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On the Development Logic of City-Regions: Inter- Versus Intra-city Mobility in England and Wales

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In this paper, we combine an allometric urban model with a hierarchical clustering method to investigate the effects of distance and spatial scale on the geography of transport-led agglomerative strategies implemented to address comparative regional economic under-performance. We undertake this study in the context of the urban system in England and Wales by constructing agglomerated city regions using city units defined at different spatial scales. As we will see, a greater importance, than is currently given, lies in local and intra-city mobility as compared with longer-distance transport schemes promoted using agglomeration theory principles. This signals a need for prioritization of mobility improvements at smaller intra-urban distances coupled with long-term densification efforts as integral to the performance of longer-distance inter-city pairings.

Keywords: urban agglomeration, hierarchical clustering, transport, densification

Subject classification codes: O18, R00, R40

Introduction

The broad appeal and utility of allometric and agglomerative models lie in their generalization of system behaviour across different sizes and scales (Bettencourt & West, 2010; West, Brown, & Enquist, 1997). Agglomeration theory is an urban example of such allometric approaches. Within such a framework, mobility improvements between previously disconnected areas, regardless of scale, increase efficiencies and productivities due to the resulting increases in effective population. Meanwhile, the literature analysing agglomeration effects, whether arguing for or against, are often locked on a regional and metropolitan spatial scale (Krugman, 1995; Glaeser & Gottlieb, 2009; Overman, Gibbons, & Tucci, 2009; Combes, Duranton, Gobillon, Puga, & Roux, 2012). When concerned with urban size, these agglomeration-based arguments often promote a ‘bigger is better’ perspective (Glaeser, 2012) whereby larger urban areas typically exhibit higher diversity, productivity, and output elasticities (Ciccone, 2002; Glaeser & Kohlhase, 2003; Bettencourt & West, 2011). Although the urban growth process within such frameworks is conceptualized as a balancing act between increasing productivities and escalating congestion costs, the formulation and consideration of the congestion related penalties remain mostly abstract (Abel, Dey, & Gabe, 2012; Henderson, 1975). The emerging Science of Cities (Batty, 2013), however, has attempted to codify these agglomeration behaviours and size-cost balances through mechanistic modelling of cities. These scaling and statistical models of cities (Bettencourt, 2013; Yakubo, Saijo, & Korošak, 2014; Gomez-Lievano, Patterson-Lomba, & Hausmann, 2017) have gained in traction both analytically and empirically supported by growing observations from different urban systems (Bettencourt & Lobo, 2016; Bettencourt, Lobo, Helbing, Kühnert, & West, 2007). In infrastructure planning, this broader agglomeration line of reasoning culminates in strategies that promote increasing effective population size through the provision of transport infrastructure and upgrades especially those of an inter-city nature enabling a number of medium-sized cities to act collectively as one larger and hence more productive conurbation (Metz, 2008). An exclusive focus on such urban boundaries, however, although intuitive, is reductionist of circumstances in scales above or below when utilizing agglomeration arguments to advocate or support planning policy especially one of a long-distance inter-city nature.

The aim of the present study is then to investigate the effects of spatial scales and distance on the geographic patterns of transport-led agglomeration strategies. To do so, we use Bettencourt's social reactor model (Bettencourt, 2013) which provides an explicit formulation and assessment of urban size-cost performance balance to identify key infrastructure interventions needed, i.e. densification and/or better mobility measures, to balance city performance. We expand on this by adapting a hierarchical linkage clustering algorithm to pair city units with complementary infrastructural requirements where pairings mirror provision of inter-city mobility links. A novelty of our approach is that it combines an allometric urban model with a hierarchical clustering algorithm to offer mathematically grounded groupings for constructing regions based on city size-cost performance balance and potential. We also investigate the robustness of such groupings by performing a co-occurrence frequency analysis examining the recurrence of specific city-pairs over different aggregation scenarios.

As already mentioned above, agglomeration-based arguments are used to argue in favour of inter-city transport infrastructure and connectivity. In the UK, broader attempts at bridging the economic performance gap that exists between the country's northern regions and London frame this divide as a mobility problem (Osborne, 2014). This has resulted in use of similar stylized agglomeration arguments in favour of implementation and upgrades of the passenger rail infrastructure to increase capacity and reduce journey times. These transport interventions and region building efforts are envisaged to enable northern regions to act as a single economic unit leveraging their virtual collective size for higher productivities (Transport for the North, 2015). As we will see, our findings suggest somewhat different interpretations. In particular, there appears to be a persistent potential for better mixing and mobility across intra- and inter-city scales, which are predominantly frequent over short or intra-city distances. In addition, these findings are largely independent from city boundary definitions. Moreover, the combinations of city units in regions assembled prioritizing size-cost considerations in our models are not necessarily in agreement with those advocated by political agendas. We therefore argue that transport infrastructure planning led by agglomeration theory principles cannot simply be applied at a single arbitrary spatial scale.

The rest of this paper is organized as follows. The next section provides a description of the methods and data implemented here. This includes a brief introduction to Bettencourt's social reactor model, the hierarchical linkage clustering algorithm used assembling city regions, and the description of scenarios studied. We then present the data pertaining to the effects of distance and resulting city region groupings in Section 3. This includes the results of the co-occurrence analysis. The forth section includes an overall discussion of the results presented and their implications followed by conclusions and a summary of findings in the final section.

Methods and data

A significant body of economics literature already deals with questions closely related to effects of population size and transport investment on productivity levels. For conceptual arguments regarding the impacts of population size and infrastructure on productivity the readers are referred to (McCann, 2013, Chapter 2 and 4) while an extended discussion of these arguments in the specific context of the UK's regional economic landscape is available in (McCann, 2016, Chapter 5 and 6).

Urban scaling frameworks, however, provide a number of additional advantages when compared with the approaches of the existing literature. Firstly, in terms of practical applications, allometric frameworks are significantly more parsimonious. This enables power-law scaling models, unlike their New Economic Geography (NEG) counterparts, to remain practical in circumstances where data is sparse and more agile when applied to an increasing number of cities and urban systems. Additionally, the few fundamental assumptions underpinning such models, as seen below, are more general and avoid strong assumptions about individual behavior. As such, these models are not driven by individual behavioral assumptions and rather the empirically observable average-aggregate behavioral patterns of cities and the urban systems to which they belong. For these reasons, scaling models are computationally more tractable which allows further expansions without increased complexity and has gained the framework wider traction particularly with the communities concerned with the creative class and consumer city hypotheses (Florida, Adler, & Mellander, 2017; Glaeser, Ponzetto, & Zou, 2016; Miguélez & Moreno, 2013). Finally, due to their roots in the physics of self-organizing systems, such models provide a direct link to the rapidly growing area of complexity theory enabling such formulations of cities to maintain compatibility with others of such nature that focus on other aspects of cities besides economic performance.

These frameworks formalize agglomeration effects captured within a system of cities and hence provide a means to evaluate *idealized counterparts* to cities of a given population size. What can be taken as an idealized city is then derived from a power-law scaling regime that underpins an overall urban system to which a given set of cities belong. These are hence frameworks of a system of cities based on the relationship between agglomeration forces and the costs of human interactions. On the basis of these, from an agglomeration-based scaling point of view, cities would follow sub- and super-linear population scaling for infrastructure, i.e. length of road network, total urbanized area, etc., and economic output respectively with the magnitude of these elasticities, here the scaling exponent, a function of geographic geometry and mobility. In this context, the idealized counterpart to a city, not an intrinsically ideal city, would be that which shows the least deviation from the desired productivity and efficiency elasticities for the same population size.

