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Coupled connectivity in the global complex network: the case of United Kingdom (1880–1925)

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Abstract

The main objective of this research is to analyse the connectivity of cities in a coupled network composed of planar (railways) and non-planar (maritime) topologies. It examines the state of the network during the 1880–1925 period, namely in the context of the first globalization wave (1880–1914), when trade and urban development were closely tied to progress in communications systems and steam propulsion especially. Edges represent intercity physical infrastructure on land, and inter-port ship voyages at sea. We tested several hypotheses in terms of inter-network specialisation and urban hierarchies with an application in the United Kingdom. The main results reveal that the networks are highly interdependent, whereas combined centrality is closely associated with city size and urban growth. We discuss the key results in light of network science, spatial science, maritime history, and transport research.

Keywords: Coupled networks, Globalization, Hinterlands, Ports, Maritime transport, Multilayer networks, Multigraph, Railway networks, Steam shipping, Urban network

Introduction

Industrialisation and the related urbanisation began in the midst of the eighteenth century, but accelerated significantly during the nineteenth and early twentieth centuries due to technological innovations, social changes, and political institutions that increasingly favoured economic growth. Before 1880, industrialisation was based on a prescribed division of labour: most jobs were dedicated to smaller tasks, and people repeated the same task indefinitely. After 1880, industrialisation relied heavily on mechanisation to increase output and maximise profits. The development of the modern electrical grid in the early 1880s facilitated these technological advances. Mass production after the turn of the twentieth century only exacerbated this effect. Consequently, the total output in the early twentieth century was higher than that in 1880. In addition, these changes, together with sanitary improvements in cities, led to population growth over the same time period.

Industrialisation, transport, and urbanisation have been repeatedly studied as interdependent growth processes. Industrialisation in Europe, specifically in the United Kingdom (Crafts and Mills 2004), and later in the United States (Kim 2005), began in the early nineteenth century with the reorganisation of manufacturing from artisanal shops to the first factories with steam power in a few industries and the emergence of new modes of transportation (Oldlyzko 2010; Marnot 2015). During the second half of the nineteenth century, manufacturing activities increased in scale, became more mechanised, and spread to many industries. This has been renamed by historians the "steam effect" or even "revolution". This effect included two modes of transportation at the time: ships and trains, which could act separately or together -a couple network–to facilitate the movement of goods, people, and services. Coupling transport networks is essential for creating integrated, efficient, and sustainable transportation systems that support economic development, social equity, and overall quality of life. By facilitating seamless connections between different modes of transportation, these networks enable safer, more convenient, and more accessible mobility options for individuals and goods alike.

However, the development of this effect differed between European countries. Some regions experienced an early surge in manufacturing, with the United Kingdom leading the way, following the invention of the steam engine by James Watt. Particularly notable was the rapid industrialisation in the second half of the nineteenth century, which not only spurred the development of transport networks, but also resulted in a significant increase in urban population growth. Other countries developed infrastructures before the industrial sector (Rietveld and van Nierop 1995). This is the case in the Netherlands, where ports acted as transhipment points of international and intercontinental scale, and consequently the country developed railway lines to connect production sites inland. In the latter case, freight transport growth occurred prior to industrial development and population growth.

The growth or decline of cities in this context, especially port cities, has been well documented by historians across the Atlantic (Konvitz 1994) and in Asia (Murphey 1969). Geographers recently proposed spatial models of transport network development in developing and developed countries under the concept of "port system" (for a recent review, see Ducruet and Notteboom 2023). The main idea behind this concept is the long-term traffic concentration between ports situated in proximity along a given coast or "range", especially at times of innovation diffusion in the transportation sector. The development of cities next to railway stations has been studied by a variety of geographers in France, Spain, Italy (Brons et al. 2009; Mojica and Marti-Henneberg 2011; Alvarez et al. 2013; Baron 2015), Portugal (da Silveira et al. 2011), the United Kingdom (Schwartz et al. 2011; Stalislov 2013), and the Netherlands (Koopmans et al. 2012), to name but a few.

Beyond local differences, scholars have reached a relative consensus on the importance of both ports and railways in the rapid development of cities during the late nineteenth and early twentieth centuries (Bretagnolle 2015). Ports in particular had to "race for constant adaptation" to keep their position in an increasingly competitive environment (Marnot 2005). Attracting maritime trade has become increasingly dependent on the ability to connect inland markets efficiently. Such dynamics have expanded the hinterland boundaries of successful gateways (for example, Rotterdam and the Ruhr hinterland) at the expense of many less-equipped nodes, such as French ports (Merger 2004). However, to better understand these effects, scholars have neglected the existence of inter-network externalities, a couple between sea and inland railway networks, and the combined role of networks in urban development. Another gap in the literature is the absence of node attributes, partially due to the limited availability of socioeconomic data at the city level, such as the urban population.

Our research is rooted in the vast literature on multiplex or multi-layered networks (Eagle et al. 2010; Vespignani 2010; D'Agostino and Scala 2014; Boccaletti et al. 2014; Garas 2016). It investigates the relationship between multiplexity, city size, and urban growth as measured by rail-sea combined centrality on the one hand and population on the other. It also echoes the longstanding literature in urban geography and economics, whereby larger cities are the most diversified and central, through economies of scale and economies of agglomeration (Li and Neal 2023). According to Pumain (2006) and Pumain et al. (2009), the "largest cities became larger because they were successful in adopting many successive innovations [while] the most advanced technologies concentrate in largest cities". In terms of maritime flows and networks, there is a path- and place-dependent process by which the most populated cities are the most diversified in terms of traffic type (Ducruet et al. 2018; Ducruet 2020).

Based on untapped data on urban population and maritime traffic covering the period 1880–1925, and the state of the railway network in the late nineteenth century, we demonstrate that city size and urban growth are not randomly distributed across space. The largest and fastest-growing cities correspond to important junction nodes between maritime and railway networks. This calls for broader applications in the containerisation era.

The paper is structured as follows: a brief literature review of cities and multiplex networks is presented in Sect. "Cities in interconnected (transport) networks". Sect. "Database" describes the database created for the analysis of the effects of coupling sea and inland railway networks on population growth. Sect. "Statistical analyses" presents the main results of the analysis of hybrid networks and population. Finally, conclusions regarding the effect of infrastructure on the nodes are presented.

Cities in interconnected (transport) networks

Inter-network externalities and urban development

Specialists of urban networks originally dedicated their efforts to studying the degree of interconnectedness among cities connected by numerous linkages of different nature and scale in the 1950s and the 1960s. The concept of urban networks has changed depending on the approach and scale adopted (see Barke 1986; Barthélemy 2010; Berry, 1964; Burton 1963; Derudder 2019; Derudder and Neal 2019; Ginsburg 1961; Hagget 1965; Peris et al. 2018; Pred 1977; Taylor et al. 2010, for useful and recent reviews). Cities have been studied in general terms as a way of organization, joined by economy, culture or politics. Numerous schools of thought emerged as well as different paradigms regarding urban networks, from the local-national to the global, and from graph theory in geography to complex network in physics (Peris et al. 2016; Derudder 2019). Due to limited data availability about flows, transport networks have often been the main material to study urban networks, considering their topology as well as their spatial or non-spatial structure (Abdel-Rahman 2004; Barthélemy 2010; Barthélemy and Flammini 2009; Camagni and Salone, 1993; Capello, 2000; Dupuy 1987; Gastner and Newman 2004; Giménez y Capdevila, 1986; Roso and Woxenius, 2009; Segui Pons and Petrus Be, 1991; Shibasaki et al. 2021; Xie and Levinson 2009; Zanon Moura et al. 2017). Since the

2000s, geographers and scientists of other domains have increasingly used complex network approaches to analyze graphs in a geographical context (Ducruet and Beauguitte 2014; Ducruet and Berli 2018; Guimera et al. 2005; Kaluza et al. 2010; Krings et al. 2009; Neal and Ronzeblat, 2022; Rodrigue, 2014; Rodrigue and Ducruet 2020; Tovar and Wall 2022; Waters 2006; Wolkowitsch 1992).

