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ABSTRACT

The development of public transport networks in polycentric regions involves making complex trade-offs between extending network coverage, densifying local connections, offering improved connections between urban centers and increasing capacity on existing links. Moreover, different modalities might be suitable for each of these development decisions depending on their speed, capacity and cost function structure. The objective of this study is to identify the influence of polycentric configurations and their respective travel demand distributions on the emerging topology of the corresponding multi-modal public transport network using an iterative growth model. Since polycentricity comes in many forms, our experimental design considers four polycentric configurations inspired by the cases of London, Tokyo, the Flemish Diamond and the Rhine-Ruhr area.

The results are analysed in terms of both the properties of the obtained network structure as well as the evolutionary path and the sensitivity of both to key model settings and design variables. We find that more uneven population distributions result with the construction of fewer links and consequently the less connected and shorter the network becomes. The network evolutionary path is marked by distinctive intra- and inter-agglomeration expansion, densification and bulking phases. While the costs associated with each investment are the same regardless of the moment at which the investment is made, the benefits are not. This path dependency means that the evolutionary path is characterized by the need to attain a critical mass to justify further developments.

1. Introduction

Consider the similarities and differences in the public transport network structure in Greater Tokyo as opposed to say the Randstad region in the Netherlands. Metropolitan regions come in many different forms and so do their public transport systems. These differences are presumably the consequence of a complex interaction between land-use patterns, economic drivers and policy making decisions and how those have evolved over a long period of time. Moreover, policies promoted by planning authorities worldwide have stimulated the development of such spatial configurations (e.g. the European Union, (Walsh, 2012), and China, (Cheng and Shaw, 2017)).

In this study we set off to examine the relation between different spatial development prototypes and their public transport network structures by means of an iterative network development model. In doing so, we will limit our perspective to how distinctive spatial patterns yield different network structures, where the former is considered exogenous and the latter endogenous in our analysis. In particular, we focus on the development of multi-modal public transport networks in the context of a polycentric urban region.

The relations between the spatial structure and the corresponding transport network serving it involve complex feedback relations as their evolution is highly inter-dependent. Studies devoted to modelling the evolution of the spatial structure of polycentric regions have either completely ignored travel impedance in their models (e.g. (Broitman and Czamanski, 2015)) or established empirically or analytically the relations that use commuting costs as an explanatory variable for the development of sub-centers (e.g. (Louf and Barthelemy, 2013; McMillen and Smith, 2003)). None of these studies have considered the underlying transport networks, not to mention the evolution thereof.

While the emergence of polycentric urban regions has been widely documented, little is known on the evolution of the corresponding public transport network. The limited empirical evidence on the development of public transport networks in a monocentric context (Cats, 2017; Yang and Chen, 2018) indicates that those are characterized by transitioning from peripheral attachment to preferential attachment, i.e. from extension to densification. Whether this also holds for polycentric urban regions is likely to largely depend on the spatial

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configuration settings. The latter exhibits large diversity among polycentric developments as recognized in the literature (e.g. (Burger et al., 2013; Brezzi and Veneri, 2015; Taubenböck et al., 2017)).

Models for optimizing public transport design adopt a top-down approach for determining the optimal solution for a single centralized design of public transport services for a given demand for public transport services and under various spatial configurations (e.g. (Badia, 2020; Chen et al., 2015; Fielbaum et al., 2016; Saidi et al., 2016)). In reality, however, public transport network growth is the outcome of a sequence of inter-dependent investment decisions which depend on the dynamic interactions between travel demand and service provision. Cats et al. (Cats et al., 2020) proposed a network growth model for a unimodal radio-centric configuration where investment dilemmas are limited to extending radial lines and constructing ring connections. In a polycentric context, development decisions involve making more complex trade-offs between extending network coverage, densifying local connections, offering improved connections between urban centers and increasing capacity on existing links. Moreover, different modalities might be suitable for each of these development decisions depending on their speed, capacity and cost function structure.

The objective of this study is to identify the influence of polycentric configurations and their respective travel demand distributions on the emerging topology of the corresponding multi-modal public transport network. To this end, we develop an iterative growth model to examine the evolution of multi-modal public transport networks under various polycentric spatial configurations. Connecting polycentric urban regions requires the development of a multi-modal public transport network since different types of public transport modalities might be suitable for connections between and within agglomerations. The proposed network growth model involves selecting among different modalities which vary in terms of stop-spacing, speed, capacity and fixed and variable costs. The model accounts for the interactions between network development, the travel impedance implied and the resulting share of travel demand opting for public transport. We analyse the public transport network evolution for several distinctive spatial structure prototypes inspired by real-world polycentric development patterns. Note that the spatial structure is considered in this study exogenous, i.e. there is no feedback loop from transport network development to spatial development. Public transport demand in our model – both the total demand as well as the distribution thereof - is however dependent on the accessibility offered by the transport network in any given model iteration.

In the remaining sections, we first present the proposed network growth model which consists of iteratively assessing candidate investments and updating the travel demand distribution for public transport and assignment of passenger flows across the network (Section 2). We then present our experimental set-up for four polycentric configurations inspired by the cases of London, Tokyo, the Flemish Diamond and the Rhine-Ruhr area (Section 3). The results are analysed in terms of both the properties of the obtained network structure as well as the evolutionary path and the sensitivity of both to key model settings and design variables (Section 4). We conclude with a discussion of the key findings and suggestions for further research (Section 5).

2. Iterative network growth model

2.1. Modelling framework

Fig. 1 shows the workflow of the proposed multi-modal network evolution model. The core of the model is the *Evolution phase* which is preceded by the *Initialisation phase*. Based on the input parameters pertaining to the overall spatial structure, travel demand distribution and the characteristics of each mode, the initialisation phase (Section 2.2) results in a latent origin-destination demand matrix. This matrix is then assigned to any network alternative, subject to evaluation in the subsequent step and remains static. The evolution phase (Section 2.3) consists of an iterative network building until the convergence criterion is met and the resulting network performance and topological characteristics are provided as output (Section 2.4). This is detailed in the subsequent sub-sections.

2.2. Initialisation phase

The network evolution model needs to be first initialised with the starting network state and demand settings. Those are then subject to the classic four-step transport demand model, performing trip generation, trip distribution, modal split and network assignment in succession as described in the following sub-sections.