Social reactor model

Bettencourt's (2013) simplified model framework derives power-law scaling of urban characteristics, e.g. economic outputs, Y, urbanized area, A_n,[1] mobility energy dissipated, W, etc., against population size, N, based on four fundamental assumptions:[2]

(1) the aggregate economic output is proportionate to the sum total of local human interactions (Glaeser & Kohlhase, 2003),

(2) the population is uniformly mixing in a way that all individuals have the minimum resources to fully explore and experience the city (Jones, 2017),

(3) the urban mobility infrastructure embedded in the city is a hierarchical network that undergoes incremental growth to keep all inhabitants connected (Samaniego & Moses, 2008), and that

(4) the average baseline human production does not vary with population size and remains constant for cities throughout the same urban system (Szüle, Kondor, Dobos, Csabai, & Vattay, 2014).

The first two assumptions can be mathematically conceptualized as

$$Y = \bar{g} a_0 l \frac{N^2}{A_n} \tag{1}$$

where the product $\bar{g} a_0 l (\equiv G)$ is the baseline human production mentioned in the fourth assumption and embodies the system-average outcome of individual interactions, $\bar{g}$, over their average area of influence, $a_0 l$, through which they experience the city, and $\frac{N^2}{A_n}$ represents the density of the total number of possible individual interactions over the urban area.[3] Assumption 4 then implies an expectation that $\frac{dG}{dN} \approx 0$ across cities belonging to the same urban network.[4]

Further combination of these assumptions culminates in a series of power-law correlations that dictate the behaviour of economic output, urbanized area, and mobility energy costs as a function of urban population according to

$$\begin{cases} Y(N) = Y_0 N^{\beta_Y} = Y_0 N^{1+\delta} \\ W(N) = W_0 N^{\beta_W} = W_0 N^{1+\delta} \\ A_n(N) = A_{n_0} N^{\beta_{A_n}} = A_{n_0} N^{1-\delta} \end{cases} \tag{2}$$

where Y_0, W_0, and A_{n_0} are constants expressing the baseline prevalence of economic output, energy dissipated in mobility processes, and urbanized area respectively.[5] Also, $\delta = \frac{H}{D(D+H)}$ where D is the urban geometry expressed through its fractal dimension, confined to $2 \leq D \leq 3$ when conceptualizing the more than two- but no more than three-dimensionality of real life geometry, and H the fractal dimension describing the average mobility path of individuals exploring the city and hence restricted to $0 < H \leq D$. Given the constraints on D and H, δ as formulated in Bettencourt's model would lie somewhere in the range $[0, \frac{1}{4})$. A direct interpretation of the second assumption, however, implies that $H \approx 1$ for an ideal and thus fully explorable city where journeys take place over its surface where $D \approx 2$. It is these basic behavioral assumptions about people's interactions and city geometry that gives rise to the theoretical expectations of the exponents of $\beta_Y = \frac{7}{6}$ and $\beta_{A_n} = \frac{5}{6}$. It is important to note that these theoretical exponent values are not assumptions within the model and are functions of the values of D and H with the physical limit of $H \leq D$. An absolute rational upper bound of $\beta_Y = \frac{5}{4}$ can also be assumed to occur at $H = D = 2$ although this would very unrealistically imply that inhabitants on average cover the entirety of the city area routinely. The aggregated evidence across the European countries for OECD's harmonized functional urban areas and the American MSAs does in fact provide a fair match with the theoretical exponents expected at $D = 2$ and $H = 1$, with the latter having provided the dataset on which Bettencourt's model has been based (Bettencourt et al., 2007; Bettencourt & Lobo, 2016). If the ideal full mobility access, set out in assumption two, is violated, however, the value of δ would tend towards zero resulting in a diminished presence of higher productivities and efficiencies in larger cities for economic output and infrastructure area respectively. What is worth emphasising before moving on is the average-aggregate systems perspective inherent to the framework. Prefactors Y_0, W_0, and A_{n_0} are derived parametrically for the average-aggregate size-scaling of a given number of cities meaningfully belonging to an urban network, say all American cities or all English cities, and given only a single city, there would not then exist a theoretical expectation at a moment in time as no population-related elasticities could be observed given a single data point. There can, however, be a temporal size scaling detailing the growth of the city through time and agglomeration efficiencies compared to the past versions of the city itself (Bettencourt et al., 2007).

Bettencourt's model also formulates the size-cost balance between economic output and the mobility costs associated with its generation as a maximization of the subtraction $Y - W$ as a function of G.[6] This size-cost performance function of Bettencourt's model in effect captures the balance between socioeconomic output generated over the area of the city and the infrastructural costs of inhabitants' mobilization over it. Figure 1 shows the parametric behavior of $Y - W$ against G. The model framework provides an interpretation as to the intervention needed to nudge cities with suboptimal $Y - W$ based on the value of their G relative to the theoretical point of optimum G^*. For a city unit where $G < G^*$ the full economic potential is not attained. Referring back to the constituent parts of G, i.e. $\bar{g}a_0l$, this would be indicative of less than desired access and mobility addressable through better provision and facilitation of transport to virtually increase $a_0 l$. Conversely, when $G > G^*$ the economic success of the city has led to an over-optimum expansion resulting in escalating mobility costs of its output. In such cases, densification of the built-area would increase the density of interactions reducing mobility costs without negatively affecting economic output.

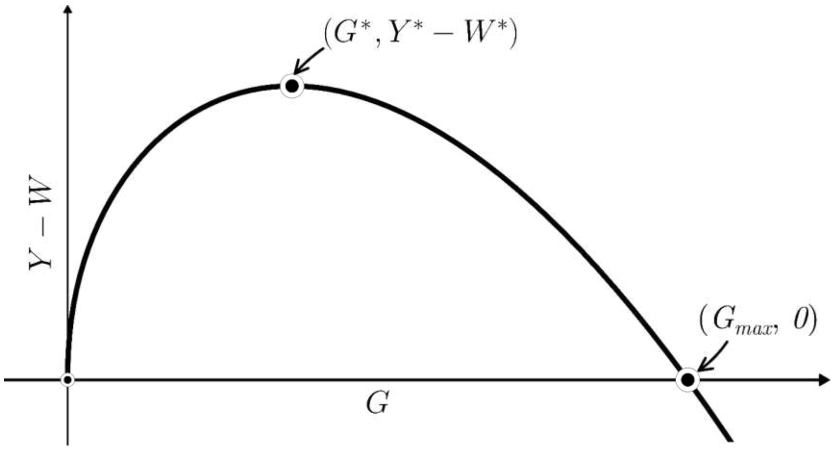

Figure 1. Schematic of the size-cost balance, $Y - W$, as a function of G.

It is worth mentioning here that location choices and related arguments are embedded and manifest in the organization of urban systems as the overall urban network would have constituting places of different kinds with different types of interactions. It is implicit within Bettencourt's model that people would have different location choices and are not fixed in place such that location choices between cities affects the system-wide adjustment from an average-aggregated perspective as individual cities grow and shrink in size in response to these choices. Bettencourt's and West's framework (2010) expects cities belonging to a coherent urban network to share and exhibit similar characteristic performance parameters from an average-aggregate perspective. In this manner, these implicit system-wide location choices and evolutionary progress of individual cities can be seen in the complementarity of the scaling exponents of Y and A_n. When cities in a given urban system systematically underperform economically (more linear elasticities than expected), they exhibit an expansion of overall urbanized area (also more linear exponents and larger areal catchments) in order to maintain overall optimality of $Y - W$. This results in cities compensating for smaller than theoretically expected output (at $H = 1$ and $D = 2$) through larger catchment areas.