What characterizes the current literature on cities and transport networks is the absence of node attributes such as socio-economic features (e.g. population, employment, and value added) and the specialisation of the approach on solely one network. However, there has been recent research on the global maritime network in the age of steam, notably examining the relationship between maritime connectivity, technological innovation, and urban development (Ducruet and Itoh 2022), but leaving aside the land-based network and ignoring inland cities. In particular, this study shows that the spread of steam shipping is closely related to city size. Some parent works have investigated such phenomena in other contexts, such as inter-network externalities between ports, canals, and roads in England between 1760–1890 (Bogart 2014; Bogart et al. 2022), or the combination of airlines and other transport networks in Southeast Asia in recent years (Dai et al. 2016). Some scholars have participated in the increased quality of urban network visualisations but have not addressed the relationship between centrality and local population growth (Chapelon 2006; Nelson 2008; Lambert et al. 2013).

When it comes to understanding the structure and evolution of multiplex networks—nodes connected by two or more links of a different nature–we have to broaden the review to other fields such as mathematics, economics, or geography (D'Agostino and Scala 2014; Garas 2016). Measuring and analysing intersections between networks continues to be a major challenge for researchers and practitioners. In that sense, we want to shed light on how different transport networks interact and whether there is a relationship between network diversity, urban hierarchy, and technological advancement.

Research question and related hypotheses

Based on the reconstruction of the global maritime network and the British railway network connected to it, the main goal of this paper is to examine how land, sea, and land-sea connectivity interplay with urban population, port cities, and inland cities in general. It is therefore an examination of the nature of urban hierarchy and specialisation, based on the hypothesis that the efficient combination of railways and shipping is more likely to help urban growth than when considered separately. The individual impacts of networks, such as ports and railways, on cities are significant, but it is equally important to understand the interplay between these networks. Exploring how railway expansion influences port development, or vice versa, sheds light on their interconnectedness and their collective impact on urban population dynamics. If the networks are centralized and coupled in a hierarchical way, high-degree railway nodes will also be high-degree maritime nodes. Thus, the whole is more vulnerable than its independent parts (Parshani et al. 2010; Vespignani 2010). This is less the case for a randomly connected network, which is more robust.

This approach echoes previous research on multilayer networks, such as the air-sea global network, with the originality of considering both planar and non-planar topologies (Ducruet et al. 2011). Existing research, such as on the sea-road combination, remained static (Ducruet and Berli 2018), with the vast majority of other works being more qualitative by their focus on actors and firms rather than network architecture (see Woodburn 2013). After presenting the main procedures for modelling a global land-sea network, we propose an application to ports, railways, and cities in the United Kingdom as a first step in this direction. We chose the United Kingdom as it is the cradle of the Industrial Revolution, the first country to develop steam power, and because it is an island, making it easier to analyse by avoiding an arbitrary "cut" of the transport links with the rest of the territory.

Based on the literature, we propose to test the hypothesis that urban growth benefits from the proximity of transport networks and that the nature of networks has different impacts on cities. To prove this, we conducted econometric analyses to obtain trustworthy results.

Database

Our analysis uses a detailed database of urban populations. The number of inhabitants was retrieved from population data collected from the Population Statistics global database (Lahmeyer 2015) and national British archives every five years between 1880 and 1925. The retained definition of cities is that of urban areas, or agglomerations, that correspond to the morphological extent of urbanisation around municipalities. The databases allow such a functional—rather than administrative—approach as they provide population data for both agglomerations and municipalities. We merged the ports in the same urban area. Compared with other existing data sources, Population Statistics have the merit and immense advantage of including small and medium-sized cities, whereas most other sources only deal with large metropolises.

To address transport changes over time and changes related to node centralities (cities as the main focus for stations and ports), different geomatic steps and calculations are required. Our maritime and railway data includes GIS shapefiles for lines and stations in every city, starting in 1880. They were created using accurate historical maps.[1] The city is the focal node connecting the maritime and railway networks along coastlines, rivers, and inland. Ports and port terminals were attributed to cities based on the extent of urbanisation from a morphological perspective (i.e. belonging or not to an urban agglomeration). In this respect, some cities may have several ports. Thus, the railway network is defined in this article by the infrastructure, while the maritime network is made up of inter-port vessel voyages (see Fig. 1).

Regarding the maritime network, we collected shipping data of ports and vessel calls from Lloyd's List corpus. More specifically, we used Lloyd's Shipping Index, which provides inter-port vessel movements on a daily basis for the world fleet between 1880 and today. From that list, we mainly considered four types of data: ports, host cities, the number of vessel calls, and the type of ship (steam or sail), between 1880 and 1925 to and from United Kingdom ports. To avoid characterising vessel movements between ports as unrealistic straight lines (Berli et al. 2018), a reconstruction of the worldwide mesh to avoid landmasses had to be made. For visualisation purposes, the lines were smoothed using Drake's method to obtain less angular lines (see Figs. 9 and 10 in Appendix point 1).

[1] Maps from different international institutions and libraries have been used, such as David Rumsey Library, Library of Congress or Bibliothèque Nationale de France.

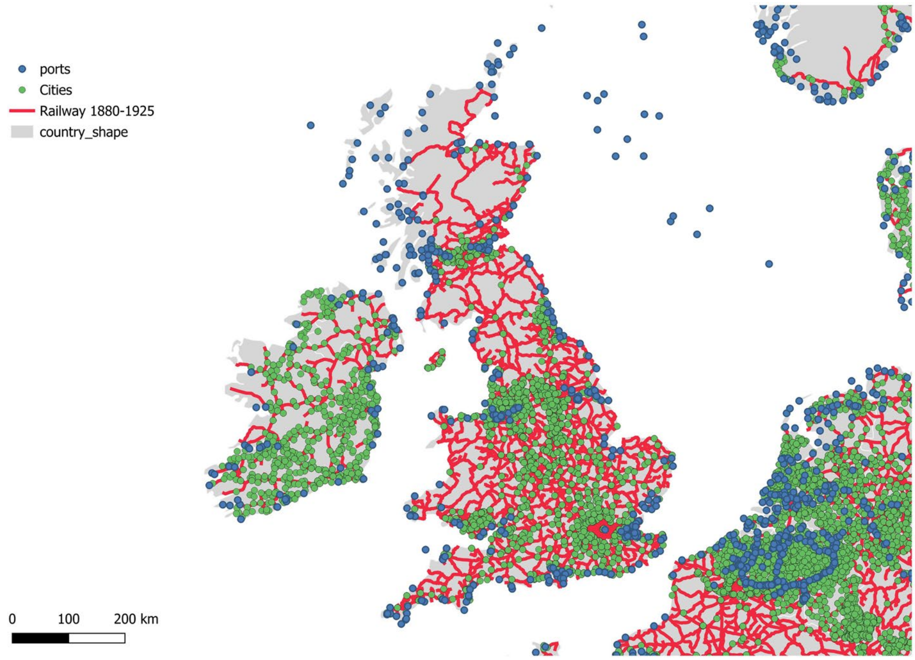

Fig. 1 United Kingdom railway, ports and cities between 1880 and 1925

We used Lloyd's data to obtain a list of unique paths, keeping in mind that if there were A—B and B—A records, we had to aggregate them into a single undirected path. After obtaining the list, we calculated all possible paths for each route on two maritime networks (one Eurocentric and one Pacific-centric) using the distance travelled as the cost. From each pair of shortest paths of the same route, we discarded the longest path, leaving us with a single path for each route (thus ensuring that an LA-Shanghai route runs directly along the Pacific, not through Magallanes, South Africa, Indonesia).These shortest paths are used as links and ports as nodes to build an undirected graph.

Obtaining traffic data for the railway network was impossible. As a result, we were inspired by previous research to use the location of cities to create a measure of accessibility to railway stations: the distance from the centre of each city node to its nearest station in a particular year and between nodes (Bogart et al. 2022).

In addition to examining both networks, we compiled a comprehensive set of variables (Table 1), including categorisations for cities belonging solely to one network, those connected to both networks, and those without any connection to either. Notably, cities solely connected by roads, which fall outside the scope of our analysis, are included in the latter category. Centrality measures are derived from the complex network framework (i.e., degree, betweenness, closeness, eigenvector, edge betweenness—absolute and normalised), while the relationships between the different networks or layers uses a Pearson correlation based on degree, or "assortativity", and, finally, variables about population size and growth like the compound annual growth rate.