2.2.1. Initial spatial configuration and network state

The input parameters prescribe the (i) number of urban agglomerations within the polycentric region, (ii) the distance (in kilometers) between each of these agglomerations, (iii) the size of each urban agglomeration (its radius in kilometers), and (iv) the distance between sub-centers within the urban agglomeration. The analysis area is overlaid with a grid of nodes with a pre-defined inter-distancing. A subset of this set of nodes is selected as centers of agglomerations based on the input parameters specifying the number of centers, as well as constraining the minimal distance between any pair of centers. This generation process results in the locations of urban centers which are randomly distributed over the analysis area. Next, population is assigned to nodes based on the selected demand distribution input specifications (e.g. linear or exponential decay function) and the radius of agglomeration area size assigned to each center. Node population is assigned in relative terms and can then be scaled to match the total population size provided as an input parameter. The generated spatial structure is considered from now on constant, whereas public transport demand patterns and the evolved multi-modal public transport network are endogenously determined and subject to evolution. Lastly, an initial network may be based on an existing network or alternatively the model can start with a tabula-rasa scenario, i.e. the set of existing links is empty.

2.2.2. Trip generation and attraction

The number of trips originating at, and destined to, each node is determined based on the population size in each node. The travel demand between each node-pair is then determined, resulting with an origin-destination (OD) matrix. A doubly constrained gravity model is used to determine trip distribution, where the total trip attraction is assumed to be equal to the total trip production:

$$q_{ij} = x_i \bullet \mathrm{o_i} \bullet \mathrm{y_j} \bullet \mathrm{d_j} \bullet \mathrm{f}\left(\mathrm{c_{ij}}\right) \tag{1}$$

While we ensure that $\sum_j q_{ij} = o_i$, $\sum_i q_{ij} = d_j$ and x_i and y_j are iteratively determined balancing factors with $x_i = \frac{1}{\sum_j d_j \bullet y_j \bullet} f\left(c_{ij}\right)$ and $y_j = \frac{1}{\sum_i o_i \bullet x_i \bullet} f\left(c_{ij}\right)$.where q_{ij} is the latent demand between origin i and destination j, o_i is the number of trips produced (originating) at origin i, d_j is the number of trips attracted (destined) to destination j. x_i and y_j are balancing factors and $f(c_{ij})$ is the deterrence function related to travel impedance c_{ij} between origin i and destination j. The deterrence combined function proposed by Ortúzar and Willumsen (2011) is adopted here:

$$f\left(c_{ij}\right) = c_{ij}^{\alpha} \bullet \mathrm{e}^{\beta \bullet \mathrm{c}_{\mathrm{ij}}^{\mathrm{A}^*}} \tag{2}$$

α and β are parameters and the impedance term, c_{ij}, is set to the minimum travel time in the case of a complete graph, A^* (i.e. where all nodes are directly connected to each other). The obtained OD matrix, Q, is then given as input to subsequent steps.

2.2.3. Modal split

In order to estimate the travel demand for a given public transport

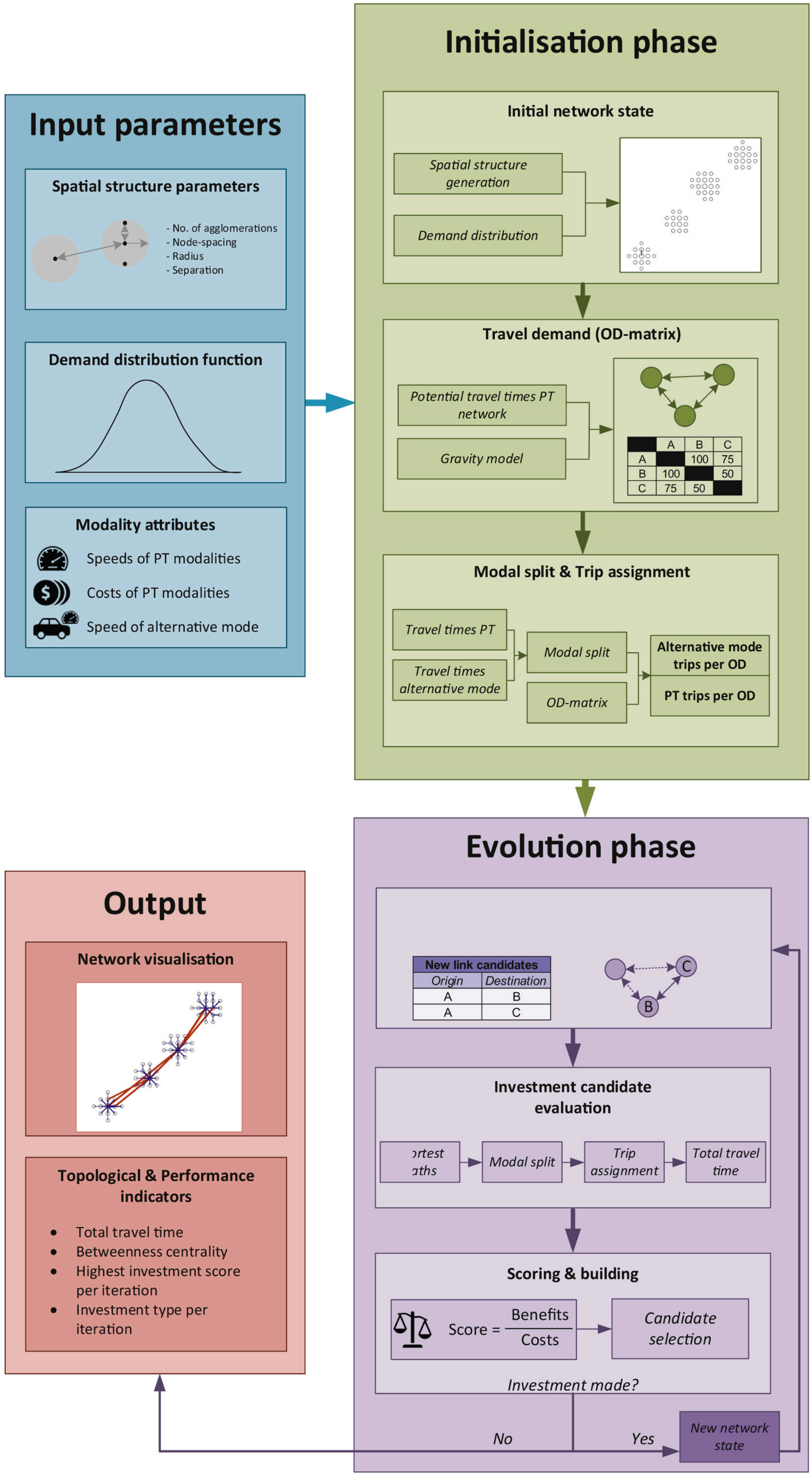

Fig. 1. Network evolution model workflow.

network, the share of travel demand that chooses travelling by public transport is calculated using a choice model based on random utility maximization (RUM). A Logit model is adopted in this study. The utility of each travel mode corresponds to the generalized travel time along the shortest path which accounts for in-vehicle time, waiting times and the number of transfers between different modalities (translated into time-equivalent terms using a transfer penalty).

