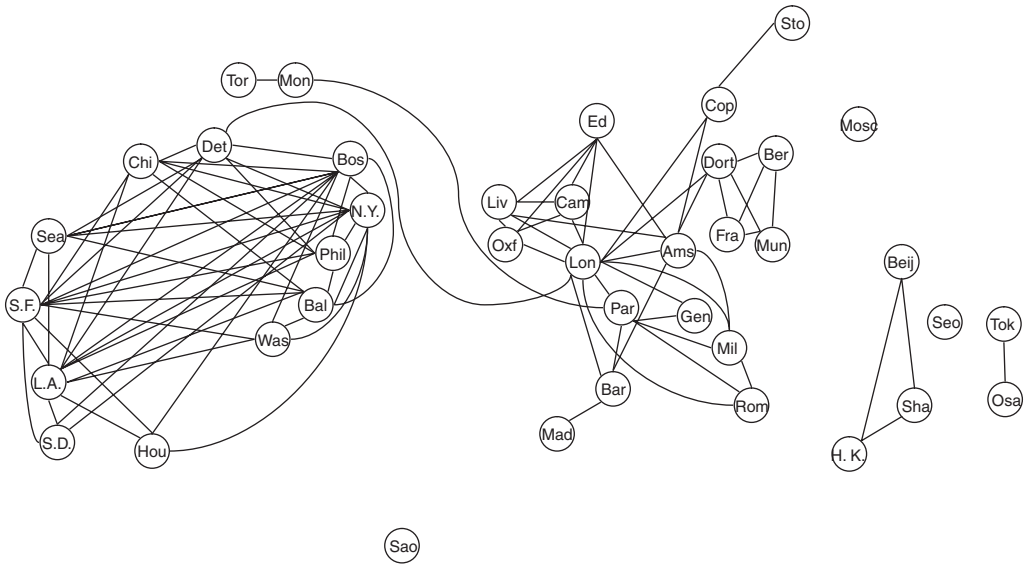

Figure 3. Connectivity of world cities of knowledge, 2004–06, measured as strong co-authorship links, for the 40 largest research centres of total research in medicine, science and technology.

appearance. The majority of all strong links are found within the US. Another system of importance is western Europe, where two national sub-systems can also be identified, in Great Britain and Germany. National systems of linkages are always of importance and, if there is more than one city from a nation in our database, it will inevitably be strongly linked to the other national centres. Intercontinental links are very few. Nodality is observed by the number of strong links and, when this is added up, the centres of dominance emerge. London is the world leader of research followed by four US centres—the San Francisco Bay Area, Los Angeles, Boston and New York.

When we isolate international co-authorship in Figure 4, the picture shifts in favour of European co-operation. North American cities do not co-operate much with the rest of the world, with the Canadian centres and the San Francisco Bay Area as exceptions. European co-operation is a patchwork of links, although distance plays a clear role. Intercontinental co-operation is of importance in this picture of strong international links. Three cities play leading roles with almost exactly the same weight—London, Paris and the Amsterdam region. They are followed by Genève–Lausanne (due to the international high-energy physic research facility, CERN, with its international profile of co-operation), the San Francisco Bay Area and Rome. The general picture of nodality is one in which the traditional European and, to a much lesser degree, North American centres play prominent roles. Asian cities are almost absent from this scene of co-operation and nodality.

The findings of research strength, links and nodality are of a rather similar nature to the findings of Taylor (2004 and 2007) on the world system of service centres. We have therefore categorised the world cities of knowledge using a tentative system, inspired by the Taylor method of hierarchical levels and bands of co-operation.[1] The categorisation is presented in Figure 5, where only cities on the upper two levels are indicated.