Table 2 presents the summary statistics for the main variables in our analysis. There are several noteworthy features. Despite the total population increase between 1880 and 1925, there are only 189 cities with a complete time series of population. In the longer timespan, the total population change was positive and the unit average log

Table 1 Variables dataset

Variable	Type	Source
Railway routes and stations	Shapefile	Historical maps from David Rumsay, French National Library and Library of Congress
Ports	Shapefile	Lloyd's List
Maritime traffic	Quantitative	Lloyd's List
Distance	Quantitative	Own source
Population	Quantitative	Population statistics
Population growth	Quantitative	Own source
Population slope	Quantitative	Own source
Type of infrastructure	Qualitative	Own source
Maritime betweenness mean	Quantitative	Own source
Maritime betweenness slope	Quantitative	Own source
Maritime degree mean	Quantitative	Own source
Maritime degree slope	Quantitative	Own source
Railway betweenness mean	Quantitative	Own source
Railway betweenness slope	Quantitative	Own source
Railway betweenness mean	Quantitative	Own source
Railway degree slope	Quantitative	Own source
Combined betweenness mean	Quantitative	Own source
Combined betweenness slope	Quantitative	Own source
Combined degree mean	Quantitative	Own source
Combined degree slope	Quantitative	Own source

Table 2 Summary statistics

Variable	N	Missing	Mean	Median	SD	Minimum	Maximum
Pop_Growth	1086	0	0.0393	0.0280	0.14059	− 0.54000	4.47000
Pop_Slope	1086	0	11,991	0.0176	4.77144	− 2.88714	71.85879
CAGR	195	891	0.0942	0.0551	0.32918	− 0.17000	4.47000
Pearson	195	891	0.0635	0.0963	0.51922	− 0.95072	0.95895
maritime_bet_mean	1071	15	2.18e0−5	0.0000	1.76e0−4	0.00000	0.00321
maritime_bet_s!o pe	1071	15	4.60e0−7	0.0000	1.48e0−5	−2.12e0−4	3.04e0−4
maritime_deg_mean	1071	15	3.64e0−4	0.0000	0.00251	0.00000	0.04288
maritime_deg_slope	1071	15	1.48e0−5	0.0000	1.97e0−4	−0.00305	0.00376
railway_bet_mean	1071	15	3.29e0−4	8.54e−6	6.63e0−4	0.00000	0.00611
railway_bet_sl ope	1071	15	−1.69e−21	0.0000	2.32e−20	−2.92e−19	2.10e−19
railway_deg_mean	1071	15	4.l6e0−4	4.20e−4	4.06e0−4	0.00000	0.00566
railway_deg_slope	1071	15	−4.53e−21	0.0000	1.38e−20	−5.90e−20	1.34e−19
combined_bet_mean	1071	15	6.63eo−4	1.03e−4	0.00140	0.00000	0.01714
combined_bet_slope	1071	15	1.22eo−6	0.0000	8.11e0−5	−6.70e0−4	8.24e0−4
combined_deg_mean	1071	15	7.81 eo−4	4.20e−4	0.00267	0.00000	0.04854
combined_deg_slope	1071	15	1.48e0−5	0.0000	1.97e0−4	−0.00305	0.00376

difference was positive. Turning to transportation, station or port access increased, and the population to the nearest station or port increased over time.

Using these variables allows us to obtain accurate information that reflects the situation during this particular period, namely the sea-land connectivity of the United

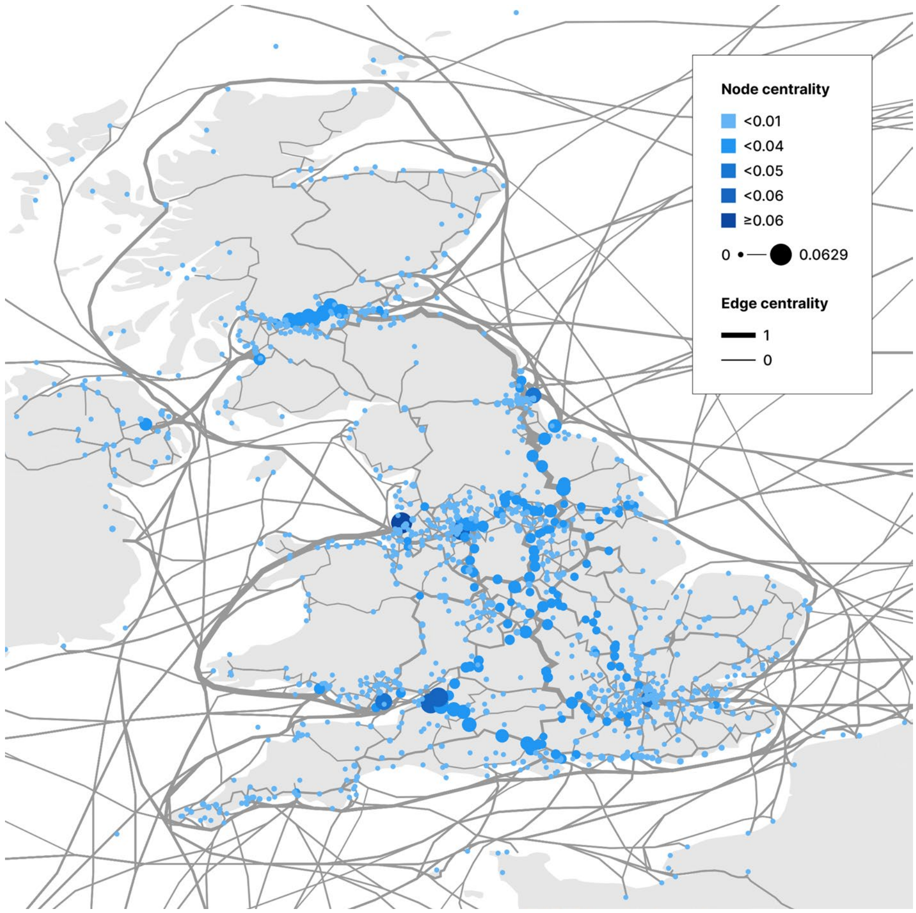

Fig. 2 Map of the hybrid UK network in 1925

Kingdom (Fig. 2) between 1880 and 1925, during the first globalisation wave, and soon after the First World War. The hybrid network is represented using different metrics, such as traffic and distance, to calculate the centrality or importance of cities in single or hybrid networks (Appendix point 1).

Statistical analyses

When it comes to understanding a cross-sectional and time-series population panel (1880–1925), the best method to verify our hypotheses is Linear Regression. The main reason for this choice is that the Ordinary Least Squares (OLS) model often allows us to make intuitive predictions about the data in urban economics. OLS is a type of global regression model that observes the (non)spatial relationships between the set of control and response variables with the fundamental assumption of homogeneity and spatial non-variability. In this case we used it to analyse infrastructure availability, combination, and connectivity and their effects on future population changes (some examples of research conducted with this model were Rietveld and van Nierop 1995; Tayman et al. 2011; Duranton and Puga 2014; Ward and Gleditsch 2018; Oshan et al. 2019; Bogart et al. 2022; Sadigov 2022).

Likewise, OLS was also applied to cities with centralities, which were divided by category: basic cities (i.e. only roads), cities with ports, cities with railway stations, and cities with a hybrid (rail-sea) network. To obtain clearer results, cities with no population data were excluded from the sample, resulting in six basic cities, 155 cities with railway stations (of which only 89 have centrality, the rest have zero centrality), and 36 cities with multimodal infrastructure. Our baseline specification is a cross-sectional growth equation as follows:

$$y_{it} = \alpha + \gamma S_{t0} + X\beta_{it} + \epsilon_{it}$$

where: Y: population growth computed in log difference; S type of connection (if port or station); X vector of explicative variables; γ, β : parameters of interest to estimate; ϵ: random errors i.i.d

With this equation, we can calculate the population growth of each city every five years regarding infrastructure, with the idea that cities grew more if they had infrastructure close by. Due to positive net migration, having a railway station or port in a unit is predicted to cause its population to grow more than in units without railway access, all else being equal.

The control vector *xi* always includes first nature characteristics and the natural log of unit population density every five years to capture effects of base year levels and prior trends. In preferred specifications, second nature characteristics and fixed effects on the dependent variable are added as controls (Farkas 2005). Standard errors were always clustered in cities. All results were compared in a graphic to better see how much each class of city grew.

A principal component analysis (PCA) as well as a hierarchical cluster analysis (HCA) were applied to describe general (static) trends and delineate distinct classes of cities. Similar to the regressions, several variables were transformed into natural logarithms to attenuate the influence of extreme values. We used the equation sign(x) * log(abs(x)) to allow the analysis of negative values (i.e., negative growth).