2.2.4. Trip assignment

The number of public transport trips between each OD pair is given as input to the trip assignment module. An assignment is performed for the initial network state as well as for any subsequent network evaluation phase. An All-or-Nothing assignment is performed, rather than an iterative network loading that yields user equilibrium conditions. This unconstrained assignment approach is adopted here because we are interested in identifying how the network structure evolves over time based on the prevailing demand patterns rather than setting optimal capacities under saturated conditions. In addition, the analysis of network evolution involves evaluating a large number of potential investments for each network state within the iterative evolution process. It is therefore crucial to apply a computationally efficient assignment module.

2.3. Evolution phase

The initial network and the OD-matrix are provided as input to the evolution phase. The evolution phase is composed of a number of steps per iteration as detailed in the following sub-sections.

2.3.1. Investment candidate generation

In the first step, a set of candidate links that can be selected for investment is generated. We consider three possible types of investments: *Expansion* - connecting an unconnected node to the network; *Densification* - connecting two nodes which are already connected to the network through existing links, and; *Bulking* – increasing the service frequency (and hence capacity) of an existing link. Candidate links must be connected to the existing network, in line with the principle of preferential attachment (Barabasi and Albert, 1999). For each PT mode, minimum and maximum inter-station distances are provided as input to determine the set of investments which are feasible.

2.3.2. Investment candidate evaluation

Each investment candidate is assessed in order to obtain the resulting travel times. The travel demand for the proposed public transport network (current network state with the addition of the proposed investment) is re-estimated (step 2.2.3) and then assigned to the network (step 2.2.4).

2.3.3. Scoring and building

In this step we calculate the construction costs and benefits associated with each candidate investment. For expansion and densification investments, the associated initial construction costs consist of both infrastructure and rolling stock costs. The construction costs of link e with a length l_e for each mode k are calculated by multiplying the infrastructure costs per km for the respective mode, $\gamma_k{}^{con}$, with the corresponding link length. The rolling stock costs are determined by multiplying the costs of the respective mode, $\gamma_k{}^{rs}$, with the respective service frequency, w_k, which determines the number of vehicles necessary for operating the respective service.

$$c_{e,k}^{con} = \gamma_k^{con} \bullet \mathrm{l_e} + \gamma_\mathrm{k}^\mathrm{rs} \bullet \mathrm{w_k} \tag{3}$$

In addition to the initial construction costs, variable costs associated with running the services are calculated for each investment candidate. The annual variable costs associated with link e of length l_e and mode k are calculated as follows:

$$c_{e,k}^{var} = w_k \bullet [\gamma_\mathrm{k}^\mathrm{var\_t} \bullet \kappa + \gamma_\mathrm{k}^\mathrm{var\_d} \bullet (\mathrm{v_k}/\kappa)] \bullet \delta \tag{4}$$

Where v_k and w_k are, respectively, the operational speed and the frequency enabled by an investment round of mode k. κ is the number of operating hours per day and δ is the number of operation days per year. The total costs are then discounted with a discount rate of r over a time horizon of n years. $\gamma_k{}^{var\_d}$ and $\gamma_k{}^{var\_t}$ are the variable operational costs per kilometer (e.g. fuel) and hour (e.g. personnel), respectively.

The benefits associated with each candidate investment refer to the travel time savings that can be realized. The benefits are calculated by monetarizing the annual travel time savings:

$$b_e = [f(\widehat{A^e}) - f(A^e)] \bullet \tau \tag{5}$$

where τ is the value of time (VoT) [€/h] and $\widehat{A^e}$ is the network state matrix prior to the addition of the candidate investment on link e. The network-wide travel impedance function, f, for a given network state matrix, A^e, is calculated as follows:

$$f(A^e) = \sum_{i \in N} \sum_{j \in N \setminus i} \left[p_{ij}^{PT,A^e} \bullet \mathrm{q_{ij}} \bullet \mathrm{c_{ij}^{PT,A^e}} + \left(1 - \mathrm{p_{ij}^{PT,A^e}}\right) \bullet \mathrm{q_{ij}} \bullet \mathrm{c_{ij}^{ALT,A^*}} \right] \tag{6}$$

In which $f(A^e)$ is the sum of the total travel impedance by public transport and by the alternative modes, each of which consists of the product of the respective demand flow and travel impedance for the respective network. $p_{ij}{}^{PT,\ A^e}$ is the probability that a passenger travelling between origin i and destination j chooses to travel by public transport under network state A^e. This probability is multiplied by the total demand for the respective OD-pair, q_{ij}, to obtain the total public transport flow. The latter product is multiplied by $c_{ij}{}^{PT,\ A^e}$, the travel impedance when travelling by public transport. Similarly, the second term in the brackets of Eq. 6 corresponds to the total passenger-time of all passengers choosing to travel by other means of travel using the assumed complete graph, A^*.

Each candidate investment is assigned a score corresponding to the ratio between the expected benefits and the estimated costs. If the ratio is smaller than 1 (i.e. total costs exceed the benefits), then the candidate is discarded. In each iteration the candidate yielding the highest score (i.e. highest benefits to costs ratio) is selected as an investment. The network state is then updated, including the new investment, and the next iteration commences. This iterative network evolution process continues until there are no more candidates with a score that exceeds a pre-defined threshold value.

2.4. Model output

The model results in the selected investment per iteration and the respective network state visualization. For each network state (i.e. network evolution iteration), a series of performance and topological indicators is available. The performance indicators include total travel time by public transport and the alternative mode(s), modal share and the investment score of the selected investment. The set of topological indicators include network length, global connectivity (gamma index), directness (detour ratio), degree and betweenness centrality per node, average link length and the share of network length per mode.

