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Deciphering and Modelling Spatiotemporal Patterns and Processes across Scales – Migratory Flows and their Implications under a Healthy City Scenario in the Ruhr Area, Germany

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1 ABSTRACT

As it has been stated over and over again, today's large-scale urban structures are becoming increasingly hard to be grasped and understood through the lens of conventional spatial and temporal scales. Due to their dynamic interactions and complex interdependencies, cities are expanding way beyond traditional - such as municipal, regional or even national – barriers and boundaries. Nevertheless, comprehensive methods and innovative tools for effectively deciphering and designing complex urban systems are still relatively few. Here, we introduce a five-step integrated methodology to understand, reveal and model dynamic spatiotemporal patterns and processes across scales. The main focus of this paper will thereby lie on factor and cluster analysis of prevailing socioeconomic contexts and on their embedding into multiscale urban modelling. We contend that a meaningful connection between empirics and modelling is a quintessential and often missing link of endeavours simulating long-term development of urban environments. Therefore, we demonstrate how - with a machine-learning mechanism called self-organising maps - empirical findings may effectively infiltrate into modelling attempts of complex urban systems. Subsequently, we will use the example of the residential and employment migration subsystem of the multiscale urban model (Lengyel and Friedrich, 2019), to study the effects of demographic change, local and regional migration flows, as well as their interdependencies with the ongoing economic structural change between 2011 and 2050 in the Ruhr region. Furthermore, we show how we can use micro-scale outcomes to identify the small-scale anchoring of latter regional processes. In our example, we determine neighbourhoods with substantial changes in their local economic and land value profiles: which might be indicators for future hot and cold spots of gentrification processes. The main aim is to inform and instigate meaningful cooperation and synchronised action between urban stakeholders and decision-makers on different scales. The latter task is perhaps even more pressing and challenging for large-scale polycentric regions such as the Ruhr Area in Germany, which will serve as the case study for this paper.

Keywords: multiscale, exploratory spatial data analysis, self-organizing maps, modelling complex urban systems, residential and employment migration

2 FIVE-STEP METHODOLOGY FOR DECIPHERING AND MODELLING SPATIO-TEMPORAL PROCCESSES ACROSS SCALES

First of all, we provide a general overview of the five-step comprehensive methodology for deciphering and modelling spatiotemporal patterns and processes across scales. Each step is being illustrated with some relevant examples from the Ruhr Area in Germany. Additionally, they seek to give practical advice for increasing the real-world applicability and efficacy of corresponding efforts. In this paper, step one, three and five are only discussed shortly (for more information please see Lengyel and Friedrich, 2020), whilst the crucial step of effectively bringing empirics and modelling together (step two) will be reviewed in detail in Section 3, followed by an extensive description of the residential migration sub-model in Section 4 (which is a crucial part of step four).

2.1 Step 1: Analysing trends and deciphering their spatial projections

To start with, we must try to identify the most influential historic as well as current trends of the area in question and thereby comprehend their important shaping factors and mechanisms. Henceforth, the operational scale of this step is a macro spatial boundary e.g. city, regional or even national layers, combined with an investigation time period of the minimum past 25 years (depending on data availability). Such macro-scale trends may include demographic (age or ethnic structure), economic (sectoral shifts) or societal (household, gender) processes. In order for this step to be applicable for both planning and policy, as well as for modelling purposes, one may carry out the following three main consecutive tasks: firstly, with the help of historical data analysis carefully quantifying spatiotemporal development tendencies, and secondly, studying their connections and interdependencies. Closely connected to this is the third and very important task (since we are dealing with urban environments), with the main goal to deduce the spatial impact of identified trends. As an example, we studied how the ongoing economic structural change in the Ruhr Area has left its massive traces on land use development of the last couple of decades and how the amplitude of impact is roughly distributed throughout the region (see Fig. 1). Over the course of this first step, we suggest an alternating method of literature review and spatiotemporal data analysis.

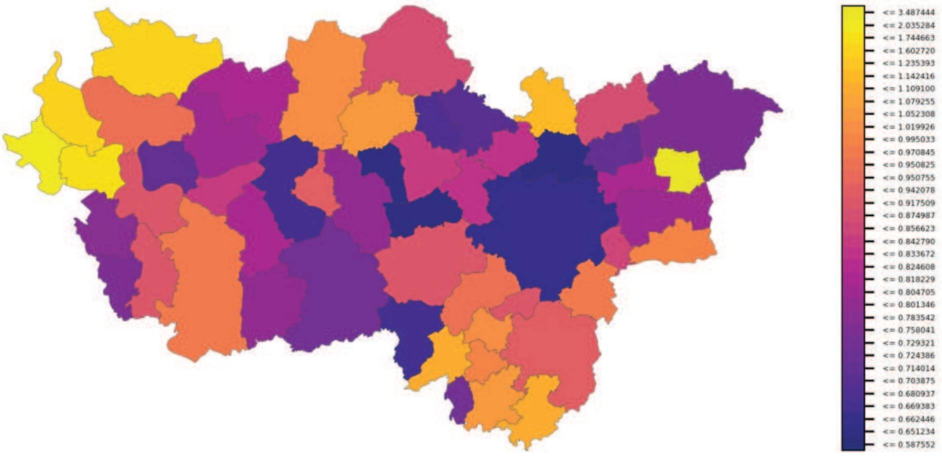

Fig 1: Commercial and industrial land use change between 1994 and 2015 (factor of change compared to 1994 values). Own graphic. For data source: see Section 4.3