In addition, to ensure the validity of our approach, we calculated a correlation matrix (see Appendix, point 2) and the Kaiser–Meyer–Olkin (KMO) Sample Adequacy Measure. Kaiser (1974) recommends not accepting a factorial model if the KMO is less than 0.5 (see Appendix, point 4, Tables 5, 6 and 7). The resulting KMO measure confirmed that the factorial model was suitable.

Results

Network-level analysis

This section reports the main results of the study in terms of the impact of railway and port networks on cities in the specific case of the United Kingdom (for workflow information, see Fig. 12 from point 5 of the Appendix). As previously mentioned, the analysis of connectivity and centrality allows us to unravel the structure of these networks separately or jointly.

For the connectivity analysis, we chose to consider sections that pass through a maximum of 5 nuclei in a radius of 10 km on the map with respect to ports, observing the average distance shown in different studies on the distance between stations, ports, and places of residence during the first half of the nineteenth century (Bogart et al. 2022).

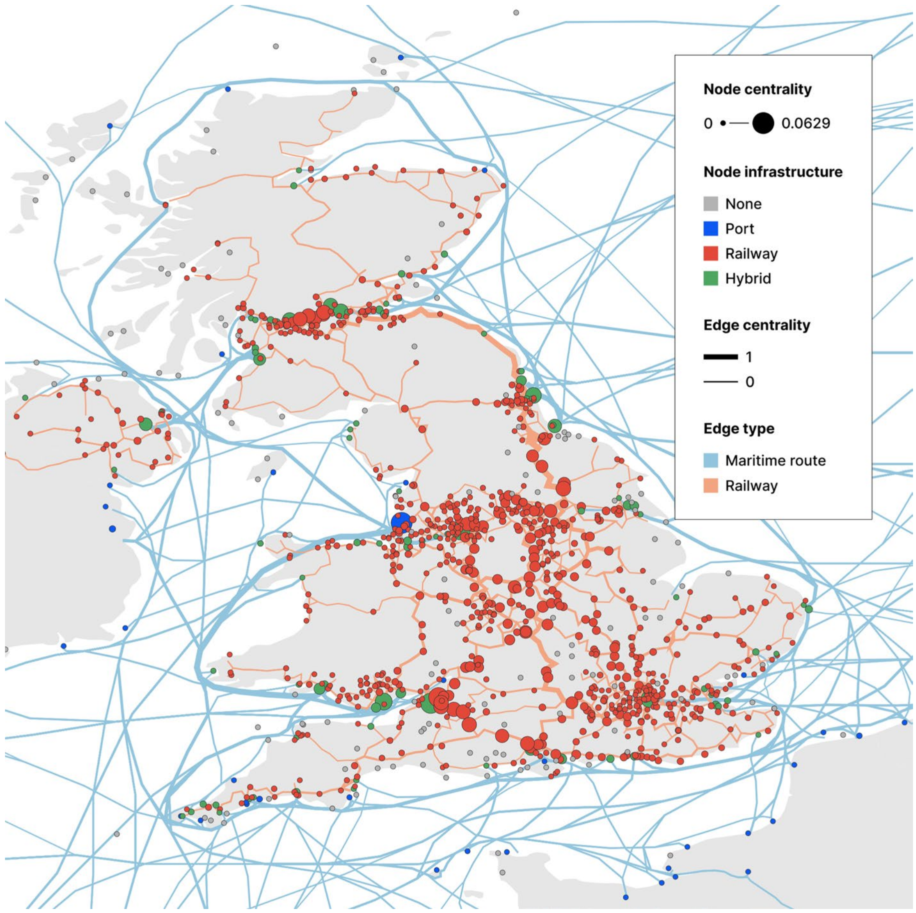

Fig. 3 Classification of cities depending on the infrastructure

Average spatial centrality makes it possible to understand the importance and distribution of network nodes. The maximum value of the degree shows the most central numbers of the network, and the mean accessibility represents the distances and spatial relationships between the different nodes. In Fig. 2 (introduced earlier), the average spatial centrality is observed with the size and class membership of cities. Fig. 3 shows the results for the different classes of infrastructure and disaggregation of the network.

In many cities in the United Kingdom, the degree of connection is almost null in the maritime network (990 cities in our database of 1086 cities with negligible values). Regarding the alpha index, the structure of the combined sea-land network is highly integrated in coastal areas, while each network is far less cohesive when considered separately. In contrast, the railway network connects no less than 586 cities.

The evolution of transportation during the industrial revolution in the United Kingdom played a crucial role in facilitating economic growth, industrial expansion, and urbanisation. The development of canals, railways, and steamships transformed the country's transportation infrastructure, enabling the efficient movement of goods, people, and ideas, and laying the foundation for the modern transportation systems we see today. Steam-powered ships replaced sailing vessels, offering faster and more reliable transportation for both domestic and international trade. Ports such as Liverpool, London, and Bristol experienced significant growth as they became major hubs for maritime commerce, as can be appreciated in Fig. 3. However, significant developments were made with the combination of vessels and trains. The development of railways revolutionised transportation owing to the rapid expansion of networks across the UK. Railways offered faster and more reliable transportation for both passengers and freight, enabling the efficient distribution of goods and facilitating the growth of industries such as coal mining, iron and steel production, and textiles. London, Liverpool, and the Manchester railways were among the pioneering railways in the UK, with the first couple networks in the country. Other parts of the United Kingdom, like Scotland, built canals to connect major industrial centres, such as Glasgow and Edinburgh, with ports, inland waterways, and railways to connect with strategic cities of England, but as can be seen, the rest of the country remained isolated.

The network clearly displays corridors that form strong relationships between the most central agglomerations and London. At the same time, the marginality of many cities (and regions) in the United Kingdom is clearly evidenced by disconnected or irrelevant nodes. As shown in Fig. 3, Scotland and the West Midlands at the time were counted with stations but not with strong corridors.

This can be expected because of the features of the network topology. The inexistence of a physical connection between major landmasses (Northern Ireland), a challenging natural environment for the development of infrastructure (the Highlands of Scotland), or the development of trade (not favouring the southeast coast of England) can be examples of this. Finally, Fig. 3 also allows us to appreciate how major central cities are peripheral, established along the coastline, and in close proximity to or well linked to ports.

Inter-network connectivity

One first attempt to evaluate the relationships between the two networks and cities was to measure their physical connectivity. A query calculated the distance between each port and the closest railway station in the worldwide railway network. In Fig. 4, the number of calls for sail vessels or steamers is inversely proportional to distance. The largest number of calls occur within ports in the class of zero kilometres. The farther away from the railways, the weaker is the port activity. This proximity did not change much over the study period, as the different classes of distance remained separated from each other in similar ways between 1880 and 1925. The spatial distribution of steamer traffic among classes is slightly clearer than for sailing ships, and the gap between 5–9.9 km and 10–24.9 km is wider for steam than for sail.

The test of assortativity (Parshani et al. 2010) allows us to answer positively the fundamental question of whether cities with both networks are larger than cities in a single network in terms of connectivity. As seen in Fig. 5, the so-called inter degree-degree coefficient, which is the Pearson correlation between the degree of node i in network x and the degree of node i in network y, oscillated between 0.50 and 0.65 over the period. This is a significant score, and its evolution is stable over time. At the UK level, the principal maritime and railway nodes are thus relatively the same locations, and they connect the respective networks in similar ways. This also implies a high level of geographic and topological overlap because the two networks are spatially

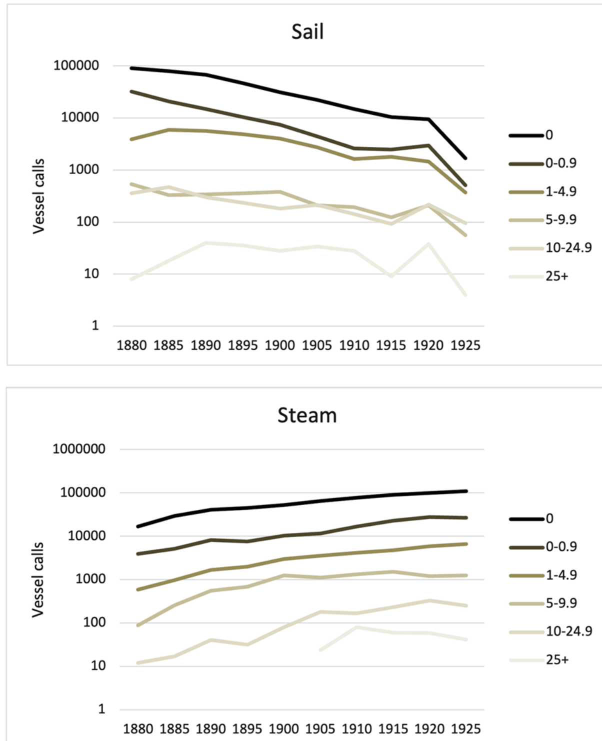

Fig. 4 Vessel traffic(calls) and distance to railways (km) by type of ship, 1880–1925