3. Experimental Set-up

3.1. Agglomeration prototypes

Many urban regions worldwide have evolved or are in the process of being transformed from a monocentric development into a more complex spatial configuration which consists of a multiplicity of urban centers. A wealth of empirical studies has illustrated the emergence of polycentric developments across the world and how sub-centers can be identified using various data such as satellite observed lighting (Tselios and Stathakis, 2020), 3D remote sensing building density (Taubenböck et al., 2017), transport network infrastructure (Liu et al., 2016), residence and workplace locations (Vasanen, 2012), aggregate transport demand flows (Cats et al., 2015) and individual mobility traces (Cats and Ferranti, 2021). There is no consensus in the literature not only in regards to how to measure the spatial parameters of polycentric regions, but even on how to overall define those as well as methodological issues associated with determining their geographical demarcation (Burger and van Oort, 2008) and identifying the number of centers involved (Zhang and Derudder, 2019). Parr (Parr, 2004) proposes seven conditions that can be used to identify a polycentric region: the number of centers, upper and lower bounds on center separation, the size and spacing of centers and the size distribution of centers, the extent of interaction among them, and a degree of specialization. He asserts that applying all of those may be too restrictive a definition and also stresses that exact metrics and values are somewhat arbitrary.

In our experiments, we have chosen to generate alternative spatial distributions of a polycentric region by varying the following parameters: (i) the number of agglomeration centres, (ii) the radius of the individual centres, and; (iii) their inter-distancing. These addresses most of the characteristics discussed in Parr (Parr, 2004). Based on initial experimentation we found this set of parameters to be adequate for generating diverse patterns that resonate with existing polycentric regions, but is by no means meant to be exhaustive. In the following, we perform a series of numerical experiments by defining four prototypes, each of which is characterized by a distinctive spatial structure and is inspired by a real-world polycentric region.

Our prototypes are inspired by the following cases: *London*, *Tokyo*, the *Flemish Diamond* (Belgium) and the *Rhine-Ruhr* area (Germany) to which we will from here on refer by these names. A summary of their spatial parameters is given in Table 1. The London prototype is closest to a single centre (i.e. monocentric) with a large radius. In contrast, Tokyo is a polycentric metropolitan area consisting of several close-by centres (Sorensen, 2001). The diameter of the centres is greater than the distance between centres, resulting with an overlap and hence a continuous built area. The Flemish Diamond represents an alternative prototype of a polycentric metropolitan area which has not grown into a single city often due to historical fragmentation (Meijers, 2007). Another example of which is the Dutch Randstad (Kloosterman and Lambregts, 2001). The Rhine-Ruhr case offers another variant of the polycentric metropolitan area where where agglomeration centres are resulting with a continuously built area along an axis (Meijers, 2007). In addition to the distances, another difference between the latter two cases is that the Flemish Diamond prototype is organized in a square or ring form, whereas the Rhine-Ruhr is developed around one or two intersecting axes. The aim of our experiments is not the exact reproduction of selected cases but rather the principal investigation of the respective prototypes.

3.2. Population distribution

We examine three population distributions in our numerical experiments: *Uniform*, *Linear Decay* and *Exponential Decay*. An average population density of 10,000 inhabitants per square kilometer is assumed across scenarios, whereas the minimum and maximum values are set to 2000 and 15,000, respectively.

Table 1
Spatial structure parameters of the four prototypes.

	London	Tokyo	Flemish Diamond	Rhine-Ruhr
Number of agglomeration centres	1	4	4	4
Radius [km]	9	4.5	4.5	4.5
Distance between centres [km]	–	6–8	20–60	8–12

3.3. Public transport layers

A polycentric metropolitan area is served by a multi-layer public transport network which comprises of a range of public transport modes which vary in terms of their inter-station distances, speed, capacity and cost characteristics. In our experiments we distinguish between three layers of public transport services: *Urban*, *Metropolitan* and *Regional*. These services can be realized by various modalities ranging from Bus Rapid Transit (BRT) and Light Rail Train (LRT) to Metro, Commuter train and Regional trains. Table 2 summarizes the mode-specific parameter specification in regards to inter-station distances, cost function, and speed that we employ in this study after consulting a number of sources, including Vuchic (Vuchic, 2002), Tirachini et al. (Tirachini et al., 2010), Deng and Nelson (Deng and Nelson, 2011) and Flyvbjerg et al. (Flyvbjerg et al., 2013). When setting the values we also aimed at ensuring that the different levels are associated with distinctive modal characteristics. Each investment in infrastructure capacity is assumed to allow operating the service with a frequency of eight departures per hour.

3.4. Scenario analysis and implementation

Our scenario design consists of combinations of agglomeration prototypes and population distributions, summarized in Table 3 below. The combination of Uniform population distribution and London is omitted since it results in a trivial case. We therefore consider a total of 11 scenarios denominated by the combination of the first letters of the agglomeration and population distribution types.

For the deterrence function defined in section 2.2.2, the value chosen for α is set to 0.5 and the β value is estimated as recommended by (Ortúzar and Willumsen, 2011), leading to a value of 0.47. Both benefits and costs are discounted for using the investment time-horizon of $n = 30$ years with $r = 0.05$, set by the European Commission guidelines (Sartori, 2015) and $\kappa = 15$. The operational speed of the alternative travel mode is set to 15 km per hour, assuming to reflect all relevant causes of disutility (e.g. parking search time and cost).

The 'Tokyo' scenarios, consisting of multiple agglomerations which are not distinctly separated, are found 'unstable'. This means that with the initially set conditions for the network to evolve, the evolution process would stop very prematurely due to low scores (<1.0) attained early on. Therefore, additional tests were performed for the 'Tokyo' scenarios in which the networks evolved freely by choosing the highest scoring investment in each iteration, relaxing the condition that the score had to be above 1.0. Afterwards, the scores in each iteration were analysed and a cut-off point was determined manually. We find that the scores were almost all above 1.0, with sometimes a low scoring investment (<1.0) in between. These scores were accepted as long as the four subsequent scores were not all below 1.0. When a series of five low scores (<1.0) occurred, the last positive scoring investment would be set as the final iteration in the evolution process.

Total model run times in MATLAB varied between 8 and 24 h for

Table 2
Modes characteristics.