2.2 Step 2: Unravelling spatiotemporal patterns and building clusters

Now that we are aware of the major influencing trends of our area, we shift focus from macro towards subjacent scales, and observe their local impact and anchoring. Firstly, with the help of exploratory spatial data analysis we study the spatial, demographic, socio-economic and economic patterns and try to capture their corresponding characteristic scales. Throughout our investigations into the Ruhr Area we observed that the spatial distribution of large number of socioeconomic indicators are still displaying a pattern which follows very closely the layered structure of the historical development zones of the region. Thus, today's city boundaries are almost invisible (see Fig. 3). Both industrialisation and deindustrialisation processes took place in several consecutive phases from the south northwards (Wehling, 2014), leaving behind some very important characteristic scales for age, economic, ethnic and socioeconomic structures. Secondly, we demonstrate how - with a machine-learning mechanism called self-organising maps – latter empirical findings can by synthesised for more clarity and for their effective infiltration into modelling attempts of complex urban systems (the latter method will be reviewed at length in Section 3). This second step may be considered as the first effort towards delineating new spatial and temporal dimensions for action, which may prove to be more efficient for some measures than operating on the scale of traditional urban boundaries.

2.3 Step 3: Delineating Future Development Tendencies

The goal of step three is envisioning possible long-term urban development scenarios for the study area and testing solutions for prevailing issues or impulses for potentials. When it comes to examining future urban development paths, one might take two important points into consideration. First, we may integrate already existing design concepts of the region in our scenarios: let these be large-scale projects such as international expos or locally relevant urban design projects at selected study areas. For this paper, we assume that the "generational project" (URL-1) implementing the re-naturalisation measures of the river Emscher and its tributaries, which have for decades served as an open sewage system, is a unique opportunity to provide sustainable intermodal mobility for the Emscher zone as well as for the whole Ruhr region. Additionally, the new transport infrastructure will most probably have a major influence on all other urban subsystems (demographics, employment, land use, etc.) and vice versa. Secondly, one might try to integrate issues of great societal relevance and interest at the time of conception – in our case this will be the transition towards more sustainable mobility patterns ("Verkehrswende" in German). The latter two efforts combined may substantially increase both the interest and acceptance by the local and regional stakeholders. In pursuance of studying these alternative development paths we use a scenario approach (Schmidt and Klemm, 2019). In more detail, this paper will review results under a "Healthy and Sustainable City" scenario. The starting point is an increased overall acceptance and awareness of the scientifically proven health risks (UN

Environment, 2019) of man-made pollution and environmental damage, such as that of fine-particulate air pollution in cities (Pope III et. al, 2009). Urbanites are now widely aware of their right to a healthy city, leading incrementally to the emergence of new sustainable models for political and administrative decision-making processes. In terms of mobility patterns, car-free and thus sustainable neighbourhoods are becoming more and more widespread in the region, where both owners and tenants progressively commit themselves to corresponding lifestyles. Sharing and on-demand transport options are becoming popular, whilst car lanes are gradually being reconstructed for autonomous buses and cycle-routes.

2.4 Step 4: Multiscale urban modelling and its calibration for a selected scenario

The multiscale urban model (MURMO) has been specifically designed for high-density polycentric urban regions (Lengyel and Friedrich, 2019). Throughout simulations, the six subsystems of population, residential migration, employment location, land price, land use and accessibility evolve simultaneously in an interactive manner. Residential and employment dynamics are captured by the well-known master equation approach from statistical physics (Haag and Weidlich, 1984), whilst land price relies on a novel method whose emphasis rests on the analogy between spatial land price fluctuations and velocity fluctuations in turbulent flows. We provide a detailed overview of the master equation method in section 5, the description of remaining MURMO methodology is however beyond the scope of this paper (please see Lengyel and Friedrich, 2019 for more information). Accessibilities values used for simulations in this paper are provided externally by the MatSIM transport model (Kaddoura et. al, 2019). Calibrated on a 100 x 100-meter spatial grid, the model is able to delineate small-scale trends of variables. At the same time it can intrinsically recognise meaningful trajectories in regional economic, land-use and population dynamics. For the example used in this paper, simulations are running from 2011 to 2050. In pursuance of translating the healthy city scenario (see Section 2.3) into MURMO we make the following assumptions:

- Immense reduction of man-made pollution and environmental damage: former large-scale industrial production and excavation sites available for new development
- Urban settings are becoming increasingly compact whilst at the same time further expansion of urban sprawl is restricted with the help of a variety of push and pull measures: areas with above average share of medium and high-density urban land use (URL-2) will become 20% more attractive by 2050. For the description of attractivities see Section 4
- Mobility in 2050 is foreseen to be intermodal, shared, walkable and active. Investment in new transport infrastructure accordingly: neighbourhoods in the vicinity of the Emscher river win attractiveness by 5% until 2050, largely due to the re-naturalidation process, improved accessibilities, etc. Accessibility values according to MatSIM measures come into existence (Kaddoura et. al, 2019)
- New urban areas may only emerge according to the official land use plan (URL-3) however they shall be strictly mixed use.