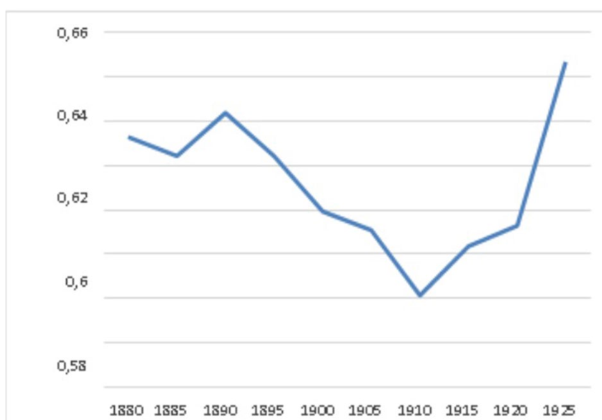

Fig. 5 Inter degree-degree coefficient in the UK sea-rail network

distributed. This makes the sea-land network relatively vulnerable to targeted attacks and failures in major cities (Vespignani 2010).

The correlation results between population and degree centrality were positive (see Appendix point 2). The overlap between the hybrid network and population increases is clear in many cases (89 of 195 cities showed a strong correlation), but in others, there was a negative correlation between the presence of railways/ports during 1880 and 1925 and increases in population in the same period.

The reason could be that from 1880 to 1925, the distance to the railway line had an effect on land cover change in the United Kingdom. Once the railway boom had reached its peak (in the 1850s), city size seemed to have reached a stable growth and maintained a nucleation pattern until 1915 (Stalislov 2013). Surprisingly, proximity to ports seems to have impeded urban growth in some cases. This could be due to the fact that rail does not enable within-city displacements but rather serves "long-distance interurban" commuting (Luo and Wei 2009).

Because of this last point, and to have a clearer vision, we calculated the ratio between combined centrality and single centrality. This step is especially useful for comparing areas that are not uniform in size or population. In Table 4, from point 3 of the Appendix, we show the first 20 biggest cities in each period with population and ratio scores for maritime and railway centrality. The centrality retained here is the betweenness centrality, which is a measure of global accessibility.

For example, London in 1880 was 810 times more central in the combined network than in the maritime network alone. In comparison, for the same year, modal specialisation and geographic location explain, in large part, the higher scores of other cities, especially in Scotland (Glasgow, Dundee) and northern England (Manchester, Newcastle). Such cities are central to the railway network, as their combined centrality overwhelms their maritime centrality. On the other hand, a moderate score is assigned to cities that are well positioned in both networks, such as Liverpool and Hull.

On the railway score and for all years, Belfast surpassed all other cities for the prominence of combined versus railway centrality. This expresses the special case Northern Ireland, with a limited railway accessibility compared with "mainland" UK. Maritime centrality thus appears as a vital complement to railway centrality in palliating the relative peripherality or isolation of certain cities. It was followed by Liverpool in 1880 and several eccentric cities such as Hull, Dundee, Newcastle, Sunderland, and Edinburgh.

In 1900, Portsmouth stood out in the maritime ratio, which expresses the relative importance of railways. This was followed by Dundee, Belfast, Bristol and Manchester. Similar results were reported in 1920. For the railway ratio, the combined centrality shows that Liverpool, Edinburgh, Hull, Nottingham, and Newcastle benefited greatly from the maritime network in 1900, with a similar order in 1920.

Intermodal connectivity and city size

The first exploratory analysis of the variables allowed us to determine how the created variables worked together (see Fig. 13 from point 6 in the Appendix). It can be concluded that differentiated groups can be formed for various combinations of variables (see Fig. 14 from point 7 in the Appendix). The population growth rate, the regression made from the population growth, had better results with the railway degree mean, instead of the betweenness, because of the lack of data related to actual railway traffic, maritime betweenness mean, and combined betweenness mean. Therefore, we ran a k-means cluster classification method. The results were divided into three groups (see Fig. 13 from point 6 of the Appendix).

A principal component analysis (PCA) provided a global view of all cities and variables (see Fig. 15 from point 8 in the Appendix). The scatter plot of the variables demonstrates the quality and robustness of the data and trends. As shown, population growth, the slope of the growth population, the presence of different infrastructure, and different analyses of centralities are correlated.

It is clearly visible (see Fig. 16 from point 9 of the Appendix) that there is some degree of conflict between clusters 2 and 3, as there is some visible overlap between them. These representations are a mixture of clustering and PCA, and indicate how each variable is represented in each component. As previously found, population growth is influenced by three variables: railway degree mean, maritime betweenness mean, and combined betweenness mean. Cities with coupled transportation systems tend to offer a combination of convenience, reliability, development, and inclusivity, supporting the needs of a diverse urban population. This group, the first in the PCA, included the same cities along the time at the top of the classification, experiencing an increase in centrality: London, Liverpool, Bristol, Cardiff, Newcastle upon Tyne, Glasgow, and Manchester. It is clear that better access to transport allowed these cities to grow in population, and consequently, size. In the second group, we find a more heterogeneous group, with multimodal cities with only trains or ports, such as Southampton, Portsmouth, Newport, Bath, and York. In the last group, one with some degree of conflict, the majority of the cities did not have access to any way of transport.

Table 3 Linear regression from variables. Silhouette method

Model fit measures

							Overall model test			
Model	**R**	**R^2**	**Adjusted R^2**	**AIC**	**BIC**	**RMSE**	**F**	**gl1**	**gl2**	**p**
1	0.942	0.887	0.837	251	272	8.07	17.8	11	25	< .001

Model coefficients—Pop_Growth

			95% confidence interval			
Predictor	**Estimate**	**SE**	**Lower**	**Upper**	**t**	***P***
Intercept[a]	−0.801	0.157	−1.11	−0.492	−5.09	< .001
maritime_bet_mean	6788.352	843.881	5132.49	8444.213	8.04	< .001
railway_bet_mean	−390.780	207.529	−797.99	16.433	−1.88	0.060
railway_deg_mean	1609.603	325.395	971.11	2248.093	4.95	< .001
combined_bet_mean	527.898	124.506	283.59	772.203	4.24	< .001
Type						
multimodal—city	6.611	0.677	5.28	7.940	9.76	< .001
port—city	1.942	1.743	−1.48	5362	1.11	0.026
train—city	5.165	0.311	4.55	5.775	16.61	< .001

Omnibus ANOVA test

	Sum of squares	**df**	**Mean square**	**F**	***P***
maritime_bet_mean	775.9	1	775.9	64.71	< .001
railway_bet_mean	42.5	1	42.5	3.55	0.060
railway_deq_mean	293.4	1	293.4	2447	< .001
combined_bet_mean	215.6	1	215.6	17.98	< .001
Type	4206.2	3	1402.1	116.93	< .001
Residuals	12,745.9	1063	12.0		

Type 3 sum of squares

[a] Represents reference level

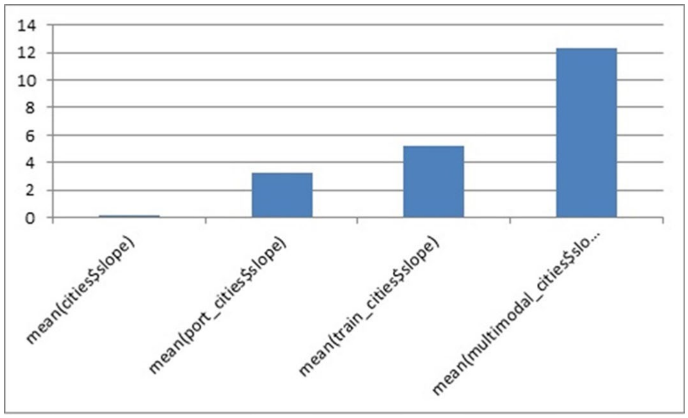

Fig. 6 Diagram from OLS results average

These results were strengthened using the OLS model. The Linear Regression of the cities' population every five years (Table 3) showed that structures of any kind—port or train—had a significant impact on the population growth slope.