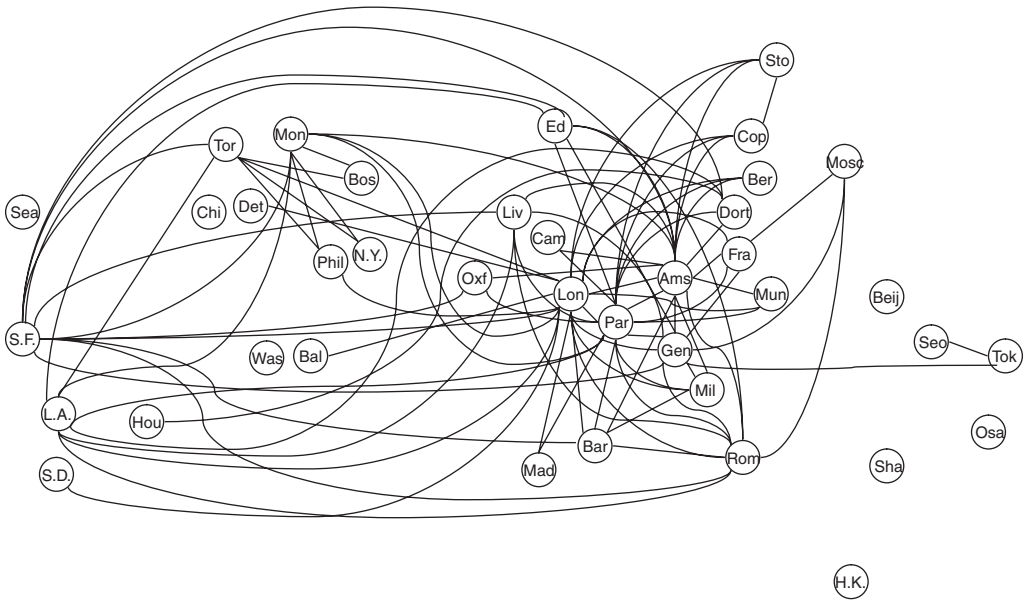

Figure 4. Connectivity of world cities of knowledge, 2004–06, measured as strong international co-authorship links, for the 40 largest research centres of total research in medicine, science and technology.

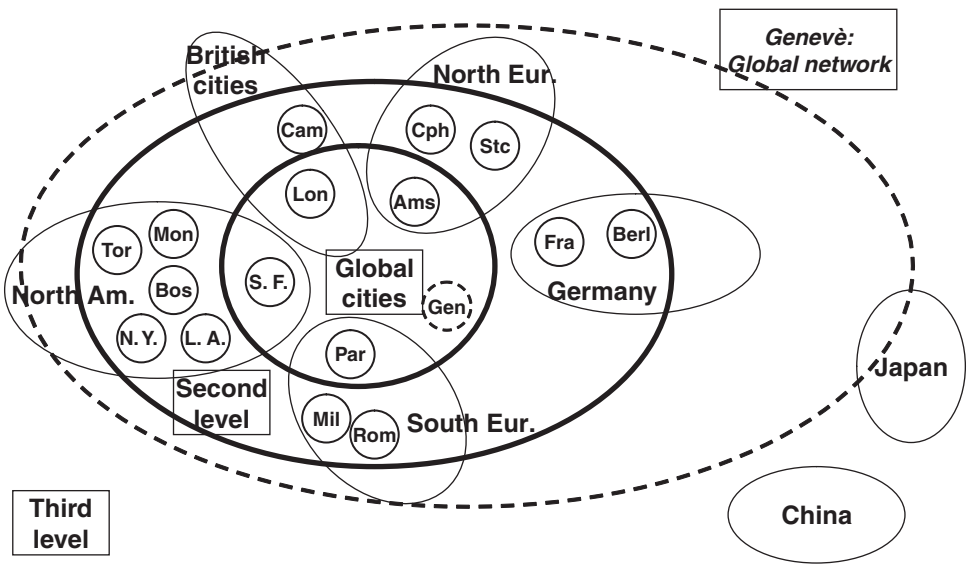

Figure 5. Levels and bands of world cities of knowledge, total research in medicine, science and technology, based on volume and international nodality, 2004–06.

The upper level of the hierarchy consists of dominating first-level global cities linked to cities all over the world. It includes London, the Amsterdam region, Paris and the San Francisco Bay Area, which are leaders of their own bands respectively. Genève–Lausanne is

also a true global first-level city, although it is a relatively small centre measured in output and although it does not have a band of its own but rather a global network. London has a band of British cities with Cambridge on the second level of global centres. The Amsterdam region plays a leading role within a north European band with Copenhagen–Lund and Stockholm–Uppsala as second-level centres. The south European band has Paris as the leader and Milan and Rome on the second level. The North American band presents the San Francisco Bay Area on the first level, but has a series of urban regions as sub-leaders: Boston, Los Angeles and New York, together with Montreal and Toronto. The German band has no first-level city, but two centres on the lower level, Frankfurt and Berlin taking the lead of this band. Japan has a band of its own with no upper-level cities, and so has China.