2.5 Step 5: Formulating recommendations for stakeholders on different spatial and temporal scales

We strongly believe that the combination of analysis and modelling results helps us to reveal competition as well as potentials for collaboration and shared interests within the 53 cities of the Ruhr area. A large potential of long-term and spatially highly resolved simulations lies in the effective application of outcomes to find suitable urban design and planning measures on and in between the newly defined characteristic scales. The overall aim is to inform and instigate meaningful cooperation and synchronised action between urban stakeholders and decision-makers.

3 SOCIOECONOMIC FACTOR AND CLUSTER ANALYSIS

Here, empirical results are brought together with the purpose of unravelling meaningful relationships between the different socioeconomic and demographic parameters as well as for dimensionality-reduction and modelling purposes. To this end, we use Self-Organising Maps (SOM) a machine learning mechanism, which "is able to convert complex non-linear statistical relationships between high-dimensional data items into simple geometric relationships on a low-dimensional display" (Kohonen, 1990). SOM is an artificial neuron network (ANN), made up of interconnected nodes - or artificial neurons - that are able to

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communicate with each other via signal-transmission, similar to the synapses in animal or human brain. These signals are numerical values that are being received by each neuron and then further processed according to the learning mechanism in question, in order to come to the output. Furthermore, there are weights assigned to both the nodes (or neurons) and their connections (or edges) which are being incrementally adjusted through the learning process. In case of the SOM, data projection happens in a way that similar values in the input space are mapped into the same neuron or to its close vicinity in the output space. Therefore, as Kourtet et. al put it, ”the output of a SOM can be thought of as a spatial representation of the statistical relations between the observations; in this map, the axes are not north-south or east-west but measures of statistical similarity, which is expressed in the distance between observations” (Kourtit et. al, 2012). In order to carry out the computational part of this analysis we used the Python package ”Sompy” (with some minor adjustments) developed by Vahid Moosavi, Sebastian Packmann and Iván Vallés (URL-4).

In our case, ten factors (see Fig. 2) are brought together and subsequently clustered into twenty-five distinct groups (see Fig 4). Figure 2 shows the component maps of the neural network, which may be interpreted in the following way. Firstly, brighter yellow colours correspond to higher values and darker colours to lower ones. Secondly, if we move on the surface showing the clusters on Fig. 4 from the right to the left (from less towards more transparency on the bivariate graph) we observe increasing median age and decreasing household size. If we move from the bottom towards the top, we encounter rising socio-economic advantages and a decrease in foreign population (from red towards blue). Henceforward, districts located in the upper left corner of the output space, can be characterised by the following parameters (each being in a strong statistical relationship with each other, in accordance with SOM rules): very high purchasing power and rent prices, below average share of foreign population and high percentages of above-65-year-olds. These would then belong to the clusters 24, 19 and 11 according to Fig. 4.

If we now observe the distribution of clusters on the regional map (Fig. 3), there is an evident pattern of more red and yellow districts in the central area (Emscher and Hellweg zones) and gray and blue colours dominating the outer regions. Firstly, these results correspond and underline the already described relationships on zonal scale (see Section 2.2). Secondly, on the two-dimensional maps on Fig. 2, the three types societal segregation patterns (Wehling, 2014) in the Ruhr area become clearly evident: namely those of nationality, age and economic power. Thirdly and perhaps most importantly, the clusters were found to be highly invaluable tools for the embedding of empirical findings into modelling as well as for an adequate implementation of scenarios into our simulations. We refer the reader to Section 4.2 for follow-up.