	Urban	Metropolitan	Regional
Minimum inter-spacing [km]	0.5	3	6
Maximum inter-spacing [km]	3	6	200
Infrastructure cost per km [M€], γ_k^{con}	8	14	21
Rolling stock cost per vehicle [M€], γ_k^{rs}	1	2	8
Time-dependent operational costs [€/hour], $\gamma_k^{var\_t}$	40	60	100
Distance-dependent operational costs [€/km], $\gamma_k^{var\_d}$	4	6	10
Operational speed [km/hour], v_k	30	50	80

Table 3
Scenario design.

Scenario name	Agglomeration prototype	Population distribution type
LL	London	Linear Decay
LE	London	Exponential Decay
TU	Tokyo	Uniform
TL	Tokyo	Linear Decay
TE	Tokyo	Exponential Decay
FU	Flemish Diamond	Uniform
FL	Flemish Diamond	Linear Decay
FE	Flemish Diamond	Exponential Decay
RU	Rhine-Ruhr	Uniform
RL	Rhine-Ruhr	Linear Decay
RE	Rhine-Ruhr	Exponential Decay

scenarios with roughly 60 nodes, depending on the complexity of the solution space when using a PC with an Intel Core i7-6820HQ 2.7GHz processor and 16GB of RAM.

4. Results

In the following section the results of the numerical experiments are discussed. Firstly, some general findings regarding the evolution process are discussed: the spatial structure of the network, the population distribution within the network, the operational costs of the network and multimodality versus uni-modality. Hereafter, for each of the main characteristics of the networks, we analyse how it impacts the network evolution pattern. Lastly the sensitivity of the model and the network evolution is discussed.

4.1. Network structure properties

We first analyse the results obtained upon the convergence of the iterative network growth model. Fig. 2 displays the final network state obtained for each of the scenarios. Each of the agglomeration prototypes yields a visibly distinctive network structure. With the exception of the case of Tokyo, all nodes are connected to the public transport network. The Tokyo case is found to require investing in non-beneficial links in order to later on unlock high gain investments on which we will expand in the next subsection. In both London scenarios, with either linear or exponential decay functions (LL and LE), the network expands from the center towards the outer areas in a radial, tree-like manner. All of the connections are served by Urban links. In contrast, the underlying agglomeration centers in the Tokyo case result with a combination of local connections extending to the entire area and metropolitan and regional connections between key nodes.

A visual inspection of the rail-bound network maps for the four prototype areas reveals some important resemblance to model outputs. The London under- and over-ground networks do not exhibit a clear hierarchy, whereas the network in Tokyo consists of well-integrated suburban and urban rail networks. Both networks are characterized by an overall radial network featuring local grids in high-density areas. Interestingly, outer ring lines – a prominent feature of rail networks in large metropolises - are not generated by the model. Saidi et al. (Saidi et al., 2014) found that urban parameters such as population density, and network size were not sufficient for explaining the presence of ring lines. The networks in the Flemish Diamond and the Rhine-Ruhr area are characterized by a radial local urban rail networks (i.e. underground, tram) inter-connected by regional services (i.e. suburban and regional trains), exhibiting overall similarity to the results obtained by our iterative network growth model.

The more uneven the demand is, the more fragmented and disconnected the network becomes. In the case of exponential decay, only regional connections are available when travelling between agglomerations. The Flemish Diamond results in densely connected local networks within agglomerations, and limited regional connections between agglomerations. A uniform distribution yields more regional connections that offer some redundancy. In contrast, the linear development axis and shorter distances in the Rhine-Ruhr case result with a greater

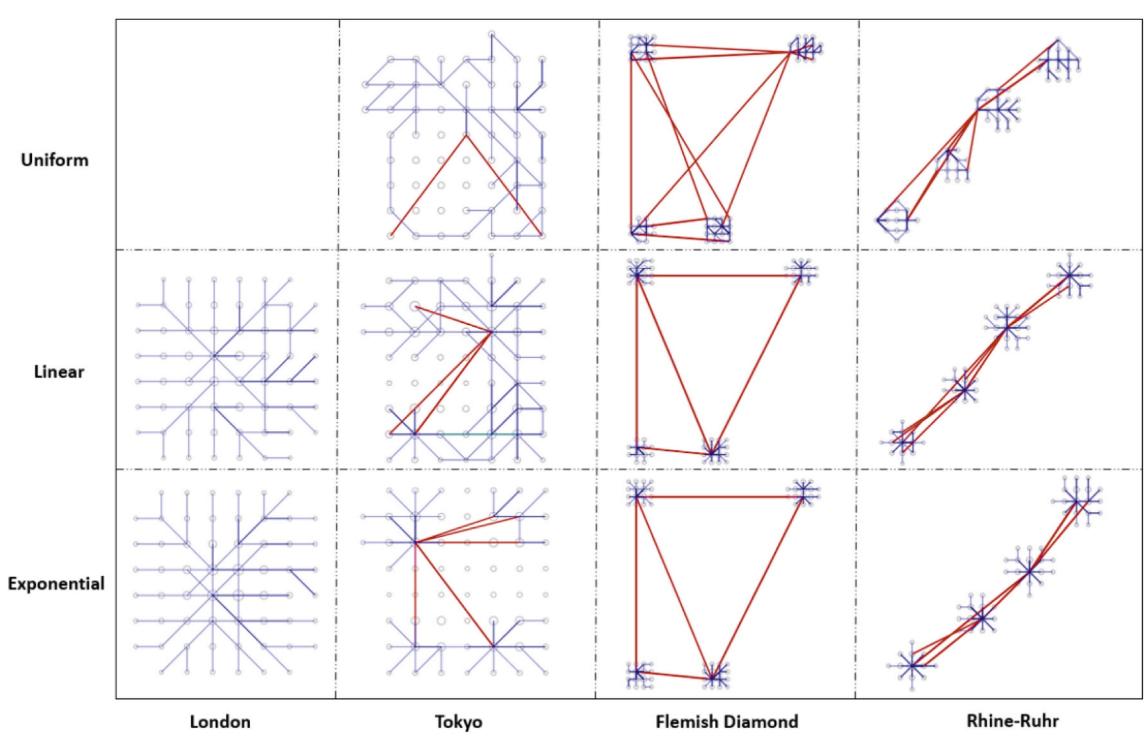

Fig. 2. Resulting networks for each of the agglomeration prototype and distribution types scenarios (Urban links in Blue, Metropolitan links in Green and Regional links in Red). Node size corresponds to population size. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

number of regional connections.