With this basic understanding of the way the upper-level world city system of knowledge functions, we want to look closer into the research question: can the next generation of winners and losers be predicted? We will first look at the general pattern of winners and losers in 1996–2006 using growth measures as indicators of success and failure. After that, we will go more into details with an example.

Winners and Losers: Total Research Output

We analyse the issue of success for 74 cities by relating growth in paper production to growth in citations per paper. We use a value-laden terminology to indicate changes of growth and reputation for the cities. This is illustrated in Figure 6, and the map-like diagram in Figure 7 presents the classification of the cities. Cities with high growth in output of research papers combined with high growth in citations per paper are labelled 'hot spots'. These are centres located in south-east Asia (Beijing, Seoul, New Delhi, Shanghai, Hong Kong and Singapore), in Australia (Sydney and Melbourne), in Latin America (São Paulo, Buenos Aires and Mexico City) and in south and eastern Europe (Warsaw, Prague, Budapest, Milan, Barcelona, Madrid) together with Oslo, Dublin and the only North American centre in this group of hot spots, Los Angeles. The second group is labelled 'focus on success'. These are centres with relatively high decrease in research output, but at the same time with high growth in citations per paper. The group presents a very distinct pattern. The two Japanese cities and the two Russian centres, together with all British cities (except Birmingham) and Gothenburg, Jerusalem and Washington constitute the group. The third group, which comprises cities with high growth in volume of output and decrease in citations per paper, is labelled 'volume up and reputation down'. The cities in this category are located in Europe (Helsinki, the Amsterdam region, Zürich and Genève–Lausanne), North America (Toronto, New York, Baltimore and San Diego) and Latin America (Rio de Janeiro). The fourth category is one of decreasing growth in both parameters and it is labelled 'black holes'. These centres are the real losers and they are found in central Europe (Brussels, Paris, Mannheim–Heidelberg, Stuttgart and Basel–Mulhause–Freiburg) and in the US (Chicago, St Louis, Denver, Dallas–Forth Worth, the San Francisco Bay Area and New Haven–Hartford). A last category consists of the cities which are close to average in respect of paper production growth and increase in citations per paper. They are labelled 'neutral' and are located in Europe, North America and Israel. The total picture of success and failure clearly identifies patterns and, to judge by means of extrapolation which cities have the potential to be the future winners of the research world, one has to look outside the traditional research strongholds of Europe and North America. The places to look for coming winners are south-east Asia, Australia and Latin America, together with south and east Europe.

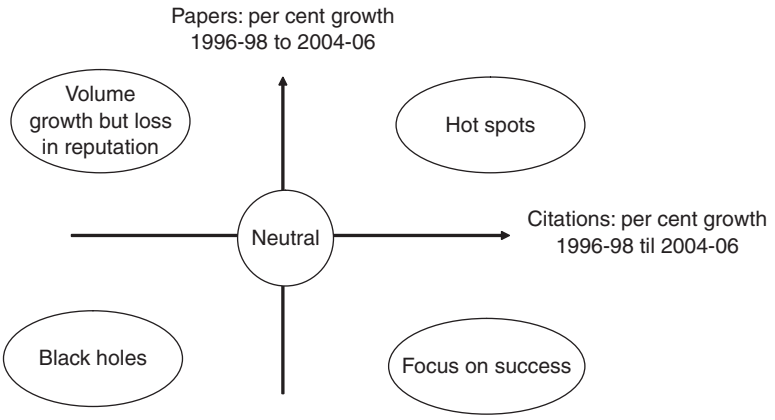

Figure 6. Growth types for world cities of knowledge, categorisation matrix.
Notes: the matrix is divided into four quadrants by the mean values of the two variables. Neutral is defined as cities with a less than 25 per cent deviation from the two means.