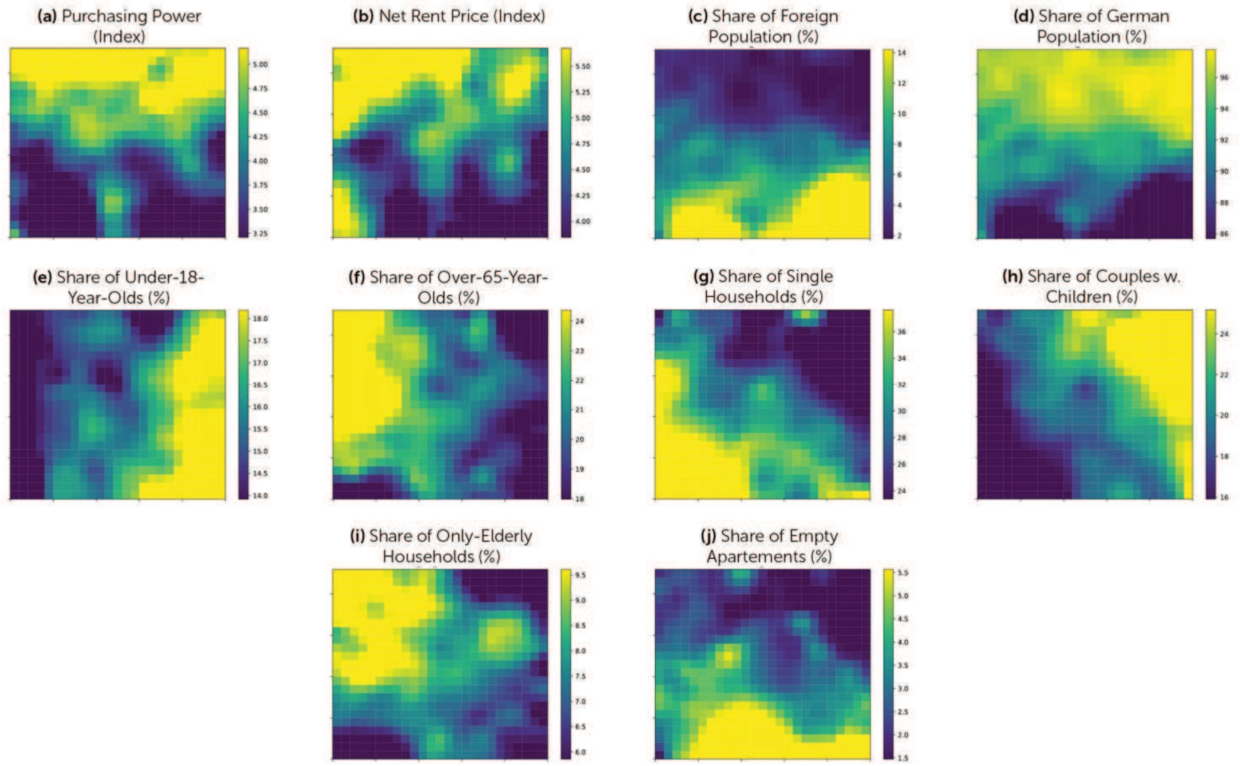

Fig 2: 2D Component maps of the SOM model-space. Data source: see Section 4.3

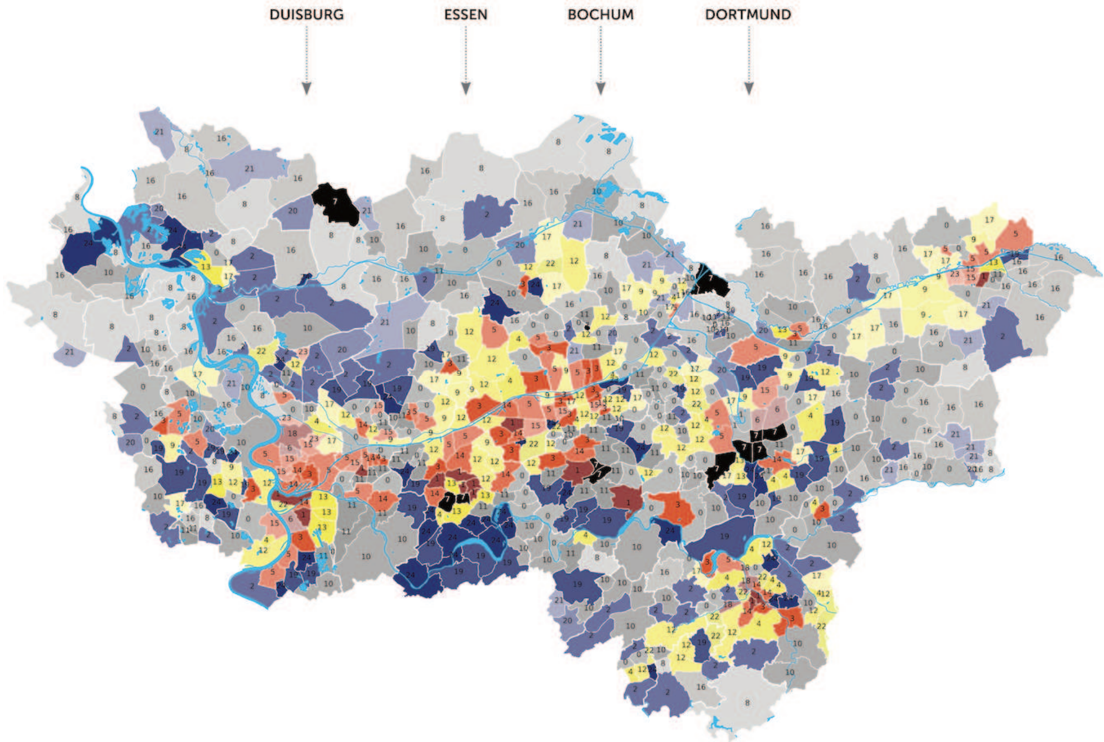

Fig. 3: Distribution of socioeconomic clusters throughout the Ruhr region in 2016. Data source: see Section 4.3