Table 4 provides a summary of network topological indicators for the final network state yielded for each scenario. It is evident that different spatial prototypes, and to a lesser extent different population distributions, result with distinctive network structures. Network connectivity is measured in terms of the share of edges in relation to the full planar graph known as the gamma index. In general, more uneven population distributions result with the construction of fewer links and consequently the less connected and shorter the network becomes. Similarly, since the network becomes more sparse with a more uneven population distribution, the number of links connecting to each node (i.e. node degree) decreases. As also evident in Fig. 2, the intermediate characteristics levels of the metropolitan connection fall beyond (LL and LE) or between what is desirable in all cases other than TL. Interestingly, there is no clear relation between the composition of local and regional network length and population distribution. In the Flemish Diamond case the more uneven the distribution the less need there is to connect regionally whereas in the Tokyo case a more uneven distribution means that few regional connections substitute more fine-meshed local connections across the region. In the following sub-section we examine the process that has leads to these outcomes.

4.2. Network evolutionary path

In the following we identify the evolution stages for different spatial prototypes and review the commonalities and differences among them. Network investments can either involve constructing a new link or increasing the capacity of an existing link. Moreover, a new link can either expand the network coverage by connecting to a new node or densifying the network by adding a new (direct) routing option between previously connected nodes. We can therefore distinguish between three types of investments as mentioned in section 2.3.1: *Expansion*, *Densification* and *Bulking*. Further, an expansion can be either within (intra) or between (inter) agglomeration centres.

We plot in Fig. 3 the type of investment made at each iteration for four scenarios selected as illustrative examples for each of the prototypes. As can be seen, the first part of the evolution process consists mainly of expansion investments, while the remaining of process involves a shift in focus towards alternating between phases of densification and bulking investments. Notwithstanding, this overall pattern manifests itself differently among the four prototypes. In the London prototype, periods of expansion are interrupted by densifications as the evolution progresses (until iteration 71) then followed by an uninterrupted series of bulking investments. In contrast, the Tokyo prototype evolution is characterized by early expansions increasingly penetrated by either densification or bulking where the converge is achieved after a series of densification investments. The Flemish Diamond and Rhine-Ruhr cases also exhibit alterations between bulking and densification at later stages with a series of bulking investments leading to convergence. Inter-centres expansion developments take place in intervals of 20–30 iterations as the network evolution exploits intra-centre local investments before gaining sufficient volumes to justify a long-distance connection to another centre.

Table 4
Key performance indicators of the final network state for each agglomeration prototype and population distribution scenario.

Scenario	Connectivity	Average node degree	Total network length [km]	Share of urban, metropolitan and regional out of network length [%]
LL	0.41	2.43	160.1	100,0,0
LE	0.39	2.30	153.7	100,0,0
TU	0.38	2.64	164.6	88,0,12
TL	0.43	2.98	205.7	79,3,18
TE	0.26	2.20	129.3	69,0,31
FU	0.54	3.20	575.8	32,0,68
FL	0.37	2.17	348.2	38,0,62
FE	0.37	2.16	357.0	40,0,60
RU	0.43	2.52	281.9	57,0,43
RL	0.39	2.29	288.7	48,0,52
RE	0.35	2.06	222.4	58,0,42

We demonstrate how the network evolves under the above-mentioned scenarios by plotting network states at selected iterations in Fig. 4. In the London scenario, the network first undergoes extensive expansions by forking out of the centre, followed by the densification of the network to allow for shortcuts. After all nodes are connected to the network, the network densifies further while the latter phase of the evolution process consists of a number of bulking investments. Unlike the London case, the polycentric Tokyo case results in alternating between local connections and regional connections within and between the most populated agglomerations. The intra-agglomeration connections form a star-like shape, while some of the agglomerations are connected by a metropolitan or regional links while travelling between some agglomerations involves transferring at another agglomeration. Investments made in the Flemish Diamond first aim at connecting neighboring agglomerations using a regional service to expand the network reach. This is followed by the development of local connections within each of these agglomerations until the network is further expanded towards a hitherto disconnected agglomeration using an regional link. This alternating process repeats until all agglomerations are connected to each other in a ring-form. Hereafter, the network within and between agglomerations is densified and existing links are bulked. The evolution process in the Rhine-Ruhr scenarios is similar to that of the Flemish Diamond with one key difference. The organization of the agglomerations along an axis and the properties of the modal layers result with connecting non-neighboring agglomerations to yield the largest gains in relation to the costs. The underlying relation between the cost function and the market that can be penetrated result with constructing a regional link followed by local developments.

We make the following observations based on a careful inspection of the resulting network evolution paths:

- *Sometimes you have to lose before you can win (again)* - Consider the iterative process of network growth where at each step a candidate set of investments is evaluated and the one yielding the highest and positive return for investment is selected. While the costs associated with each investment are the same regardless of the moment at which the investment is made, the benefits are not. The demand for public transport depends on the current network state and therefore the marginal benefit induced by a certain investment depends on all past investments. This path dependency means that the evolutionary path is characterized by the need to attain a critical mass to justify further developments. Occasions at which such a critical mass is attained are denominated tipping points. For all simulations it is observed that the networks need to gain a critical mass at the starting phase and accept losses in order to evolve because as long as the initial state of the network is too limited, the creation of new links is not beneficial. While this critical mass of necessary initial links for the network to evolve beneficially differs for different scenarios, this phenomenon is observed in almost all scenarios. Fig. 5 illustrates this phenomenon for the London case where the critical mass is reached at iteration 8, marking a tipping point after which individual investments yield positive returns. The Tokyo case includes also intermediate episodes of having to accept a series of investments with negative returns before positive returns can be yielded from subsequent investments.
- *Finding the missing link* – when examining the score (Eq. 5) associated with the selected investment over iterations, irregular peaks can be observed (Fig. 5). These peaks correspond to cases where large travel time reductions can be achieved by introducing a shortcut in the network, i.e. constructing a missing link in the evolutionary path. For example, iteration 60 of the London case shown in Fig. 5 corresponds