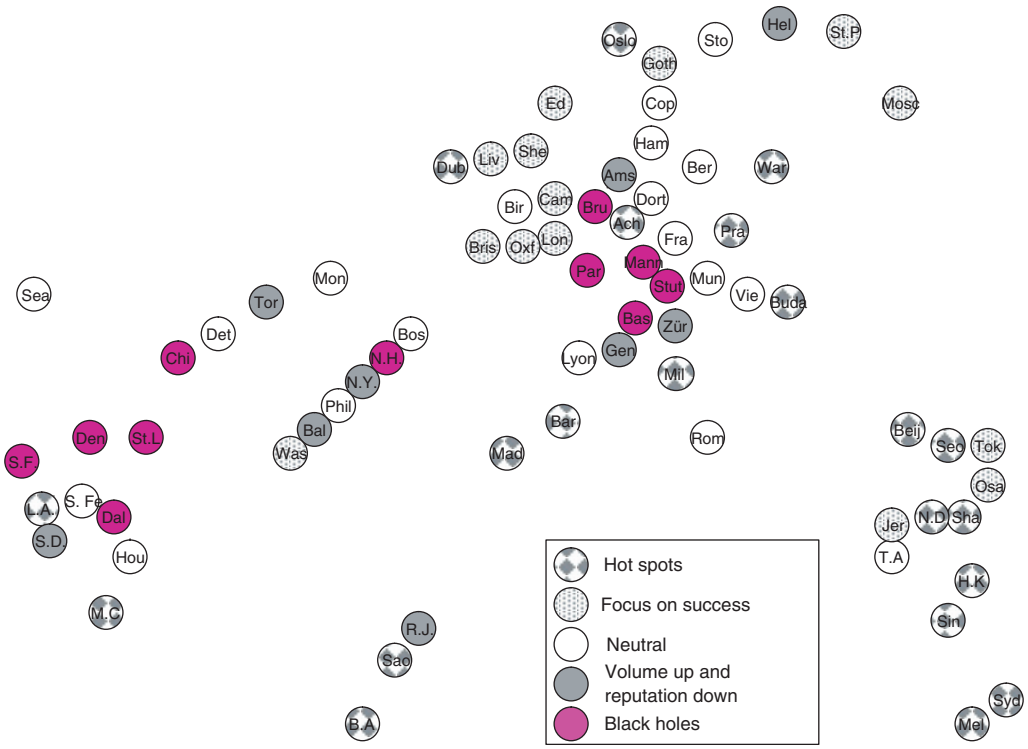

Figure 7. Growth types for world cities of knowledge, based on total research data (medicine, science and technical research), 1996–98 to 2004–06.

Information and Communication Technology Research: An Example

We have arbitrarily selected this discipline for further analysis because it is often considered to represent new and dynamic research and because the pattern deviates from the general pattern of research output and dynamics. At the global scale, information and communication technology research produced 98 414 papers in 1996–98, of which 25 613 or 26 per cent were from the 30 largest centres, and 187 967 papers in 2004–06, of which 62 345 or 33 per cent were from the 30 largest centres. Total growth has been 91 per cent and the growth of the top 30 cities has been 143 per cent, which demonstrates a very active concentration process. This discipline produced 5 per cent of all research within medicine, science and technology during 2004–06. Figure 8 presents the top 30 list of cities within this research measured by output in 1996–98 and 2004–06.

Two cities top the list in 1996–98—Tokyo–Yokohama and the San Francisco Bay Area. They are followed by a group of six centres, London, Los Angeles, Osaka–Kobe, the Amsterdam region, Houston and Paris. The heavy centres in 2004–06 are Seoul and Beijing and the next level of six centres comprises Tokyo–Yokohama, Houston, the San Francisco Bay Area, Singapore, London and Paris. Clearly, production has shifted. South-east Asian cities are challenging the North American, European and Japanese field. Three Asian cities are now at the very top of the list. Most of the cities on the 2004–06 lists (16) are European, seven are North American, six are Asian and one is Australian. Compared with the top 30 list of all research, there is an overweight of European centres and an underweight of North American centres, and the specific ranking of cities deviates rather much from the top 30 list of all research. In comparison, the two top 30 lists of this discipline show a group of very fast climbers from Asia and Spain. This group consists of Seoul, Beijing, Singapore, Shanghai, Madrid and Barcelona. Two cities have dropped dramatically and Moscow and Washington DC are no longer in the top 30 list. Most other losing cities have only lost a few steps in the rankings.

In Figure 9 we have indicated the 4 per cent strongest links of all possible links between the 40 largest centres within information and communication technology research. The diagram presents four distinct systems of co-operation, continental Europe, Britain, the US and south-east Asia–Australia, but also 15 strong intercontinental links. The European system presents national patterns of co-operation combined with more internationally connected German, Spanish and Italian sub-systems. The Amsterdam region and Genève–Lausanne are the top nodes of this continental European system in respect of international links, followed by Paris, Berlin, Vienna and Zürich. British cities constitute a rather isolated sub-system with London and Cambridge as nodes. The US sub-system has the San Francisco Bay Area as the principal node followed by Los Angeles and New York. A last sub-system is constituted by Asian and Australian cities, but excludes Seoul and the Japanese centres. This sub-system has the small centre of Hong Kong as its node. The picture of links is completed by the interrelated but isolated Japanese centres and by the interrelated but connected Canadian cities.