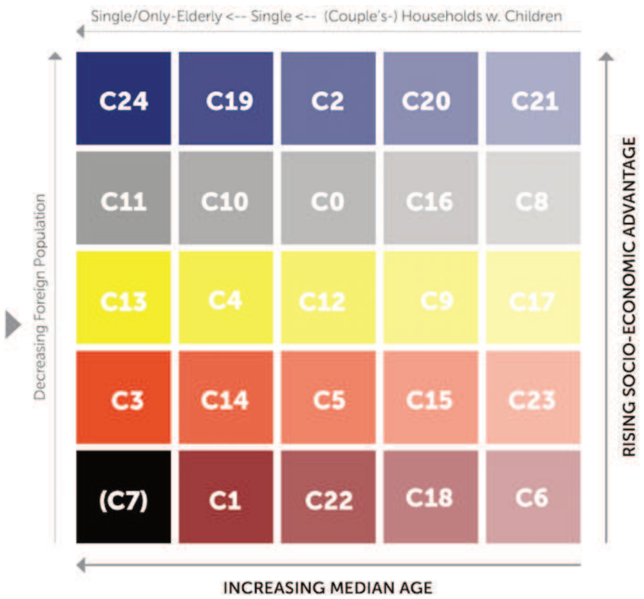

Fig. 4: SOM clusters on 2D model-space (see component maps on Fig. 2). Data source: see Section 4.3

4 MODELLING RESIDENTIAL MIGRATION WITH THE CAREFUL INTEGRATION OF SOCIOECONOMIC CLUSTERS IN THE RUHR AREA

In this section we give a brief review of the recently developed multiscale urban model (Lengyel and Friedrich, 2019). One of the main questions that we hope our model will answer is how the Emscher (and Ruhr) region and its inhabitants may react to different influences, e.g., changes of infrastructure (the re-naturalisation of the Emscher river, transport, housing, recreational areas), economic changes (labour market, increased spending power of certain neighbourhoods), and attractiveness changes (urban amenities, land price, congestion phenomena) that arise from in- or outside the urban system. In this context, we contend that due to many uncertainties in such systems, especially if we take long-term urban development into consideration, we cannot expect to capture each and every decision that is being made individually. Therefore, the residential and employment model relies on a *statistical description of urban structures* via probability density functions (PDFs) of certain key quantities, using the statistical model by Haag and

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Weidlich (1984). We also refer to the monographs (Haag, 2017 and Weidlich and Haag, 1999) for further details and applications. Here, the PDF $f_N(\mathbf{n},t)$ of a certain socio-configuration $\mathbf{n} = \{n_1,n_2,...,n_L\}$, where n_i denotes the number of members of the population in area *i*, is governed by the so-called *master equation*

$$\frac{\partial}{\partial t} f_N(\mathbf{n},t) = \sum_{\mathbf{k}} \left[p(\mathbf{n}|\mathbf{n}+\mathbf{k}) f_N(\mathbf{n}+\mathbf{k},t) - p(\mathbf{n}+\mathbf{k}|\mathbf{n}) f_N(\mathbf{n},t) \right] \tag{1}$$

where $p(\mathbf{n} + \mathbf{k}|\mathbf{n})$ stands for the *transition probability* from socio-configuration **n** to socio-configuration **n** + **k**. Transitions from area *i* to area *j* are favoured if the so-called *utility function* $g_i(n_i)$ in area *i* exceeds the utility function $g_j(n_j)$ in area *j*. Therefore, utility functions can be roughly considered as a measure of "**attractiveness**" of a given area in comparison to another area. The latter feature makes this modelling approach particularly suitable for urban design and planning purposes, since it makes scenario-calibration rather straightforward. The utility functions (2) are further evaluated in terms of a Taylor series of the population number n_i

$$g_i(n_i) = \delta_i + \kappa_i n_i + \rho_i n_i^2 \tag{2}$$

of each area *i*. Utility functions are being constructed with the help of three trend parameters, which are divided into the *preference parameter* δ_i (availability of schools, cultural offerings, climate, landscape, desire to remain in someone's birthplace), the *cooperation parameter* κ_i (offers of employment, increasing rent, accessibilities), and the *saturation parameter* ρ_i (constricted housing situation). As the intricate interplay of the three trend parameters fully determines where residents (and firms) may move to, their precise and adequate definition is of outmost importance – the task of Section 4.1 and Section 4.2.

4.1 Household types

In case of residential migration, we were interested in the drivers of a household's decision to move or to stay at their prevailing places of residence. Henceforth, we were curious about what crucial variables might affect the attractiveness of a region for the different household types or, in other words, which are the location choices that residents are most likely to make (once they decided to move). In the followings we refer to such influencing variables, according to the Weidlich-Haag model, as spatial preferences parameters. Due to data limitations, where we could not get hold of precise number of individuals per household-type per grid cell, we substitute households with age groups in our simulations. They can be hypothesised to have the following associations with household structure, living-space demand, urban amenities, land price and tendency to migrate (Haag and Weidlich, 1984, Haag, 2017, Lengyel and Friedrich, 2019):

- Under 18; Households with children. Vicinity to kindergarten, schools and playgrounds may be significant. Potentially high living-space demand per household. Low mobility (0.00005).
- Between 18-29; Association with single households or flat shares. Young adults possibly moving out from home for the first time. Probable importance of closeness to higher education, daily urban amenities and public transport. Might prefer lower rent prices. Normally low per capita living-space demand. Age group with the highest mobility (0.0002).
- Between 30-49; Young professionals that may or may not be starting a family. Associated with both single households and couples with children. Might be able to afford higher housing and land prices. Potential importance of proximity to jobs, cultural, and recreational facilities as well as to kinder-garden and schools. Might be moving towards ever higher living-space demands per household. High mobility (0.00023).
- Between 50-64; Double households living with or without child or children. Possible role of vicinity to jobs, schools or leisure facilities. Low to medium mobility (0.00008).
- Over 65; Associated with households with seniors-only as well as with single households. Potential importance of proximity to health facilities, daily urban amenities and public transport. Lowest mobility (0.00002).