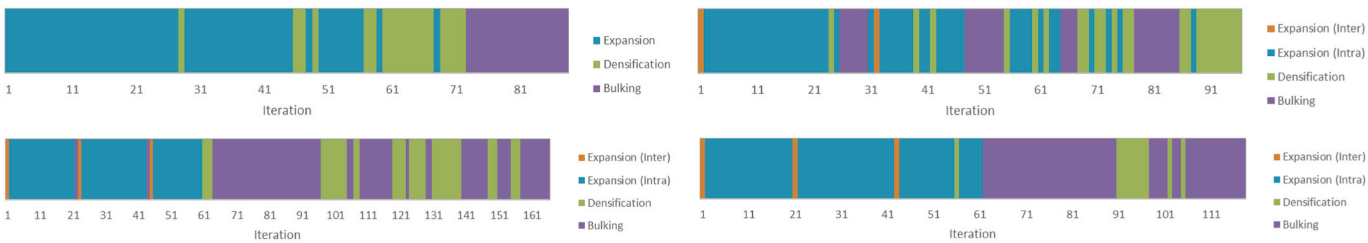

Fig. 3. Timeline of investments made during the evolution process of LL, TL, FU and RL scenarios (clockwise starting from top left).

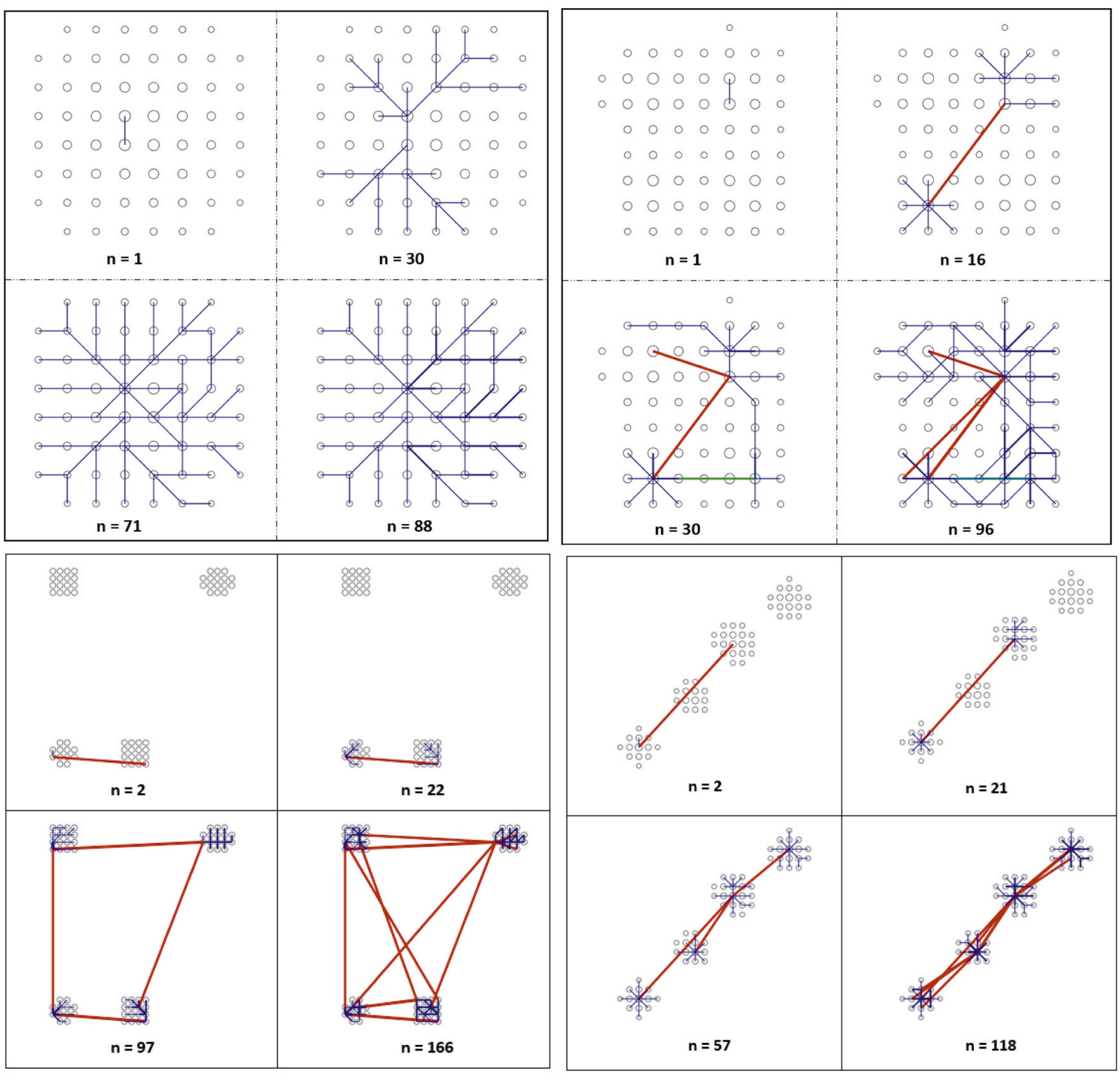

Fig. 4. Key evolution phases the LL, TL, FU and RL scenarios (clockwise starting from top left).

to a new link allowing travelling between the north-eastern and south-eastern parts of the network without going through the centre (see also Fig. 4). In other cases, the high peaks often correspond to interregional links that connect a disconnected node - with a high demand located in a hitherto isolated center - to the existing network.

- *Path dependency in the rich getting richer* – the path-dependency in network evolution implies that nodes with similar population size may still result with a different hierarchy role as a consequence of the emerging network structure. Depending on which of the nodes gets expanded to first from the existing network, this node becomes more accessible and new expansions are more likely to start or end at these nodes. This can be seen in Fig. 4 where the north-eastern node in Tokyo that serves an inter-regional connection in iteration 16 is then further enhanced by subsequent inter-regional investments. This is also visible in the Flemish Diamond and Rhine-Ruhr cases where nodes connected by interregional links also become locally well connected, gaining a hub function.

4.3. Sensitivity analysis

We examine the sensitivity of the network evolution as well as the

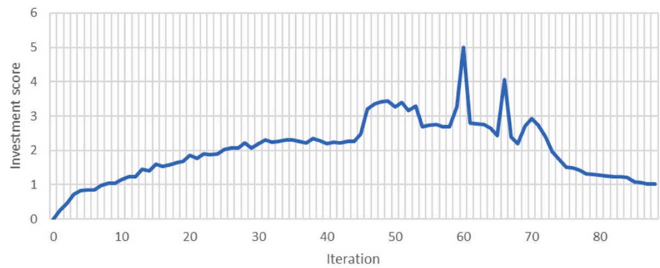

Fig. 5. Investment score per iteration under scenario LL.

resulting network state to model parameters which are key determinants of the costs and benefits associated with alternative investments: population size, the speed of the alternative mode and the cost components of the public transport modalities. In addition, we also test how the networks evolve when instead of starting *tabula-rasa*, they are initialised with a certain initial network state. We briefly summarize below the main findings for the series of experiments conducted to test model sensitivity.