The findings for information and communication technology research strength, links and nodality are summarised in Figure 10 using the same Taylor-inspired method as for the diagram in Figure 5, demonstrating hierarchical levels and bands of co-operation. Only cities in the upper two levels are indicated. The upper level of the hierarchy consists of dominating first-level global cities. The centres of this research discipline do not constitute one overall system in the same way as the total research linkages did, but are grouped in a series of rather independent systems with weak interrelations. The three

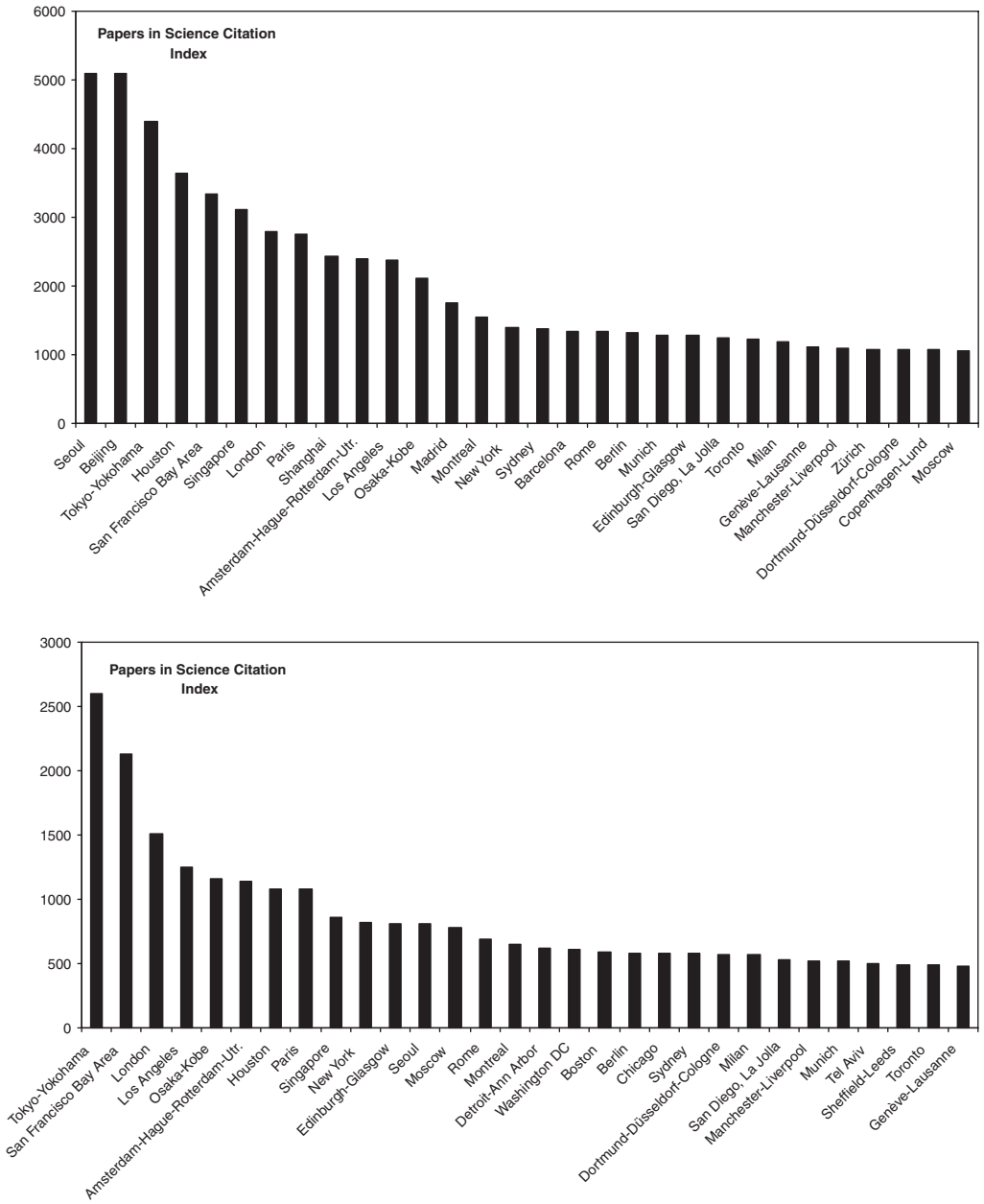

Figure 8. Ranking of the 30 largest world cities of knowledge, 1996–98 (lower graph) and 2004–06 (upper graph): information and communication technology research.