4.2 Spatial preferences of socioeconomic clusters

Over the course of our simulations, each household type (see Section 4.1) is described by its own master equation (1) and has its own set of preference parameters. We compiled values for more than hundred parameters on our grid and sought to find the most influential locational factors for each of the age groups with the help of multiple regression models. Moreover, we carried out the regression analysis for the twenty-five SOM clusters separately. The latter step is extremely significant for two reasons. Firstly, we gain a very detailed knowledge of the spatial preferences for each socioeconomic cluster and therefore a better numerical description of the real-world situation. Secondly, since it is the tangled combination of preference, cooperation and saturation parameters which drives the master equation (see Section 4) and therefore our migratory flows, we may have achieved a highly effective way of interlinking the findings of empirical analysis with the internal dynamics of our model. We now demonstrate the regression analysis on two selected clusters.

	PCT_U18_S	PCT_18_29_S	PCT_30_49_S	PCT_50_64_S	PCT_O65_S
Intercept	-1.2545*** (0.1340)	-0.5135*** (0.0990)	-0.8202*** (0.2591)	-0.0486 (0.1983)	2.3016*** (0.0893)
AM_Shops_pro_100res_S					0.5781** (0.2815)
Access_Public_Transport_S					0.7571*** (0.1572)
Age_Mean_S			-0.3339** (0.1560)		
Amount_attractions_pro_100res_S			0.4500** (0.1640)		
Area_BUI_Sport_Recreation_pro_100res_S		-0.1944** (0.0794)			
Area_Playgrounds_pro_100res_S				0.9044* (0.4563)	
Area_Public_Green_pro_100res_S					0.2230*** (0.0510)
BUI_Size_mean_S	0.4940*** (0.1619)				
Employees_pro_100res_S		0.4026*** (0.0442)			
I(Newly_Built_BUI_S ** 2)				0.3238* (0.1664)	
Newly_Built_BUI_S			-0.3036** (0.1315)		
Nr_Commercial_BUI_pro_100res_S	-0.1994*** (0.0356)				
Nr_MixedUse_BUI_pro_100res_S			0.2952** (0.1308)		
Nr_Property_AP_pro_100res_S				0.4277*** (0.1468)	
Purchasing_Power_mean_S	0.2198* (0.1197)	-0.3845*** (0.0890)			
R-squared	0.70	0.83	0.63	0.57	0.66

Table 1: SOM Cluster Nr.24: Multiple regression analysis for the preference parameters of the five different household types in the residential sub-model. Standard errors in parentheses. * p<.1, ** p<.05, ***p<.01. Abbreviations; BUI: Building, PCT: Percentage, AP: Apartment, HH: Households, S: Standardized, U: Under, O: Over

Results are summarised in Table 1 (for cluster 24) and Table 2 (for cluster 5). The first column of the tables displays the explanatory variables which were identified to be significantly associated with one or more of the household types in the neighbourhoods belonging to the two selected clusters. What stands out in these tables is that there is not only a difference between the coefficients and statistical weights belonging to one parameter, but also that differing preference parameters were found to be significant both for the response variables and for the clusters themselves. As an example, for Cluster 24 (C24) the average building size, the level of commercial building stock and mean purchasing power seemed to be the best predictors of the percentage of under 18-year-olds per grid cell. What is interesting is the relatively high positive parameter estimate for purchasing power (which is somewhat uncommon in the Ruhr area for this age group), suggesting that households with children are rather affluent in C24 neighbourhoods. Let us now compare these results with those of Cluster 5 (C5). Firstly, the intercept shows that children are much more likely to live in C5 than in C24 clusters and that the share of under-18-year-olds is in a very strong positive correlation with vacancy rates. Furthermore, their corresponding parent-clusters seem to be living in the vicinity of commercial and industrial areas, which is in general a rather undesirable locational factor. Finally, no significant (positive) correlation was found for any of the age groups with more desirable determinants, such as that of new building-stock, ownership or rising rent prices. These three findings are pointing towards more disadvantageous life settings for people living in C5 cells. As a last example, we observe a very high occurrence of seniors in C24 clusters, as daily urban amenities, good access to public transport and proximity to green seem to be the most important locational factors for them. Finally, cooperation parameters κi of the residential sub-model (see section 4) were obtained by similar methods as described above, and were found to be associated with land price, employment rates and the different accessibility values (public transport, car, walk, bike) for a given area.