Building city regions

As previously stated, the argument for city regions connected through effective centre-to-centre transport is often put forward through agglomeration principles whereby higher productivities are expected to result from the increase in the effective urban size via the upgraded transport. From the perspective of the Bettencourt's model, however, such inter-city mobility measures would not exhibit their full potential when all the cities to be connected already have inadequate levels of mobility, $G < G^*$.

An overall complementarity can then be seen between cities that fall to the either sides of the point of optimum. Suppose that city A, according to the social reactor model, requires further densification to address its size-cost balance, $\eta_A \left(\equiv \log\left(\frac{G}{G^*}\right)\right) > 0$, and that its neighboring urban area, city B, is suffering from a lack of adequate internal mobility, $\eta_B < 0$. If one were to consider the performance of this pair as though they were a single unit, A+B, which implicitly assumes provisions of instantaneous mobility between the pair, then the resulting city pair would theoretically lie somewhere closer to the point of optimum, $\eta_B < \eta_{A+B} < \eta_A$, and on average with a reduced perceived need for further infrastructure intervention, one way or the other, as a result of an adjustment in spatial scale. Figure 2 provides an instance.

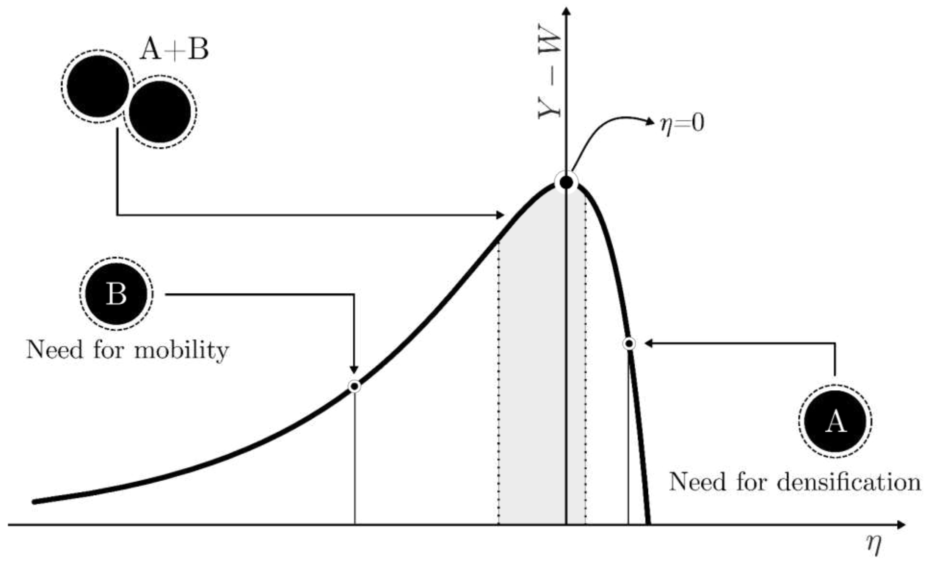

Figure 2. Schematic showing the individual comparative cost-size performance, $\eta\left(\equiv \log\left(\frac{G}{G^*}\right)\right)$, and combined city-pair performance.

Consideration of the combined cities could thus be thought of as a scale change in the local city boundary. This rearrangement of the boundary results in consideration of a city unit that has the aggregate sum of ‘infrastructural extent’ and ‘economic output’ of the parent units. For this hypothetical unit to then deliver on this aggregate infrastructural and output potential, i.e. in essence relocating closer to the stationary point on the $Y-W$ curve, would then require the aggregate inhabitants to have been provided with mobility levels, H, that is at least similar to the parent units across the combined area of parent units. This is to say mobility means, which are at least comparable to those connecting parent units internally, already exist or are subsequently provided across the two.[7]

This can be used to systematically identify regional clusters where such agglomerative inter-unit mobility upgrades provide a perceived closer-to-optimal size-cost balance. We employ an agglomerative hierarchical linkage clustering method (Murtagh & Contreras, 2012) grouping units together at each step where the distance function is expressed as

$$D(A,B) = |\eta_{A+B}| = \left|\log\left(\frac{G_{A+B}}{G^*}\right)\right| \qquad (3)$$

with A and B filling in for any set of city units or city regions. Although the distance function could alternatively be taken as $D(A,B) = |G_{A+B} - G^*|$ or other similar formulations, the clustering sequence would not change since this is only effectively affected by the sorted order of the hypothetical pairs which, unlike the absolute magnitude of the distance, would not change by function specification. The combined baseline production can be estimated through a simple rearrangement and manipulation of Equation 1

$$G_{A+B} = \frac{(Y_A+Y_B)(A_{n_A}+A_{n_B})}{(N_A+N_B)^2} \qquad (4)$$

If all city units in an urban system did in fact strictly follow a population power-law scaling for their economic output and urbanized area, an empirical approximation of the optimal baseline production could be estimated as

$$G^* = Y_0 A_{n_0} \qquad (5)$$

Theoretical estimates for Y_0 and A_{n_0} can then be obtained by employing constant gradient OLS fits, at $\beta_Y = \frac{7}{6}$ and $\beta_{A_n} = \frac{5}{6}$ for economic output and urbanized area, to estimate the average intercept values corresponding to $H = 1$ and $D = 2$. This would in effect entail minimizing the non-weighted sum of squared residuals when fitting a line of known slope where the only variable available to estimate is the intercept. It is useful to point out the subtle distinction between optimal $Y - W$ performance and desired/idealized agglomeration elasticities. The theoretical choices used for *idealized* exponents, β_Y and $\beta_{A_{n_0}}$ at $D = 2$ and $H = 1$, provide average expectations for agglomeration elasticities given the internal model assumptions the consistency of which, as previously mentioned, is validated against the empirical observations of these exponents for both European and American urban systems (Bettencourt & Lobo, 2016; Bettencourt et al., 2007). While the choice of D and H affects the value of G^* at which $Y - W$ maximizes and hence the size-cost optimality of cities, the overall maximization remains manifest regardless of the magnitude of the agglomeration elasticities. See supplementary material.

Boundary definitions

We conduct our analysis over the English and Welsh urban network[8]. Table 1 summarizes the city boundaries used. For density-based city units the City Clustering Algorithm (CCA) (Rozenfeld, Rybski, Gabaix, & Makse, 2011) is used over the GEOSTAT $1km \times 1km$ population gird (Office for National Statistics, 2016b) aggregating neighbouring grid cells over the density cut-off values and discarding resulting units with a total population below the minimum values, N_{min}, shown in Table 1. The minimum population cut-off values are obtained by employing the methodology described by Caluset et al. (Alstott, Bullmore, & Plenz, 2014; 2009). The method estimates the minimum population value above which a coherent Zipfian power-law distribution can be assumed to exist among the units' population size within each boundary definition (Cheshire, 1999). This prevents the estimates for the idealized counterparts of the urban system to be skewed by the observations from disproportionately larger number of the smaller units.[9]

Table 1. Boundary definitions used for clustering and the number of units in each definition.