true global world cities of information and communication technology research are the San Francisco Bay Area, the Amsterdam region and Genève–Lausanne. Four central systems—or bands—are identified, two with cities that interlock directly with the upper level hierarchy and two with cities linked into the second level of the hierarchy. The US cities constitute a very distinct band with the San Francisco Bay Area as the nodal centre and New York and Los Angeles on the second level. Continental European cities likewise

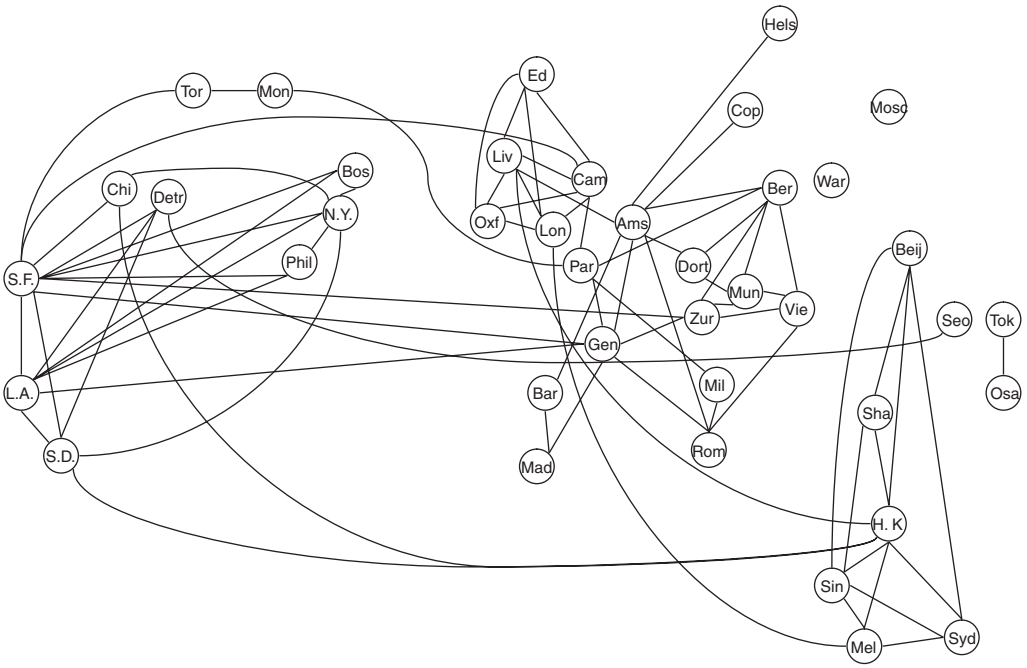

Figure 9. Connectivity of world cities of knowledge, 2004–06, measured as strong co-authorship links, for the 40 largest research centres of information and communication technology research.

form a distinct band with two centres on the upper level, the Amsterdam region and Genève–Lausanne. Britain has no true global centres, but London and Cambridge are the leading—but second-level—cities of this band. The same type of pattern is presented by the Asian–Australian band, where the leader is Hong Kong. Canada has a low-level band of its own and the Japanese cities have an almost disconnected band, also without upper-level cities.

We then use the same classification system and the same terminology as indicated in Figure 5 to identify winners and losers in respect of growth figures in information and communication technology research output and citations per paper. The result is presented in Figure 11. Only one hot spot city is found in North America (Houston) and three in Europe (Bristol–Cardiff, Barcelona and Dublin). Three hot spots are located in Asia (Singapore, Beijing and Shanghai) and two are in South America (São Paulo and Buenos Aires). Cities with a focus on success in information and communication technology research are concentrated in the US and the group also comprises two European centres (St Petersburg and Sheffield–Leeds) and New Delhi. Volume up and reputation down cities are southern and eastern European centres, together with Mexico City, Rio de Janeiro and Seoul and the Black holes in this respect are European centres plus Tel Aviv and New Haven–Hartford. The neutral centres are located in central and northern Europe, in North America, Asia and Australia. The total picture of success and failure clearly identifies patterns and, in order to judge which cities have the potential of becoming the future winners of the research world, one has to look outside the traditional research strongholds of Europe. The places to look for coming winners within the research discipline of information and communication technology