	PCT_U18_S	PCT_18_29_S	PCT_30_49_S	PCT_50_64_S	PCT_O65_S
Intercept	0.6763*** (0.0952)	-2.7986*** (0.8107)	-0.1960** (0.0935)	-0.2423* (0.1297)	3.1641** (1.1569)
Amount_attractions_pro_100res_S				3.1360* (1.7247)	
Area_Playgrounds_pro_100res_S	0.8046** (0.3598)				
Area_Woods_pro_100res_S		-56.6641*** (14.2296)			62.9386*** (20.2871)
Area_cimlu_pro_100res_S			1.8446*** (0.5405)		
BUI_Size_mean_S				-0.5141*** (0.1216)	
Newly_Built_BUI_S					-0.3223*** (0.1089)
Nr_Empty_BUI_pro_100res_S				-0.2769** (0.1001)	
PCT_Empty_AP_S	0.4557*** (0.0955)				
PCT_Flatshare_HH_S		0.5388*** (0.0779)			
PCT_OnlyElderly_HH_S			-0.4905** (0.2010)		
PCT_Single_HH_S	-0.3687* (0.2121)				
R-squared	0.65	0.69	0.40	0.57	0.44

Table 2: SOM Cluster Nr.5: Multiple regression analysis for the preference parameters of the five different household types in the residential sub-model. Standard errors in parentheses. * p<.1, ** p<.05, ***p<.01. Abbreviations; BUI: Building, PCT: Percentage, AP: Apartment, HH: Households, S: Standardized, U: Under, O: Over

4.3 Data Sources

For the purposes of this study we only used secondary observational data. All city level information stems from the official database of North Rhine-Westphalia (URL-5). For more detailed analysis, we subdivided the 53 cities into their 736 municipal districts. Values on this level were either provided by local municipal authorities or aggregated using higher-resolution data from the following sources. Socioeconomic and employment data was acquired from the German 2011 census database (URL-6), the micro-dialog data of the German post, and from the Hoppenstedt firm database (URL-7). We collected land use material from the Urban atlas of the Copernicus Land Monitoring services (URL-2), and from the database of Regionalverband Ruhr (URL-3). Points of interest were provided by the Regionalverband Ruhr. Finally, in accordance with the 100 x 100-meter grid of the German Population Census in 2011 (URL-6) we further sub-divided city districts and obtained almost half a million grid cells for the whole Ruhr area. Data sources of this level are either directly from the German Census Database (URL-6) or accumulated using the same data sources as described above.

5 RESULTS OF MIGRATORY PROCCESSES UNDER A HEALTHY-CITY SCENARIO

This section is dedicated to the discussion of modelling results using the example of the residential migration sub-model. The goal is to unravel some important effects of demographic change, local and regional migration flows as well as their interdependencies with small- and medium-scale changes in rent price profiles between 2011 and 2050. First of all, and as expected - due to assumptions made under the healthy city scenario - there is the ubiquitous tendency of falling population numbers: by 5.64% on a regional scale compared to values of 2011. What is interesting though is that zones of the outskirts (Kreis Moers, Kreis Recklinghausen and Lippe zones) have lost 4.61% more residents than their central counterparts (Emscher, Ruhr, Hellweg), implying rather strong densification tendencies and periphery-core migration flows. It is the

Northern and Southern Emscher zone combined, which is showing the least population decrease with solely minus 2.67%. Spatial projection of latter trends is the incremental occupation of vacant and newly accessible land (former industrial sites) in between already high-density urban areas to cater for the increased interest in central zone living (which is clearly observable on Fig. 6). As for the Emscher zone, changes were most likely further amplified by the accumulative effect of improved accessibilities, enhanced environmental qualities, new land availabilities and a massive investment in public infrastructure (see Section 2.4).

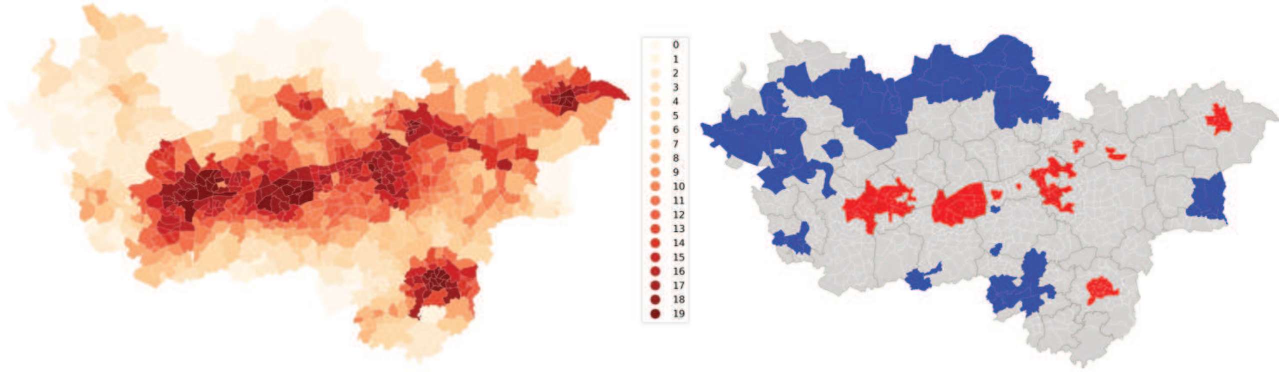

Fig. 5: Spatial lag twentiles of relative change of mean rent price on the district level between 2011 and 2050 (left). Hotspots (red) and cold spots (blue) of change in mean rent price values on district level between 2011 and 2050 (right). Own Graphic.