Boundary		N_{min}	No. of units	No. of units ($N>N_{min}$)
C100*	Population density-based	3895	2867	586
C350		7627	2928	480
C500		59698	2475	103

C750		57698	2021	111
C1000		55031	1692	119
C1400		67495	1435	96
C3500		66671	859	48
LAU1[1]	Administrative	101355	348	214
NUTS3[2]		499766	141	34
TtWA[3]	Functional economy	510149	173	28
UA[4]		159581	83	55

While the constrained number of units has been used to estimated model parameters, for the administrative and functional economy boundaries the full set of units have been used in the hierarchical clustering.

[*] The numbers in density-based labels indicate the minimum population density cut-off (prs/km^2) used in each boundary

[1] Local Administrative Units Level 1

[2] Nomenclature of Units for Territorial Statistics Level 3

[3] Travel-to-Work Area

[4] Urban Audit

Urbanized area is calculated by intersecting boundary polygons of units in each definition with that of the contiguous built-up areas (Office for National Statistics, 2016a) and calculating the intersected area. Since regional economic output data have only been available at NUTS3 level for the year 2011, the OECD’s approach (OECD, 2012, p. 47) has been used to break GVA values down to the GEOSTAT cells assuming uniform density over the gird cells according to

$$Y_{cell} = \sum_i \frac{Y_{NUTS3} \times \frac{N_{cell}}{A_{cell}} A_i}{N_{NUTS3}} \qquad (6)$$

where Y_{cell}, N_{cell}, Y_{NUTS3}, and N_{NUTS3} refer to GVA and population of the GEOSTAT cells and NUTS3 city units. A_i denotes the area of the i^{th} segment of the grid cell intersected by the NUTS3 units and A_{cell} the total area of the grid cell. Once the GVA share of each cell is estimated, GVA at other boundary definitions is calculated by reversing the process in Equation 6 to sum values up at larger boundaries.[10]

model scenarios

Clustering city units of each boundary in Table 1 according to the formulation in

Equation 3, however, would not account for the geography of the urban system and would thus pick the most optimal pairings regardless of their proximity and physical distance between them. To embed the geographic information, we consider a complete graph where city units constitute the nodes and edges are weighted based on the Euclidean distance between the corresponding city units.[11] This enables a selective trimming of the city pairs to be clustered based on a distance threshold such that only units or sets of units that are closer than the threshold are considered for clustering. Additionally, due to the agglomerative nature of such clustering approaches, an unconditional clustering would terminate only after having consumed all city units within a single unit. In order to both provide a termination criteria and an alternative benchmark for the clustering outcomes, we consider two parallel clustering procedures. In one, at each step we seek the city-pair with the smallest distance, η_{A+B}, in the other, in each step, we select the pair that also satisfies the added condition that its performance improves on both parent units. The clustering for both scenarios then terminates when the latter exhausts mutually improved pairings. In this way, we both limit the number of steps allowed to be taken in the original purely agglomerative approach and provide a clustering benchmark in which connections have improved on both units involved.[12]

For the implementation of the distance threshold (DT), we consider two approaches. In the first, we choose a desecrate approach (CD); trimming the graph of edges weighted over a chosen DT and then applying the hierarchical clustering. In the second, a more continuous setup is employed where a lower and upper bound for DT and a step size are selected (SD). The graph is initially trimmed for the smaller threshold and the clustering algorithm is employed until all viable moves are exhausted. This is implemented as a node contraction where of the two original units to be merged the one with the smaller overall GVA is absorbed into the one with larger economic output, which consequently inherits the sum of the attributes of the two units. DT is then increased according to the step size with some previously eliminated edges put back. This is repeated until the DT exceeds the larger bound specified. Together, the CD and SD methods enable examination of both city regions developed with no scale hierarchy and those developed prioritizing mobility starting from a local to larger regional scales.

To isolate regionally-specific potentials, we also consider three regional scenarios. The base scenario (S0) is assigned as that with only the distance threshold limiting the clustering of city units making all units from across the country available for a pairing. A second scenario (S1) is devised where, in addition to the DT, city pairs with connections crossing the country's North-South divide are disallowed.[13] Similarly, a third scenario (S2) is considered regionally isolating the English north, south, and the midlands according to the groupings of the NUTS1 areas.[14] We implement the S1 scenario as a means to investigate pairings where the available units can be considered to be more similar across a range of indicators, e.g. life expectancy to house prices (Dorling, 2010). This is while scenario S2 enables us to examine consistent alternatives to/for the current pattern of city-regions proposed in the north and the midlands based on LAU1 and NUTS3 units (Transport for the North, 2015; Midlands Connect, 2017). Table 2 provides summary of the scenario combinations considered in this study while Figure 3 shows a flowchart detailing the overall process.

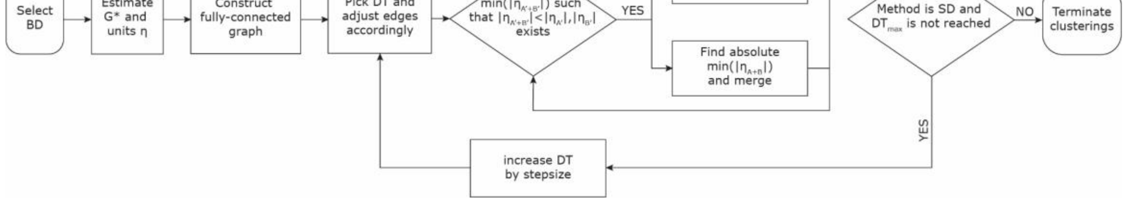

Figure 3. Flowchart capturing the process of hierarchical grouping of city units into city regions.

Table 2. Summary of the scenario matrix and DTs used.

		Clustering Approach		
		Purely Agglomerative	Mutually Improving	
		Geographic Scenario		
		S0	S1	S2
Linkage	SD	Starting at $DT = 20$km expanding towards $DT = 180$km with 10km step size		
Method	CD	Clustering at $DT \in \{20, 40, 60, 80, 100, 120, 140, 160,180\}$		

City regions in England and Wales

We start by examining the resulting clusters for the local authority units (LAU1). Given that LAU1 units breakdown larger functional urban units, in particular that of the Greater London Area where a highly functioning inter-unit transport system already exists, we would expect the clustering procedures, especially the SD scenarios, to capture these short distance internal pairings. This is tested for by mapping the LAU1 units to the TTWA units within which their centroids fall and then performing a frequency analysis on the occurrence of city pairings between TTWA units. Table 3 shows the top 5% of the most frequent pairings aggregated over all SD scenarios, i.e. combined S0, S1, and S2, for LAU1 units. As can be seen for the purely agglomerative approach, when mapped to TTWA units, the most frequent pairings do indeed show connections between units within the same Travel-to-Work area, i.e. London, Manchester, and Derby, with the two most frequent capturing the connections within London and between London and Heathrow as expected.[15] Moreover, 10% of all mapped LAU1 city pairs are those capturing intra-TTWA connectivity and mobility. All the while, for the mutually improving approach, despite changes in the ranking of individual pairings, the overall mix of pairings shows very similar constituting members including mostly intra-TTWA pairings. While London already has an effective inter-city transport infrastructure managed through Transport for London (TfL) and Manchester is moving in that direction (Transport for Greater Manchester, 2017), the rest of these units are yet to implement such infrastructure systems flagging up a lack of adequate mobility provisions at spatial scales smaller than that of existing functional urban areas. The important implication here is that intra-city projects targeting congestion, as they seem to be articulated currently, may be missing the broader problem of quality and diversity of available transport modes and the overall internal connectivity of urban areas.

Table 3. Showing the top 5% of the LAU1 pairings mapped to their parent TTWA with pair frequency.