As expected, the model is sensitive to inputs that affect the costs and/or benefits and to the initial network which is assumed while the sensitivity of the model to these aspects differs per scenario. An increase in population size leads to additional investments, in particular additional bulking investments are made prior to convergence (except for the case of the Flemish diamond, or in combination with densification as in the case of Tokyo). Beyond a certain increase in population size, further increases result with additional phases of expansion and densification to be then followed by another bulking phase.

As expected, decreasing the speeds of the alternative mode makes investments in public transport more attractive. However, it does not simply lead to an extension of the evolution process as is the case for an increase in population. As different investments are made in early stages of the process, the resulting networks also follow a different evolution path and result with distinctive final states. These differences are more present in spatial structures where relatively shorter distances are covered, such as the Tokyo prototype.

For varying values of the cost components of the public transport layers (Table 2), it is found that the impact this has on the generated networks also differs for different spatial structures. These differences are again more pronounced for spatial structures where relatively shorter distances are covered, such as the 'Tokyo' prototype. Furthermore, by decreasing the values of the cost component of one specific layer, this layer becomes dominant in the network. This can even eliminate the necessity for having any other layer. We also experiment with reducing the operational costs (e.g. in the event of vehicle automation) and find that, as can be expected, the evolution process is then prolonged as investments become more attractive. While the order in which investments are made may vary, the network obtained in our base case scenarios is contained in the larger network obtained in the case of lower operational costs. Finally, when only one modal layer is allowed, the network rapidly starts expanding to all agglomerations first as opposed to alternating between local connectivity and inter-centers connections as we have seen in our scenarios. The resulting unimodal network is less hierarchal with a more even distribution of node betweenness centrality since it does not involve the emergence of a hub function resulting from few nodes offering long-distance options.

Lastly, when feeding the evolution phase with different initial network states, we find the impact that this has on the final network state is more visible in spatial structures where there are less distinctly separated agglomerations, such as the 'Tokyo' prototype. This prototype has more 'degrees-of-freedom' in terms of how it can evolve and has no clear-cut solutions in terms of how to connect the agglomerations. It is therefore exercising greater path dependency, making it easier to steer it in a certain direction at early stages and more difficult to shift away from the direction taken in earlier decisions.

5. Conclusion

We developed an iterative growth model to examine the evolution of multi-modal public transport networks under various polycentric spatial configurations by adapting the model developed by Cats et al. (Cats et al., 2020). The model is used to analyse the public transport network evolution for several distinctive spatial structure prototypes inspired by real-world polycentric development patterns.

The results provide insights into the network structure properties for various spatial structure prototypes and different population distributions. Our findings from a series of experiments suggest that different spatial prototypes, and to a lesser extent different population distributions, result with distinctive network structures. In the most monocentric prototype (inspired by London), the network expands from the center towards the outer areas in a radial, tree-like manner using only urban links. In contrast, in the more decentralized prototypes (inspired by the Flemish Diamond and the Rhine-Ruhr area) yield densely connected local networks with different degrees of regional connections between agglomerations, depending on the geographical configuration. The hybrid case of a polycentric metropolitan area consisting of several close-by centres with overlapping agglomerations (inspired by Tokyo) results in a combination of local connections extending to the entire area and metropolitan and regional connections between key nodes. Furthermore, we find that more uneven population distributions result with the construction of fewer links and consequently the less connected and shorter the network becomes. The network evolutionary path is marked by distinctive intra- and inter-agglomeration expansions, intra-agglomeration densifications and bulking phases.

In all experiments we observe that the network must gain a critical mass at the starting phase before being able to justify further developments. This demonstrates the mechanism that underlies the network effects previously recognized in many domains, including in the context of highway (Condeco-Melhorado et al., 2014) and rail (Banister and Thurstain-Goodwin, 2011) infrastructure investments. We also find that certain links which may be redundant early on in the evolution phase, may in fact be crucial at a certain point later on down the evolutionary path. Furthermore, we observe that the emergence of hierarchy in nodes is path dependent and is inherent to the evolution process, as slight differences made in investment choices at the start of the process may lead to different resulting networks. This is in line with the principle of preferential attachment, driven by the *the rich get richer*.

Due to path-dependent historical development and related organizational barriers, the development of public transport networks tend to be developed at the individual city level, with highways connecting urban centers (Kloosterman and Musterd, 2001). Moreover, the geometry and economics of public transport system often result with a more radial development. There is a risk therefore that polycentric urban regions might become more car-oriented in the absence of targeted policies. Such policies can either target the car alternative and related negative externalities or the improvement of public transport accessibility. An example of the former is road pricing which needs to be adapted to be successful in polycentric settings as concluded from a pilot project in Belgium (De Vos, 2016). Related to the latter, Park et al. (Park et al., 2020) concluded based on the analysis of data from 28 metropolitan regions in the US, that a minimum of 5–35% of regional job access within 30 min by public transport was important in explaining the successful formation of polycentricity.

Our analysis is by no means exhaustive since polycentric urban regions exhibit great diversity and even the dimensions used for classifying and identifying them are subject to an on-going scientific debate. Nevertheless, the approach proposed can contribute to our understanding of how a certain spatial structure can stimulate the development of certain network structure properties. Future research may integrate our iterative network growth model with an evolutionary spatial development model. Our study can be considered the mirror-figure of the one performed by Börjsson et al. (Börjsson et al., 2014) where the metro network evolution in Stockholm was considered exogenous and known a-priori while the land-use structure was endogenously simulated. A future integration of the two evolutionary models will allow investigating the co-evolution of the underlying spatial structure and the corresponding service network, including the impact of accessibility on urban and regional development. This will allow closing the feedback loop between spatial and transport developments. Furthermore, the proposed network model can be extended to generate and assess alternative line configurations, thereby assessing the service network structures resulting from combinations of cost functions and demand distribution patterns.

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