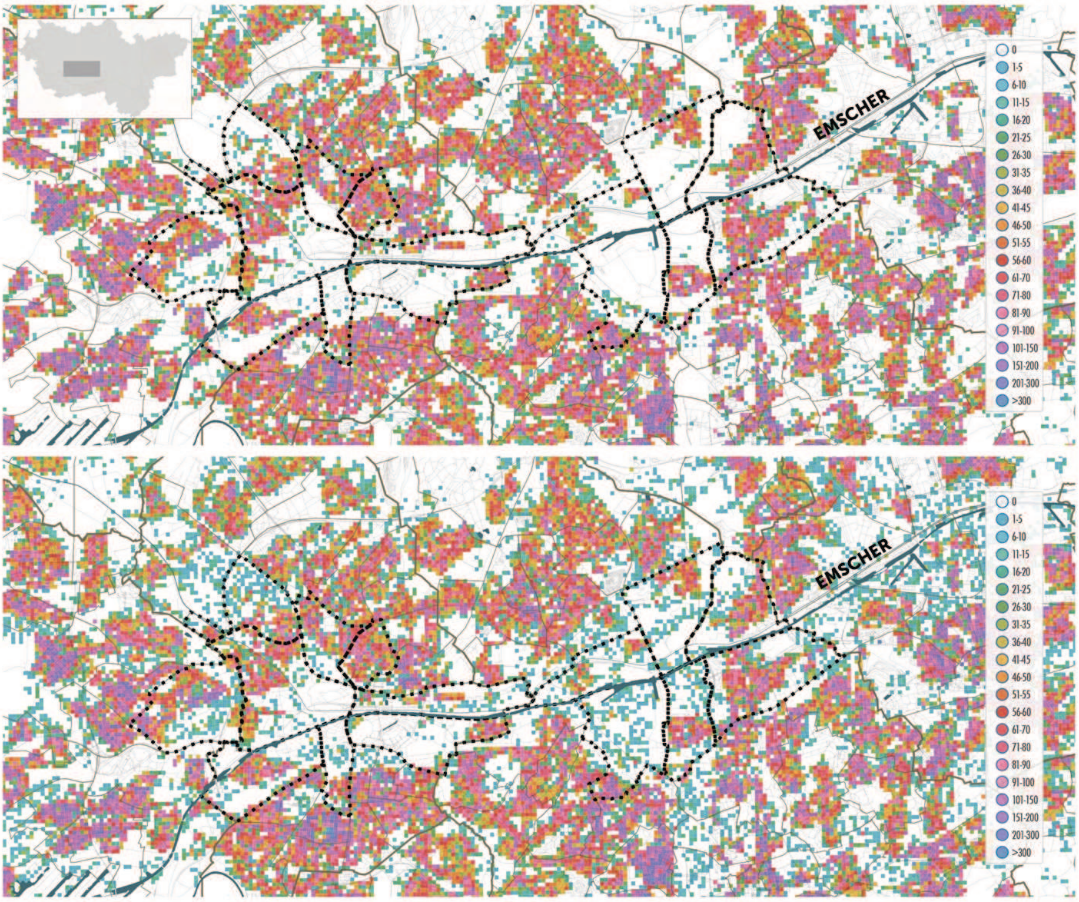

Fig. 6: Number of Residents per Grid cell in 2011 (Above), Number of Residents per Grid Cell in 2050 (Below). Own Graphic

Against the above background, it may come as no surprise that the observed spatial and demographic development trajectories around the Emscher river are associated with a substantial increase in average net rent prices: by 60.20% between 2011 and 2050 compared to an only 26.17% growth in the whole Ruhr region. Hence, it would now be extremely important to find clues for the amplitude and location of potential gentrification processes, in order to apply timely alleviation measures. Due to the high spatial resolution and the innovative computational methods of the MURMO model, we can easily identify districts which are hotspots and cold spots for rent price changes under the Healthy City scenario. Figure 5 reveals that hotspots concentrate in central Oberhausen, north of Essen, south of Bottrop, Castrop-Rauxel, the western neighbourhoods of Dortmund and in the urban cores of Hamm and Hagen. In contrast, cold spots accumulate in the outskirts of the Ruhr area. We must stress here, that latter changes in mean rent price are largely outcomes of residential and employment location choices as well as demographic, transport and land use change processes, as the six subsystems are in close interaction throughout the modelling process.

6 CONCLUSIONS AND OUTLOOK

The present study firstly set out to give an overview of the five-step integrated methodology for deciphering and modelling urban processes across scales and illustrated it with practical examples from the Ruhr area in Germany. Secondly, it made a case for effectively connecting analysis findings with the internal dynamic of the multiscale urban model. Thirdly, we have seen that over time the closely entangled reciprocal dynamic of the six MURMO subsystems led to a variety of substantial changes in the urban structure. These may be indicators for the following processes: attracting new landscape and urban design projects, anchoring a range of additional businesses (or superseding existing ones) or altering real estate prices along with their local socioeconomic profiles. Finally, we showed how modelling results can be applied to identify small scale anchoring of major urban development processes under a chosen scenario. The primary intention of this paper was that the generated knowledge may provide a cohesive framework for both spatial and non-spatial measures. Several questions however still remain to be more carefully investigated. For instance, there is an urgent need to improve the scenario approach specifically for computational modelling attempts of urban environments. We should seek ways to enhance their quantifiability and modelling-applicability in order to yield even more transparent simulation results.

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