Purely Agglomerative			Mutually Improving		
Origin	Destination	Freq.	Origin	Destination	Freq.
London	London	63	London	London	63
Slough and Heathrow	London	34	Slough and Heathrow	London	24
Manchester	Manchester	15	Leicester	Leicester	11
Slough and Heathrow	Slough and Heathrow	12	Medway	London	9
Derby	Derby	12	Brighton	Crawley	9
Chelmsford	Chelmsford	9	Manchester	Manchester	9
Chelmsford	Southend	9	Luton	London	9
Nottingham	Derby	9	London	Crawley	9
Birmingham	Worcester and Kidderminster	9	Leicester	Derby	8
Leicester	Leicester	9	Nottingham	Derby	7
Luton	London	9	Chelmsford	Colchester	6

Having sense checked the clustering approach, we proceed to examine the implications of city pair distance and choice of boundary on the city regions clustered.

Local versus regional

Figure 4 shows the cumulative distribution (CDF) of the distance between city units paired in each boundary definition disaggregated, in grey, for different geographic scenarios and distance threshold methods. The two red lines show the overall CDF of city-pair distance across all scenarios and clustering approaches. It is quite clear that the choice of clustering approach, be it purely agglomerative or mutually improving, does not have noticeable effects on the distances over which potentially complementary city-pairs exist.[16] In fact, on average, half of the pairings take place between units that are only a short distance apart regardless of the scenario choice although clusters created vary in unit composition. When considering the top 10% of the most frequent pairings in S0, S1, and S2 scenarios using the SD method, 21%, 27%, and 26% of all pairings across various boundary definitions are not only of small distances but take place between units within the same TTWA. This prominence of short distance intra-urban solutions is also evident when we repeat the frequency analysis for the superposition of the clustering outcomes over all boundary definitions.

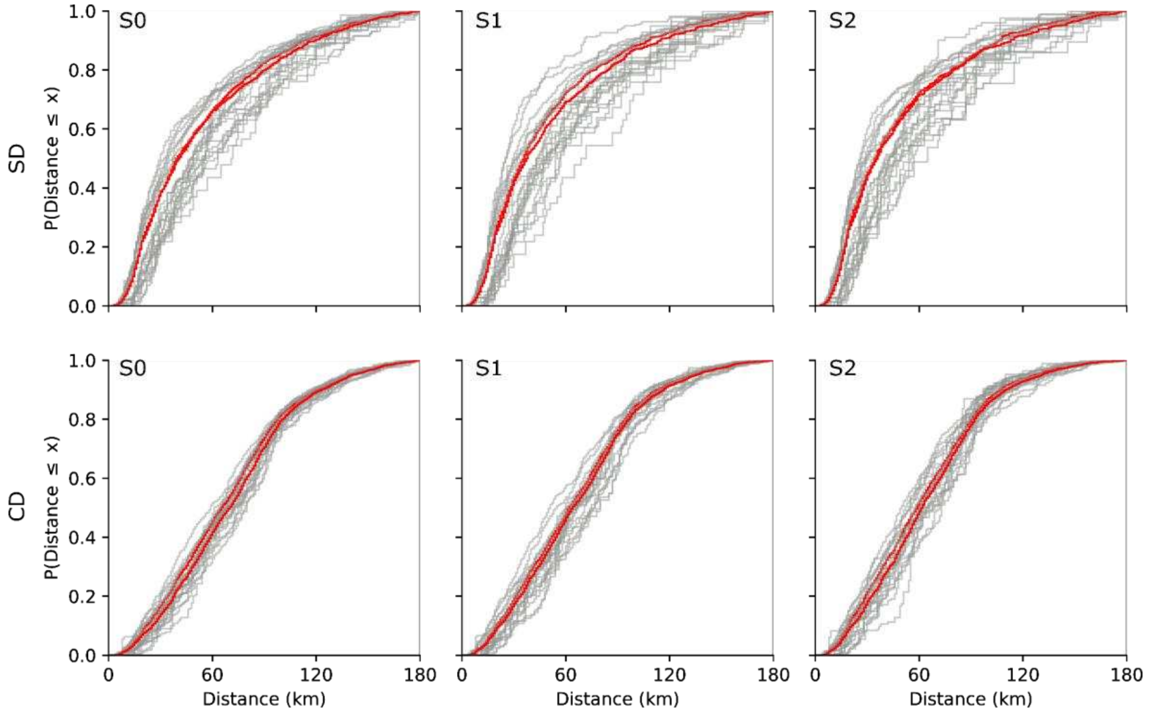

Figure 4. Cumulative distribution function of the distance between city-pair centroids in each geographic scenario for linkage methods SD (top row) and CD (bottom row).

While the SD method could be assumed partial towards shorter distances, the significance and prominence of within-city connections can be shown by considering their frequency distribution. Table 4 shows the percentage of intra-TTWA pairings comprising all pairings, the top 20%, and 5% most frequent pairings when mapping all SD and CD outputs to TTWAs and also those specifically of S0 scenario with CD method at 180km. We would have expected the intra-city pairings to be uniformly distributed throughout the overall distribution of city pairs were the intra-city pairings a small and insignificant part of the distribution or random occurrences within it. Despite the diversity of the city boundary definitions, distance thresholds, and clustering approaches, the percentage of intra-TTWA pairings increase for the increasingly more recurrent pairings. Even at the most permissive scenario, i.e. CD at 180km, despite constituting much smaller fraction of pairings, they make up a larger portion of higher frequency pairings. It is also worth mentioning that the most frequent connection remains that of those connecting units within the London TTWA even when only considering scenario S0 using CD at 180km.

Table 4. Percentage of intra-TTWA pairings across scenarios.

	% of intra-TTWA pairings					
	Fully Agglomerative			Mutually Improving		
% top pairing frequency	SD	CD	S0 – CD180	SD	CD	S0 – CD180
All	7.4	3.5	1.4	7.7	3.0	1.3
20%	18.9	7.3	1.6	16.2	5.9	1.0
5%	27.8	7.5	2.4	24.5	8.6	4.2

This prominence of short-range potential mobility links is in agreement with similar scaling analysis of the urban system in England and Wales over similar boundary definitions by Arbabi et al. (n.d.) who identify a systemic lack of adequate mobility and accessibility for a large portion of city units, especially those located in the north or along the coast. Although the effects of inadequate mobility and economic under-performance are more easily noticeable at larger inter-city distances and scales, the prominence of intra-TTWA pairings suggests a persistent opportunity to address combined performance at smaller scales and within intra-city boundaries. Consequently, because of the inherent hierarchical nature of spatial scales and distances, although inter-city transport-led agglomeration strategies are fitting, when implemented alone, would only mask transport and mobility shortcomings at smaller scales without addressing underlying causes of such under-performance. Diao et al. (2017) study of the inter-city high speed rail in china and its negative effects on intra-city congestion provides a demonstration for this point. Meanwhile, initially addressing the $Y - W$ balance, Figure 2, at smaller scales and distances would inherently be beneficial to larger scale mobility. This would enable the transport infrastructure implemented over larger distances to contribute towards uniformly increasing the urban system's overall baseline productivity. In contrast, a larger-distances-first priority would still be at the mercy of inadequate connections or overwhelming mobility costs at smaller scales. It can then be argued more generally that limiting the spatial scale of infrastructural intervention, whether to inter- or intra-urban, only arbitrarily constraints available solutions for a problem that otherwise appears to require a more concurrent consideration across spatial scales.