However, as shown in the diagram (Fig. 6), the mean of each OLS result showed not only a clear impact of infrastructure, but also that of the hybrid network over city size and population growth. It can be concluded that the combination of networks has a greater influence than that of each isolated network.

Comparing these results with the centrality of each city was also illustrative; having a port or a port and a railway station had a greater impact on the population. On the other hand, having only one railway station did not seem to have any influence. An important result is that the population of cities with infrastructure grew more than that of ones without.

Finally, the linear regression (Table 3) applied to centralities confirmed the first result: population growth is stronger in cities with ports or railways and ports, compared to those which had only railway infrastructure, whose growth was slower during the period. It is worth noting that these results are influenced by the availability of data from vessel calls, in contrast to the unknown circulation on the railway. We believe that the inclusion of railway traffic data will make these results even more meaningful (Fig. 7).

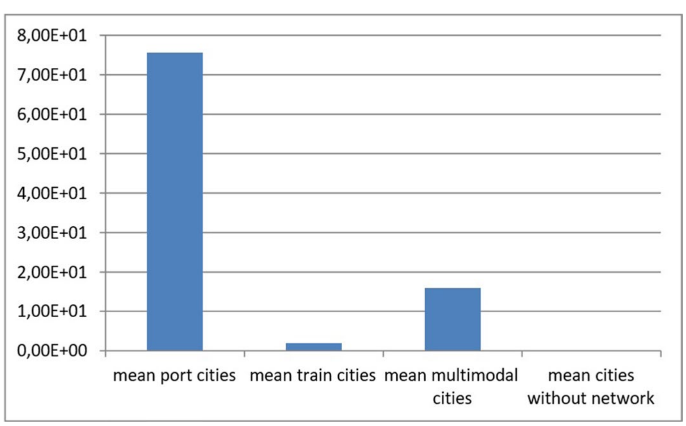

Fig. 7 Centralities taking into account betweenness

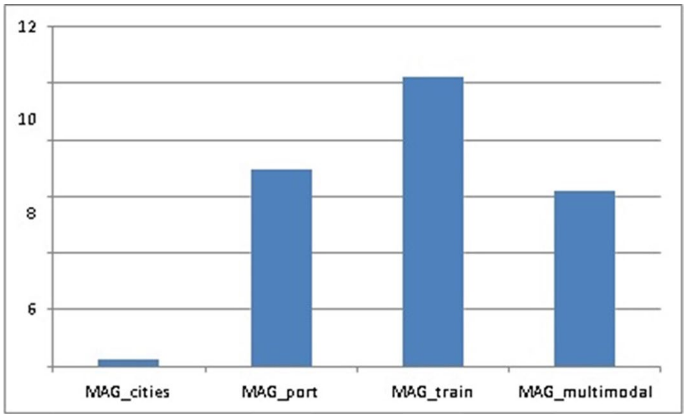

Fig. 8 Mean compound annual growth rate of cities with different infrastructures

All of these results are supported by the mean annual growth. We calculated this from the population data available by applying a compound annual growth rate (CAGR) formula to each available city (Fig. 8), out of which only 195 had at least two data points on the time series needed to apply the calculation. We then classified the cities with and without infrastructure.

Discussion and conclusions

This study provides the first empirical analysis of the relationships between maritime networks, railway networks, and urban development in the age of steam. A thorough review of the existing literature revealed that only a few studies have actually measured the local impacts of multiplexity, compared with studies of either maritime or railway networks. This work is challenging because it does not solely analyse an isolated network, but rather considers the presence of multiple networks—planar and non-planar—and the level and diversity of urban population. Identifying a link between coupled networks and population growth makes this study successful.

By combining data from railway connectivity, Lloyd's List, and population at the city level, our main results confirm how population changed over time as a result of the development of various modes of transportation and the role of external factors such as vessel traffic. We have highlighted that throughout the late nineteenth and early twentieth centuries, all UK cities underwent demographic growth, but even more so those with railway connections, and in particular railway and port connections.

The contribution of this study to the field is threefold. First, it synthesises recent empirical findings on cities, transport networks, and diversity. Second, it zooms in on the case of the United Kingdom, which, by its situation as an island, is more likely to witness a correlation between the observed layers. Third, it focuses specifically on the effects of a hybrid network on city size and growth.

Proximity to rail transport is generally considered to have influenced the population distribution. Negative effects were reported for regions that were not favourable to transport, or for areas that had already had a dense rail network for some time. Proximity to the railway has also encouraged conversion to residential areas and the development of high-density housing. However, the evidence on the role of rail in increasing employment density is inconclusive, suggesting that its success depends more on exogenous factors, such as ports and the attractiveness of the area, which are particularly favourable in coastal areas.

Regarding the maritime network, studies generally suggest that the presence of or proximity to major ports is associated with conversion to urban land, increased employment density, and commercial and industrial development. However, this is not always the case for residential purposes, suggesting that living in close proximity to these areas may be unattractive (Ducruet et al. 2022).

Of the studies that have examined both rail and port access, almost all found high coefficients for rail access compared to port access, regardless of the period studied. However, it should be noted that many studies have focused mainly on the changes in the second half of the twentieth century and later, when the rail network is considered to have lost its initial influence.

As we have shown in this study, the presence of any type of infrastructure has a great impact on population growth. Econometric analyses allowed us to study the relationships between infrastructure and the connexion of a hybrid network with population size in depth. The use of different quantitative variables confirms this hypothesis. Further research may complement this work by analysing the combined global rail-sea network. The time period should also be extended to better observe the long-term evolution, with a snapshot of the global railway network in 1950, 1980, and 2010, together with port, maritime, and urban data.

Appendix

1. Meshing grid

The meshing grid presented a problem of incompleteness owing to the method of map creation in every software (maps are represented in a 2D space, not in a 3D space). Grass software helped to solve the problem of representing three-dimensional features in a two-dimension surface, and to connect the grid within the Pacific Ocean, due to the focus on Europe in most maps using the Mercator projection (Figs. 9, 10).

To that mesh, ports were added using a 1.5 degree tolerance, to connect ports on islands, as it is optimised for the mainland coast. Thus, the study of connectivity, accessibility, and centrality measures is possible. The essential elements that compose such a spatial system are the urban centres/ports and the connections between them; that is, in topological terms, the nodes and arcs of the graph. The nodes are constituted by ports, which allow the inclusion of all urban and semi-urban centres in the topological network. Arcs are defined by the layout of the ports that connect the different nodes of the network.

For each edge, we measured the distance as a cost and disabled certain shortest paths that were unrealistic for the maritime transport of goods, such as certain rivers (that is, the Volga, Rhine, and Danube), the Panama Canal (opened in 1914), the Dead Sea, and the Arctic. As the exported vector of the mesh is not continuous—nobody can go around the world continuously, it has "extremes"-, we repeated the previous steps with the inverse vector. For example, America´s continent first at one end, and then at the opposite end.