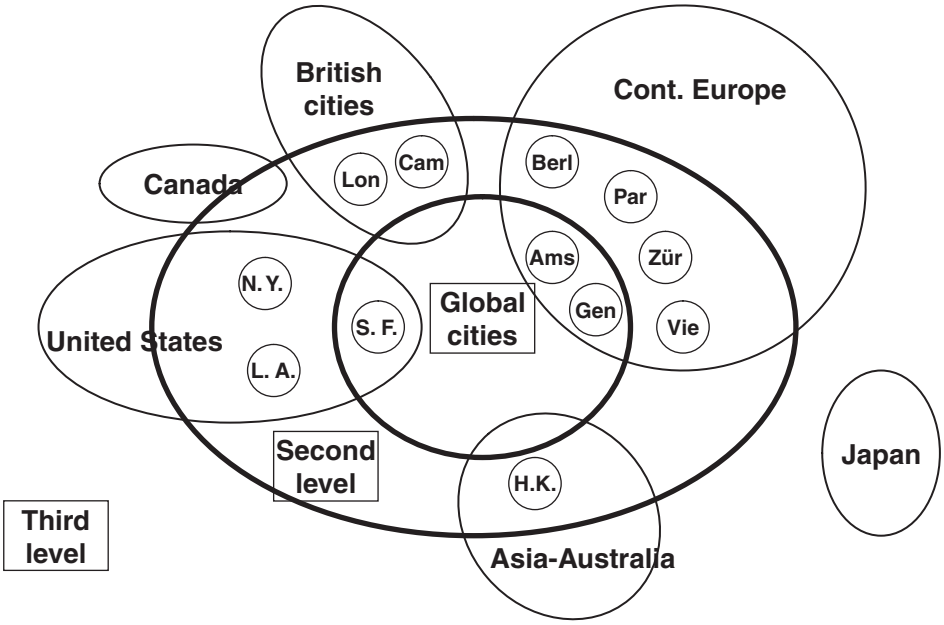

Figure 10. Levels and bands of world cities in information and communication technology research knowledge, based on volume and international nodality, 2004–06.