City regions and recurrent centres

As a nationally driven infrastructure policy, the overall efficacy of agglomerative region building cantered on the provision of mobility and of transport infrastructure can also be explored by investigating the fraction of city units, out of total, the infrastructural and productivity woes of which can in fact be addressed through better connectivity with other city units. Figure 5 shows the strip-plot of this ratio calculated for each boundary definition using SD and CD methods for purely agglomerative and mutually improving approaches. Error bars show the standard deviation around the overall average ratio at each boundary definition regardless of the method used. As can be seen, the average ratios observed across boundaries hovers more or less consistently around 60%.

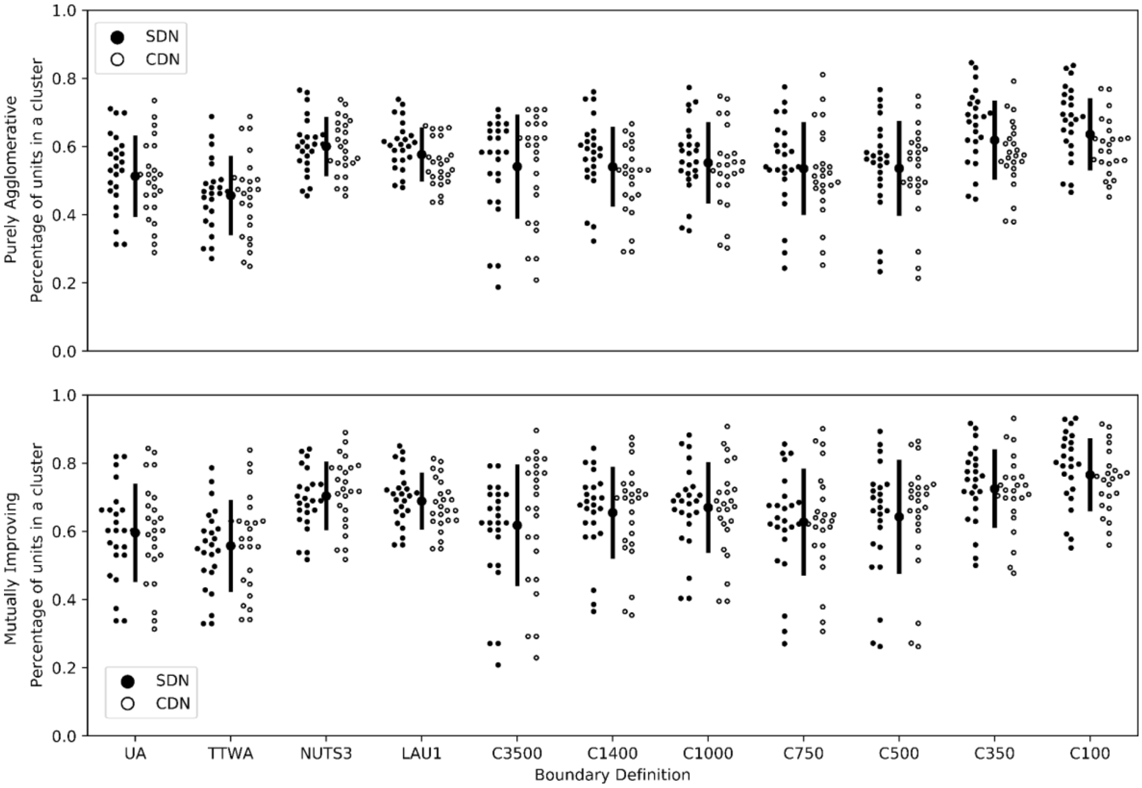

Figure 5. Strip-plots showing the distribution of the ratio of cities clustered in a city region over the total number of initial city units.

The implications are two folds. Firstly, considering administrative and functional boundaries, the inter-city transport connectivity as a way of addressing economic under-performance, at least in an English and Welsh context, does not appear to provide a universal solution. Despite few clustering outcomes reaching ratios as high as 80% towards the 180km distance threshold, the average ratio remains around 60%. Spatial agglomeration arguments implemented through transport should, as such, be applied discerningly and wider national infrastructure planning needs to be tailored for a majority of city units individually.

Secondly, the seemingly larger ratios of the density-based boundaries can be misleading and once again brings us back to the importance of intra-city connections laid out in the previous section. The administrative and functional economy boundaries, as compared with those that are density-based, constitute smaller number of overall units where each unit depending on the boundary might contain multiple urban cores and their hinterlands, the case of the functional economy boundaries, or vast extents of relatively low-density areas, the administrative boundaries. The density-based boundaries, on the other hand, could potentially break up such units into new ones around their populated centres most of which while disconnected are close neighbours. These are then put back together through the clustering procedure when infrastructural needs are complementary.

Finally, we interrogate the geographic consistency and robustness of our synthetic city regions. This is done by geographically embedding the aggregated TTWA-mapped frequency analysis as a weighted network where the weight of each edge is linked to the overall frequency of the connection between the two TTWAs or between units of other boundaries located within the two TTWAs. Figure 6 shows this network visualization when aggregating across all scenarios (S0-2), methods (SD and CD), and distance thresholds isolating the top 1% of all edges.[17] The insets at the bottom show separate aggregations for SD only (A), CD only (B), and CD-180-S0 only (C). It should be noted that the 1% connected clusters in the north does not include Manchester and the edge is that of Bradford-Crewe. The partitioning shown has been done applying a modularity-based community detection algorithm finding communities where edge-weighted connectivity between community members is more significant than inter-community connectivity to the full extent of each graph (Blondel, Guillaume, Lambiotte, & Lefebvre, 2008). While the two main panel in Figure 6 show the most frequently recurring city regions regardless of the connectivity distance thresholds and/or regional reach and limit, the insets provide variations reflecting different planning priorities and clustering approach. Inset A, showing the most frequent links for the SD method, demonstrates city region configurations where intra-city mobility improvements have been prioritized. Inset B, in contrast, shows a multi-scale provision of connectivity effectively superimposing optimal pairings across scales, hence the larger connectivity. Lastly, inset C demonstrates a focus on long-distance pairings. It is noteworthy that community modularity for the purely agglomerative CD-180km-S0 broadly partitions units along Dorling's north-south divide (Dorling, 2010) used in scenario S1 while isolating London-Birmingham-Manchester as an individual community cluster. The London-Birmingham-Manchester grouping, especially the more frequent London-Birmingham link, incidentally picks up the current major transport infrastructure project in the national pipeline (Infrastructure and Projects Authority, 2015).

Of particular interest is, however, the differences and similarities of regional clusters created through the purely agglomerative and mutually improving approaches. Although the clusters produced by the two approaches are visually distinct, especially for those at CD-180km-S0, the combined optimal city-region of the midlands cantered around the Leicester-Nottingham-Coventry triad remains stable throughout. The only other high-frequency pairings to remain stable across approaches and scenarios are the intra-TTWA links within London and Manchester.