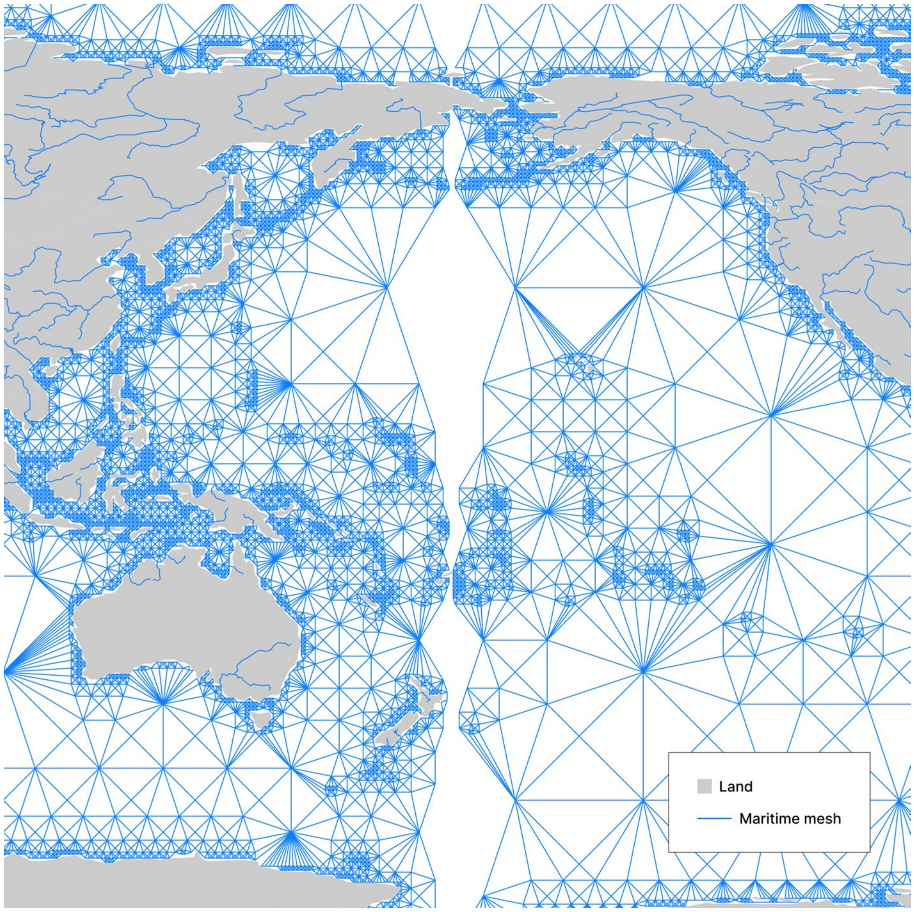

Fig. 9 Connection mesh problem in the Pacific Ocean

Once we settled the mesh with nodes and edges, centrality measures were possible with R to obtain centrality. This indicates the greater or lesser structural complexity of the network, which is directly linked to the number of nodes, arcs, and their spatial arrangement (Kansky 1963). Centrality, accessibility, and connectivity measures allow the analysis of the spatial organisation of the network, so the nodes establish a hierarchy based on the ease of access of each node to the rest of the nodes of the graph. The concept of accessibility is diverse, and several measures can be used to assess it. In general, it is defined as "the sum of the relative opportunities for contact and spatial interaction from the system as a whole" (Calvo Palacios 1993). However, the location of the network must be interrelated with other agents, such as the distance, cost, and time required.

In this work, only the distance is considered as a function of the nodes and arcs of the network, without considering other variables, so that the method can be improved in subsequent studies. The initial step in this analysis was the preparation of an accessibility matrix, where the topological distance was reflected by the shortest path between the nodes of the graph. Several accessibility measures are also deduced from this matrix.

When we created the routes from one port to another through this grid, the routes were straight, as happened in every GIS software, but thanks to Drake´s method in Grass that allows to smooth the lines, the routes acquired a natural curve through the oceans and seas.

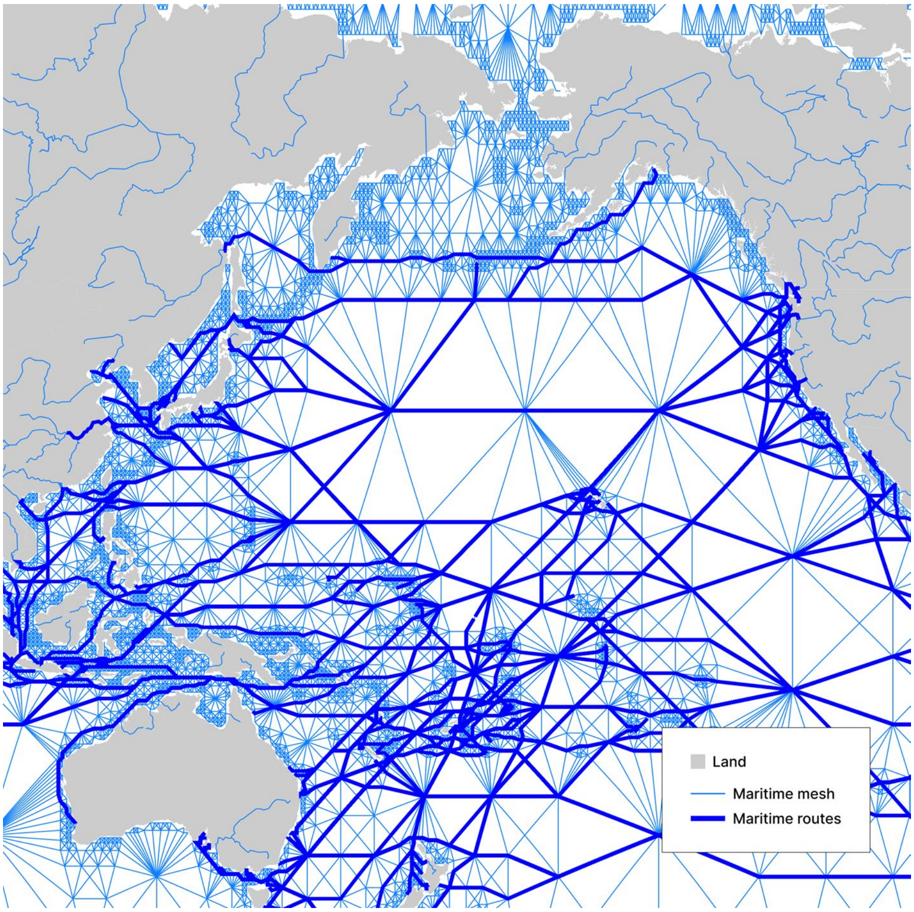

Fig. 10 Unconnected mesh problem for routes solved

2. Correlation matrix

See Fig. 11.

Correlation Matrix

		Pop_growth	railway_bet_mean	combined_bet_mean	railway_deg_mean	maritime_bet_mean
Pop_growth	Pearson's r	—	0.189 ***	0.466 ***	0.359 ***	0.491 ***
	df	—	1069	1069	1069	1069
	p-value	—	< .001	< .001	< .001	< .001
railway_bet_mean	Pearson's r	0.189 ***	—			0.160 ***
	df	1069	—			1069
	p-value	< .001	—			< .001
combined_bet_mean	Pearson's r	0.466 ***	0.549 ***	—		0.624 ***
	df	1069	1069	—		1069
	p-value	< .001	< .001	—		< .001
railway_deg_mean	Pearson's r	0.359 ***	0.491 ***	0.549 ***	—	0.318 ***
	df	1069	1069	1069	—	1069
	p-value	< .001	< .001	< .001	—	< .001
maritime_bet_mean	Pearson's r	0.491 ***	0.160 ***	0.624 ***	0.318 ***	—
	df	1069	1069	1069	1069	—
	p-value	< .001	< .001	< .001	< .001	—

Note. * p < .05, ** p < .01, *** p < .001

Fig. 11 Correlation matrix

3. Ratio scores

See Table 4.

Table 4 Ratio Scores

City	1880	Score maritime	Score railway	Name	1900	Score maritime	Score railway	Name	1920	Score maritime	Score railway
London_GBR	3815	810.1	3.58	London_GBR	4537	1033.4	4.04	London_GBR	4485	712.1	3.15
Liverpool_GBR	552	1132.0	15.88	Glasgow_GBR	762	17,394.0	4.54	Glasgow_GBR	1034	30,258.7	5.92
Glasgow_GBR	512	2621.9	4.45	Liverpool_GBR	702	988.2	11.59	Birmingham	922		1.19
Birmingham	401		1.67	Birmingham	653		1.30	Liverpool_GBR	803	1079.8	13.28
Manchester_GBR	342	18,457.0	1.58	Manchester_GBR	544	2437.4	4.15	Manchester_GB	730	2000.0	4.65
Leeds	309		1.76	Leeds	429		2.26	Sheffield_GBR	491		1.39
Sheffield_GBR	284		1.63	Sheffield_GBR	409		1.24	Leeds	458		2.49
Edinburgh_GBR	228	244.1	6.35	Belfast_GBR	349	3539.5	205.42	Edinburgh_GBR	420	544.8	22.01
Belfast_GBR	208	3067.2	164.31	Bristol_GBR	329	3734.4	6.59	Belfast_GBR	415	2583.5	196.07
Bristol_GBR	207	3999.4	6.05	Edinburgh_GBR	305	1504.4	34.00	Bristol_GBR	377	5882.2	6.59
Bradford	183		1.99	Bradford	280		4.68	Bradford	291		4.80
Hull_GBR	154	434.6	26.62	Hull_GBR	240	390.5	36.71	Hull_GBR	287	284.5	4.80
Stoke-on-Trent	153		26.62	Nottingham	240	390.5	36.71	Newcastle upon Tyne	275	284.5	42.15
Newcastle upon Tyne	145	6957.3	6.90	Newcastle upon Tyne	215	889.4	8.74	Nottingham	263	635.1	7.85
Dundee_GBR	143	2716.4	6.90	Stoke-on-Trent	215		0.85	Ports mouth_GB	247	3675.4	4.71
Portsmouth_GBR	128	0.0	4.00	Leicester	212		1.71	Stoke-on-Trent	240		1.03
Leicester	122		1.79	PortsmoLith_GBR	188	22,900.0	3.92	Leicester	234		1.64
Sunderland	116		4.00	Bolton	168		0.15	Plymouth_GBR	210	955.0	2.53
Nottingham	112		1.81	Cardiff	164	782.2	5.83	Cardiff	200	781.7	2.53
Oldham	11		2.16	Dundee_GBR	161	3698.3	3.32	Croydon	191		0.16

4. Robustness measures

See Tables 5, 6, and 7.