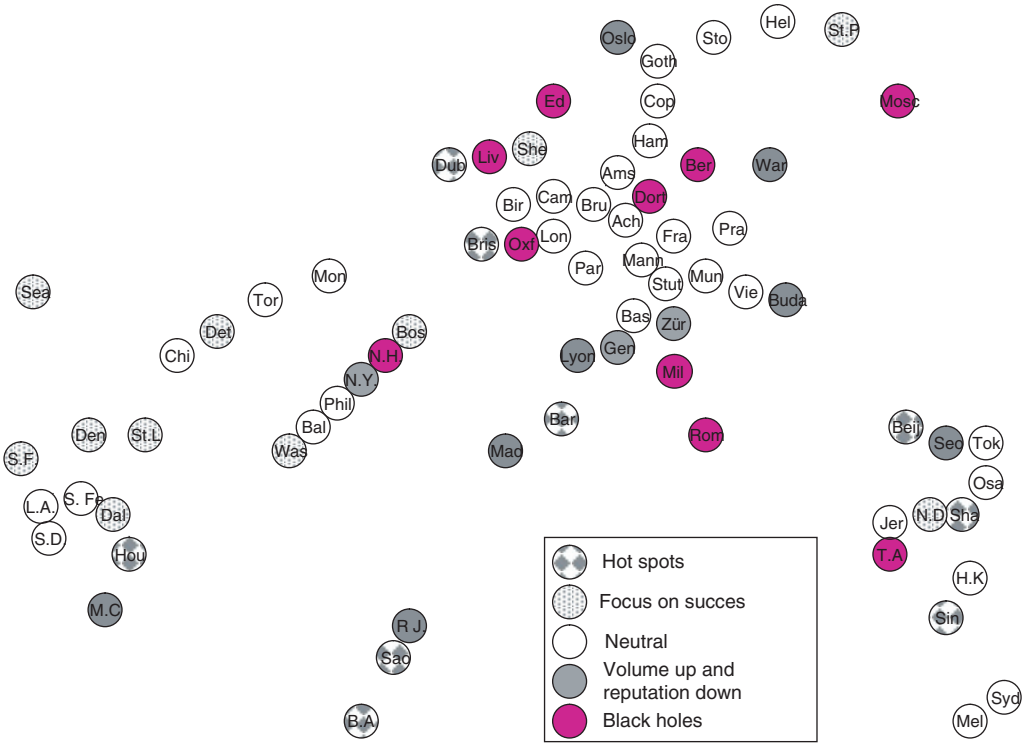

Figure 11. Growth types for world cities of knowledge, based on research data for information and technology research, 1996–98 to 2004–06.

are small peripheral European centres, the US and some upcoming cities of Asia and South America. Beijing and Hong Kong are on the way towards prominent positions.

Discussion

In this paper, we have demonstrated structure and nodality of the system of world cities of scientific knowledge. We have identified a high degree of inertia in the system, but also a recent shift in location patterns. We find in accordance with other presented findings an extremely high and growing degree of concentration in the large centres, in combination with a series of new centres of concentration. The traditional strongholds of research in Europe, North America and Japan are rapidly being supplemented with fast-growing centres, especially located in south-east Asia.

Inspired by the GaWC group's work on the system of world cities using data on multinational financial and business services co-operation, we have tentatively constructed overviews of the world cities system of scientific knowledge in terms of levels and bands using their overviews as a model. We use collaboration data and evaluate dominance and subordinance in the collaboration. We present a simple picture of the structure of the system of knowledge centres and we obtain a more refined picture of the structure than by using size of output only. This picture accentuates nodality. The GaWC-group-inspired presentations consider cities in relational terms, as the product of interurban networking activities of co-authorship and focus on which scientific knowledge centres are the organising 'hubs' of research globalisation. We consider the system of knowledge centres as not merely a sub-system of the world cities system, but as a combination of such a sub-system and a system in its own right. Knowledge production and distribution constitute a significant network. The upper level of the hierarchy consists of dominating first-level global cities linked to cities all over the world. It includes London, the Amsterdam region, Paris and the San Francisco Bay Area, which are leaders of their own bands respectively. Genevé–Lausanne is also a true global first-level city, although it is a relatively small centre measured in output and does not have a band of its own but rather a global network. When it comes to nodality, the traditional European and North American strongholds of research still play the leading roles.

With this basic understanding of the way the upper-level world city system of knowledge functions, we have looked closer into the research question: Can the next generation of winners and losers be predicted? We have investigated this question by relating growth in paper production to growth in citations per paper and we use a value-loaded terminology to indicate changes in growth and reputation for the cities. The total picture of success and failure clearly identifies patterns and, to judge by extrapolation which cities have the potential to be the future winners of the research world, one has to look outside the traditional research strongholds of Europe and North America. We have then arbitrarily selected the discipline of information and communication technology research for further analysis because we considered it to represent new and dynamic research. We find a picture deviating from the general global pattern of research output and dynamics. Again, one has to look for coming winners of this discipline outside the traditional research strongholds of Europe and North America. It is not the old research heavy-weights of Japan, who by this exercise can be foreseen to join the upper ranks of the world cities network of research. It is Beijing and Hong Kong.

We relate to the discussion on how research collaboration patterns are highly influenced by geographical proximity and we find that this can be clearly identified in our results on research connectivity and on levels and bands within the global system of scientific knowledge world cities network. We do identify two cities which deviate from this rule of

geographical proximity. The San Francisco Bay Area's international collaboration pattern is mostly emancipated from the distance factor and so is the collaboration pattern of Genevé–Lausanne. The first probably reflects realistic collaboration patterns, but the second's position could very well be the consequence of an address confusion as the huge number of guest professors at the CERN facility could give their home address when they write together at CERN.

We do recognise the limitations inherent in bibliometric data and especially those relating to the problems with author addresses. We have focused also on the problems connected with delimitating functional urban regions in a similar way all over the world. With a global view, we cannot simply use the European Union's NUTS system or the MSA concept of the US. We have aimed at solving the problem by manual work and by overbounding. Our next research step will be to develop and test methods which are not just inspired by, but are similar to the methods of the GaWC group and to co-operate with this group on the issue.

Note

1. This approach is explained in numerous publications that can be downloaded from www.lboro.ac.uk/gawc.

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