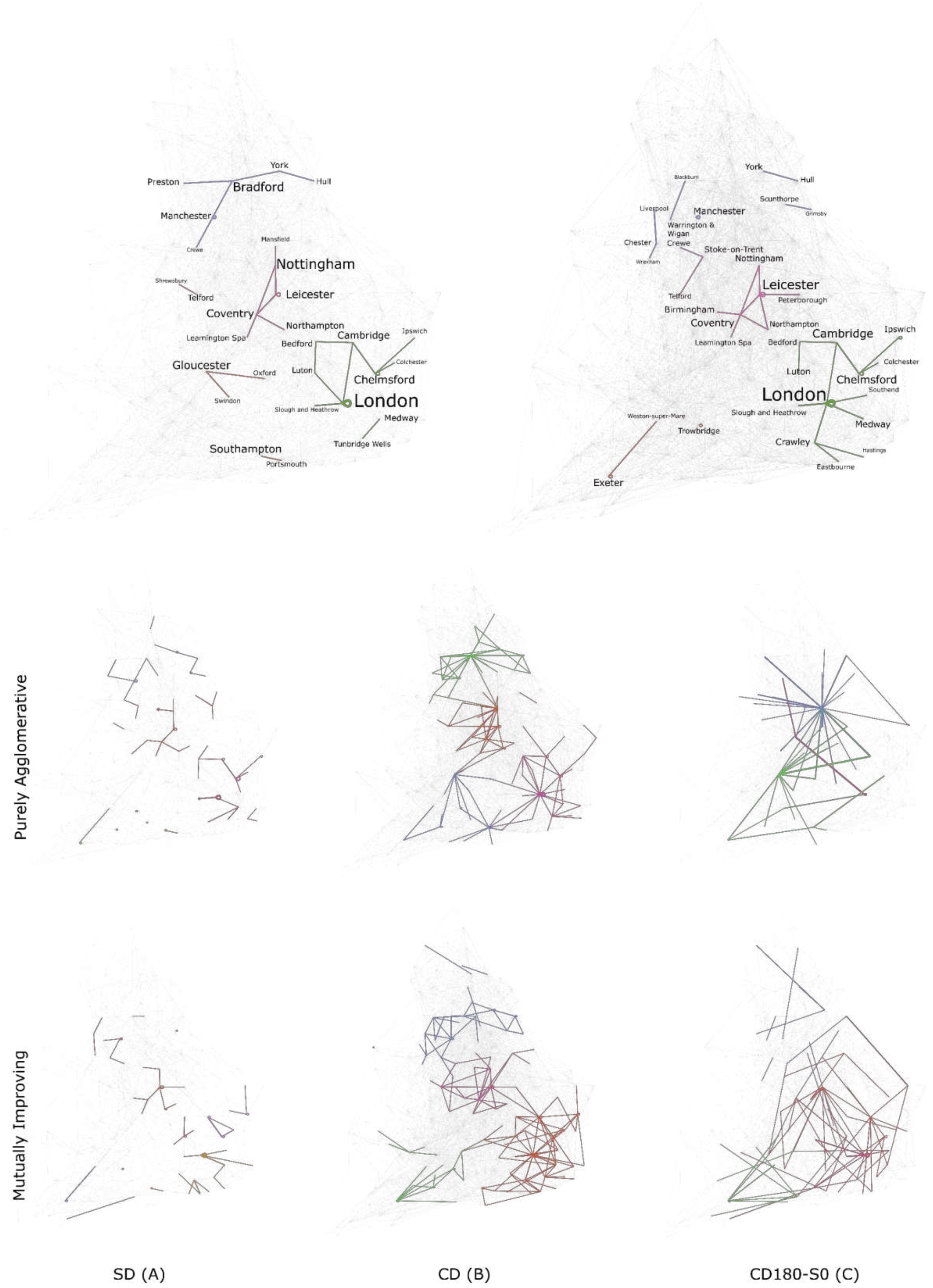

Figure 6. Weighted network of overall pair frequency highlighting the top 1%. Insets include top 5% pair frequency for SD, CD, and CD-180km-S0 – label size is proportional to the city weighted degree.

For intra-city transport at a TTWA scale, areas such as London, Medway, Cambridge, Chelmsford, Coventry, and Manchester show potential to benefit from an infrastructure that enables mixing within their TTWA boundary. Some of the same areas also constitute the larger urban areas at the core of larger city regions to be connected via inter-city transport schemes. For the most parts, when considering the overall network and insets A and B, the broader connected communities are consistent with a regional aggregation of NUTS1 areas. This is for the exception of the connectivity divide in the south of England between the southwest and the southeast which is more consistent with the geography of the clusters developed by Arcaute et al. (Arcaute et al., 2016) when analysing the connectivity of the road network in Great Britain through hierarchical percolation. We reiterate that a point to bear in mind regarding the intra-city self-loops is that while all these urban areas show a potential to benefit from a better-mobilized population within the boundary of their respective TTWAs, London is the only area currently equipped with an overall transport infrastructure that delivers this through Transport for London.

Discussion and long-term implications

We begin the discussion with the acknowledgement of a common obstacle faced by spatial analyses of urban areas. Empirically, all spatial statistics, and scaling frameworks in general, are subject to the 'modifiable areal unit problem' (Openshaw, 1983). This is precisely why the approach presented in the manuscript explicitly looks at realizations of city units at varying spatial scales and boundaries underpinned by a multi-scale hierarchical approach. By looking through a multi-level lens, we have empirically examined the stability and consistency of the problem across spatial scales.

From an analytical perspective, by then mapping the clustering connections made to the TTWA units and examining connection frequencies, we have obtained persistent complementarities that remain stable despite changing spatial scales. Due to the intrinsic definition of TTWAs that implies areas within the same boundary constitute a unified economic marketplace, we can view intra-unit connections as existing complementarity within an existing urban unit that can be boosted through better *intra*-TTWA mobility, if not already in place similar to that of London. By contrast, the inter-unit connections then highlight currently competing units whereby complementarity exists such that were they to act cooperatively as a single and unified unit, given a mobility infrastructure enabling efficient *inter*-TTWA mobility, the larger metro area would achieve closer to optimal $Y - W$ performance. Additionally, we suggested earlier that this process of combining units can be thought of as local adjustments in unit boundary. As such, achieving the combined maximized $Y - W$ in practice would depend on satisfying the implicit inter-unit mobility assumption across the new combined boundary. This would be the case provided either the mobility/accessibility measures already exist, e.g. Greater London Area, or are subsequently provided and that through them the parent units can over time reorganize such that they act as a single 'functional urban area'. Understandably, if this change in the spatial scale of the boundary is not followed up by such an integration, the optimality of their combined G remains theoretic, simply highlights the potential that exists in their combined extent of infrastructure and the human capital, and not truly conducive to maximizing the $Y - W$ performance.

It should, however, be noted that there is no theoretical expectation regarding the pairing distance from the perspective of the scaling framework or Bettencourt's model. While the observation that short-distance or intra-TTWA connections are significantly frequent might appear trivial after the fact, given the particular geography of the urban areas in England and Wales, the observed clusters, regardless of the approach used, are in conflict with the current transport plans promoted relying on similar agglomeration principles that target inter-city connections at larger distances.

Moreover, it is crucial to be aware that neither Bettencourt's model in itself nor the clustering scenarios discussed here directly provide any recommendations on transport investment from a return-on-investment perspective. Since the pairings are based on performance balance *potential* and not cost-benefit analysis, rather than direct investment recommendations, the clustering exercise provides a mechanism for the prioritization of transport/planning schemes the cost-benefit studies for which is to be further considered. The imbalance discussed is then not of transport per se but of a mobility-output trade-off. As an illustration, suppose one thinks of or expects each of city units at a given spatial scale to have an adequate economic performance balance on its own. At each boundary definition, then, there are two issues to consider: i) is the overall output or urbanized area scaling exponent close to the theoretical and ii) for each city is the estimate of G close to the theoretical optimal. Note that the two are to some extent independent. An overall number of city units can show systemic mobility problems whereby the elasticities approach linearity while the $Y - W$ is optimal because they compensate for deviations in the scaling of one, say GVA, through deviations in the other: lower than expected economic output (per capita productivity) through larger urbanized areas (increased territory and hence available population) or vice-versa. The clustering has only addressed the potential for balancing $Y - W$ through matching complementary Gs.