Table 5 KMO Measure of Sampling

KMO measure of sampling adequacy	MSA
Overall	0.719
Pop_Growth	0.633
Pop_Slope	0.852
combined_bet_mean	0.864
Port	0.833
Train	0.666
railway_deg_mean	0.658
maritime_bet_mean	0.637
combined deg mean	0.650
railway bet mean	0.685

Table 6 Bartlett's test of Sphericity

Assumption checks Bartlett's test of Sphericity		
x^2	df	*P*
2749	6	< .001

Table 7 Scale reliability statistics

Adequacy scale reliability statistics	
Cronbach's α	
scale	0.974

5. Workflow information

See Fig. 12.

Fig. 12 workflow information

6. Exploratory analyses

See Fig. 13.

Fig. 13 Exploratory analyses variables

7. Clusters from variables

See Fig. 14.

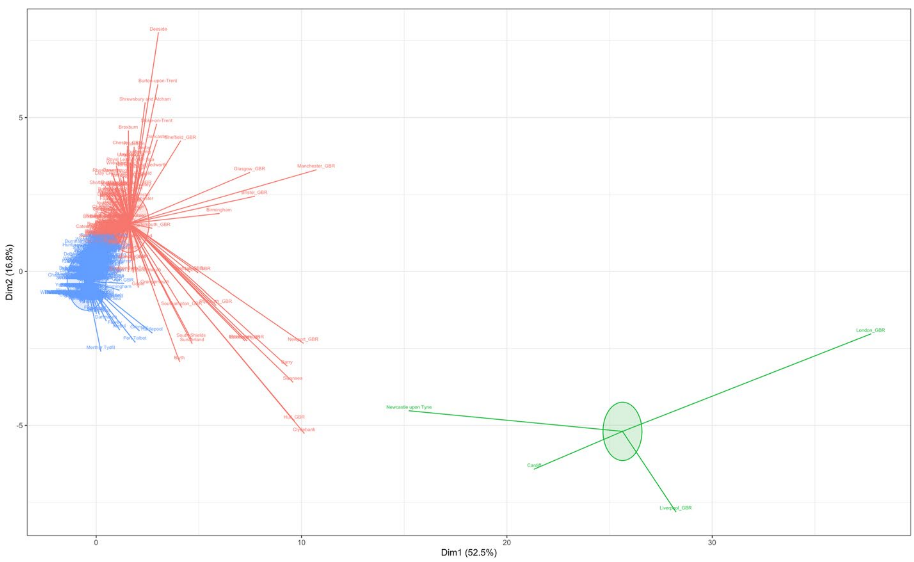

Fig. 14 K-means clusters from variables

8. Principal component analysis (PCA)

See Fig. 15.

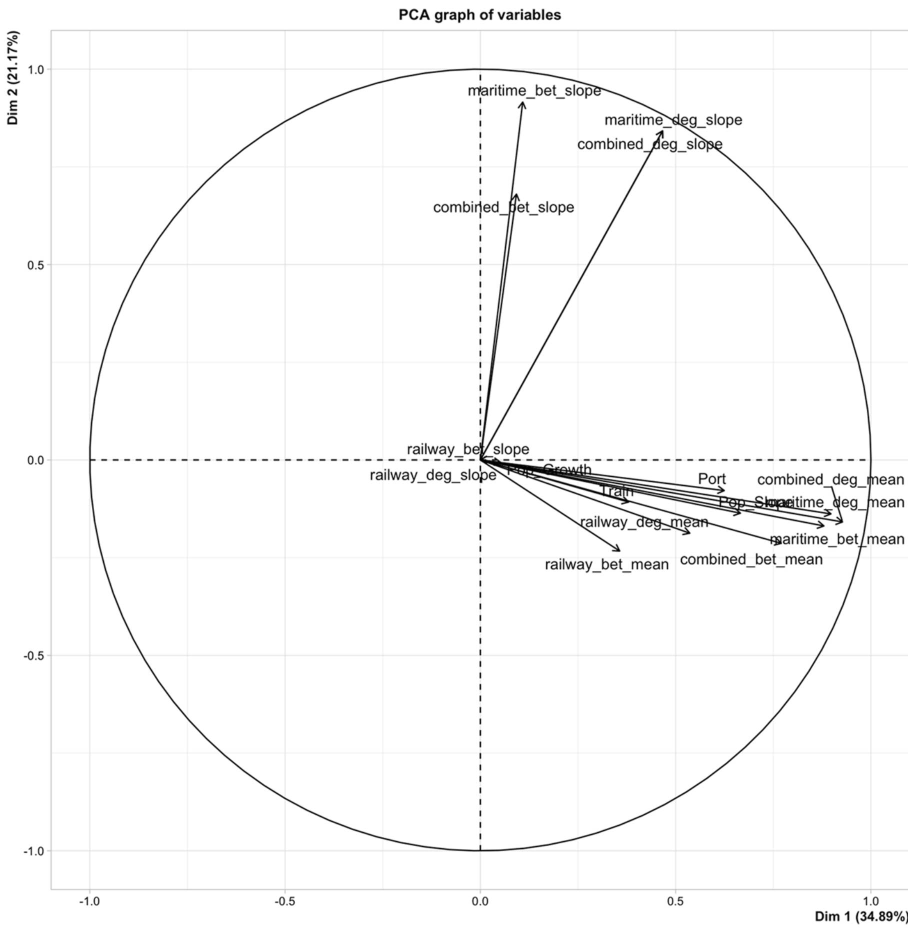

Fig. 15 Principal component analyses

9. Clusters from PCA

See Fig. 16.

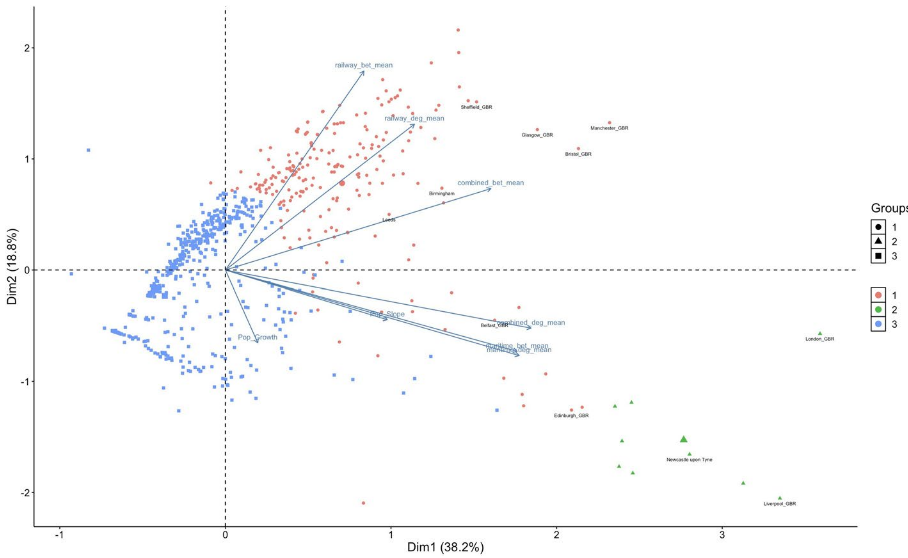

Fig. 16 Clusters from the principal component analyses

Author contributions
BP performed the historical context and analysed and interpreted the population data regarding PCA and OLS models, made tables, made the figures, and was a major contributor in writing the manuscript. CD performed a complex network context, made tables, and was a major contributor to writing the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Data availability
The data that support the findings of this study are available from Lloyds; however, there are restrictions to the availability of these data, which were used under licence for the current study, and so are not publicly available. However, data are available from the authors upon reasonable request and with permission from César Ducruet, Director of Magnetics.

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