We continue with a brief commentary on the long-term planning implications of using such scaling models for region building aimed at maximizing size-cost performance by an examination of the connections identified in Figure 6. A simple reading of Bettencourt's model used in interpreting these connections would frame the infrastructural intervention required as provision of better mobility. While generally a valid reading, interpreting all pairings without a consideration of the nature of the boundaries as transport related would prove short-sighted. When combining for a closer-to-optimal size-cost performance the model assumes an adequately mixing and mobile population. For contiguously urbanized areas, e.g. London and Manchester, intra-city connections indeed imply a need for an implementation of better transport infrastructure.[18] For Travel-to-Work areas with a less uniform population extent and non-contiguous urbanized areas, e.g. Chelmsford, Cambridge, and Exeter, lack of adequate mobility is both a matter of access and the inherent distance between populated land patches. Considering Equation 1 again, a supposed recommendation for better intra-city mobility for such units would have to include both transport improvements, i.e. increasing average $a_0 l$, while also increasing effective population density through densification, i.e. decreasing overall A_n. This signals at a need for long-term densification of the most populated centres in these units.

A similar point can be raised about inter-city links where both units have similar conditions, e.g. Exeter-Yeovil, or those where one unit is significantly more uniformly dense and contiguous in urbanized area than the other, e.g. Bradford-Crewe and Coventry-Leamington Spa. In such cases, the clustering recommends a pairing based on the ‘potential’ that exists in the combined population size and urbanized area extent towards achieving agglomeration economies. The existing economic under-performance, however, results in the current clusters to have compensated for this productivity gap through the addition and increase of urbanized areas and hence population to maintain optimal size-cost balance. A more relevant interpretation of an increase in mobility and access for these scenarios would be policies aimed at further urbanization of the existing developed areas and moving inhabitants from several distant settlements to single contiguous urbanized areas over time. The ‘potential’ population aspect of these pairings is then in line with the notion of urban ‘borrowed size’ (Alonso, 1973; Burger, Meijers, Hoogerbrugge, & Tresserra, 2015). From a purely cost-size perspective, however, such conurbations would benefit over time from densification and a decrease in the overall number of city units. More generally, from a scaling perspective, any policy proving successful in narrowing the economic under-performance needs to be accompanied by longer-term densification efforts in order not to result in escalating mobility costs over longer periods. This is true for low-density pairings in our clusters as well as units like London which can benefit from densification as a comparatively near ideal mobility infrastructure has already been implemented (Arbabi et al., n.d.). Such arguments, while on the surface would appear mostly compatible with those promoting brownfield development in an English context, might not be consistent with their objectives. This is due to potential discrepancies between places with brownfield space available for development and those where densification strategies are needed as indicated by the model (McCann, 2016, Chapter 5 pp. 318-325).

Conclusions

The main contribution of this paper lies in its examination of an often-overlooked aspect of transport focused spatial agglomeration that is choice of spatial scale and optimal mix of connected areas. We have showed a novel application of urban scaling models combined with a hierarchical clustering approach in identification of optimal city regions for a given idealized size-cost performance using the urban system of England and Wales as a testbed. The paper broadly argues that a single-scale approach and focus when analysing transport infrastructure and intervention without reasonable justifications, whether to inter- or intra-urban, only arbitrarily constraints the available solution space for a problem that would otherwise require a more concurrent consideration across spatial scales and distances.

The analysis involves a hierarchical aggregation of English and Welsh city units over differently-scaled boundary definitions and a number of different distance and geographic constraint criteria. Altogether, our observations note a persistent lack of adequate mixing and mobility across scales but particularly over short or intra-city distances.

Acknowledgements

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Notes

1 Note that the subscript n used in A_n is used by Bettencourt (2013) to differentiate between overall arbitrary area of a city unit, A, and its *networked* area, A_n, which is representative of the built-up, urbanized, and infrastructural extent of a unit. Here, for the sake of consistency we implement the notation originally adopted by Bettencourt and widely used in the scaling literature.

2 Full derivation of the model by Bettencourt is available in (Bettencourt, 2013) and a discussion regarding the strength and validity of the assumptions for the particular case of England and Wales in (Arbabi et al., n.d.).

3 We can alternatively disaggregate $\bar{g}a_0 l\frac{N^2}{A_n}$ into the average outcome of any given interaction between two inhabitants, $\bar{g}$, the area through which an average individual travels/experiences the city, $a_0 l$, multiplied by the city's density, $\frac{N}{A_n}$, providing an average number of interactions for each individual further multiplied by population to provide sum total of interaction outcomes, Y, across the population. Note that while the maximum number of interactions given N inhabitants would be $N(N-1) \approx N^2$, this would imply that on average inhabitants *routinely* traverse the entirety of the city's area, $a_0 l = A_n$, and as such would be grossly unrealistic.

4 Bettencourt's conjecture that baseline human production, G, is independent from city size, N, would imply a lack of correlation between the two variables, Pearson's $R = 0$, across an

urban network which in linear form can be seen as a differential of zero for the two expressed either as $\frac{dG}{dN} = 0$ or alternatively $\frac{d\ln G}{d\ln N} = 0$.

5 The baseline production G, from Equation 1, is now embedded within constants Y_0, W_0, and A_{n_0} for the scaling of each urban property.

6 A summary of Bettencourt's original model derivation resulting in the optimization of $Y - W$ in G and an ancillary discussion of the $Y - W$ optimization for urban networks with non-ideal mobility, i.e. $H < 1$, is included in online supplementary information.

7 While this minimum could be thought of as the addition of an inter-city mobility link that provides inhabitants of one parent city access to transport means embedded in the other city, any physical infrastructure or planning policy that would encourage and result in homogeneous mixing of the aggregate population would theoretically suffice.

8 The economic and population data used are those reported for the year 2011 while the 2012 CORINE land cover data has been used for estimating urbanized area.

9 Distribution plots showing the application of this can be found in the supplementary material.

10 Note that the simplicity of the OECD method in more general cases could potentially result in miscalculations when aggregating back up to units not significantly larger than the original grid cells due to the linear proportionality of the equation used and its inherent uniform population density assumption. In acknowledging these potential issues, we have included in the online supplementary information a sensitivity analysis detailing the impact of potential inaccuracies introduced as a result of the methodology used in the estimation of Y.

11 Here, we use centroid-to-centroid distance where the centroids are obtained for city units polygons using the QGIS package.

12 Sample scripts used for the clustering are available on GitHub (https://github.com/cip15ha/city-region-logic).

13 For this, city units within each boundary are assigned a region based on their position relative to the North-South boundary developed by Dorling (2010).

14 Maps showing the boundaries used for S1 and S2 are available in the supplementary materials.

15 The original TTWA methodology does indeed aggregate London and Heathrow areas as the same TTWA for 2011 Census data. The final separation of the two areas is done based on results of stakeholder engagement and expert views (Coombes & Office for National Statistics, 2015).

16 A more disaggregated overview of the city pair distance distributions for individual scenarios is available in the supplementary materials.

17 Larger network figures are available in the online supplementary material.

18 As previously noted, London provides the example where such infrastructure and public transport services have already been implemented on a multi-modal basis through TfL.

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