Land consumption by urban sprawl - a new approach to deduce urban development scenarios from actors' preferences

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Abstract

A new modelling approach to urban sprawl dynamics is introduced which allows representing qualitative knowledge on relations between moving actor populations and properties of locations. The results of this Qualitative Attractiveness Migration (QuAM) Model are scenario-like sets of possible future developments of the urban system, much in contrast to quantitative forecasts gained by traditional modelling approaches. QuAM-models allow for the interaction between internal dynamics and external influences. The application of the new approach is exemplified by the case of urban sprawl in Leipzig since 1990. It was possible to reproduce the observed qualitative development and to calculate future scenarios. The scenario runs project a new wave of middle class driven residential sprawl and suggest implications for sprawl reducing policy interventions.

Keywords: urban sprawl, land consumption, preferences, qualitative differential equations

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1 Introduction

This paper aims to introduce a new modelling approach to urban sprawl which allows representing qualitative knowledge on relations between properties of locations and moving actor populations. Such an approach enables the formalization of interactions that are difficult to quantify, i.e. social and socio-economic processes such as migration and the relation between actors and their environment.

A qualitative dynamic modelling approach can deal with a number of problems that are difficult to answer with quantitative modelling. Variables can be measured on ordinal scale instead of real or ratio-scale, which is often difficult, particularly when social and socio-economic processes are to be formalized [38]; relations are represented by large classes of functions, thereby avoiding specific and sometimes poorly justified parameterisations; results are sequences of trend combinations forming qualitative instead of quantitative trajectories, often forming a more adequate representation of our knowledge of the system; and the possibility of branching in the qualitative trajectories allows for alternative future developments that are in accordance with the model assumptions. Particularly the last feature bridges the gap between techniques which analyse future development by alternative scenarios mainly based on plausibility [46] and unique quantitative trajectories based on, e.g., systems of differential equations [1]. We could show the appropriateness of the dynamic qualitative modeling approach for other socio-ecological systems with hardly quantifiable relations, e.g. in the realm of sustainable agriculture [17, 43], fisheries management [16] and forest overexploitation [17].

In the urban sprawl model presented here the influence of environmental characteristics and other actors on the households' location attractiveness is described. Our qualitative modeling approach is well suited to formalize the relation between different actor classes and between actors of the same class of moving households, e.g. families with children, elderly people, young childless couples etc, through the actor classes' impact on their environment and its characteristics. Changing quantities of certain household classes cause dynamics and generate scenario-like, qualitative development paths of spatial migration due to their interdependencies to other household classes. We show that this approach generates valuable information to support policy and plan making in urban, suburban and potentially other environments.

We will illustratively describe the approach by way of an empirical example of migration dynamics of suburban households in Leipzig/Germany. Our focus reflects the general trend in urban development in Western city regions, which, at least since the II. World War was mostly centrifugal [48]. This process known as suburbanisation or urban sprawl describes the extension of urban settlements beyond the original urban fringes, mainly along major transport routes, incorporating low-density development and mono-functional land use (see, for example, [24, 54]). Increasing living standards, spare time and modern transportation technology have enabled private and economic actors to re-evaluate spatial characteristics in order to live and work in more pleasant surroundings. Social and technological changes put more emphasis on the value of environmental characteristics. Debate about the consequences of sprawl often results from the discrepancy between the positive consequences for private entities willing to relocate to suburban regions and the negative consequences for the environment, the community as a whole, the environment and the economy [39, 54]. Causes and consequences are not seldom located in different spatial areas and scales. This spatial mismatch makes sprawl difficult to manage [50].

Success in controlling urban sprawl is limited so far [26]. This leaves the impression that sprawl processes are not fully understood yet. We assume that an important, even crucial, aspect has not received adequate attention, which is the relations (in-)between migrating actors conditioning the location characteristics of a place, and that this is - at least partially - due to the limited possibilities of traditional dynamic modelling to represent the respective knowledge adequately. Our assumption is that household interactions are very important in the suburban realm and therefore need to be incorporated in simulation tools of population development at the urban fringe. Brueckner and Largey [7] empirically found that social interactions in the low-density, suburban realm are stronger than in dense, urban environment. They thereby disproved the counter-argument, which has long been advocated, e.g. by Putnam [45] and others. People are influenced by others; follow other actors' choices and opinions. Therefore, the social composition of neighbourhoods is an important issue for residential migration, as it is for economic actors, i.e. represented by the importance of synergy effects [25]. Thus, actors contribute to the attractiveness of a region in multiple, mutual ways. Actor populations are a feature of an area and this must be at least qualitatively included in both firms' and residents' evaluations of spatial attractiveness [1]. By considering this, we strive to contribute to a more comprehensive understanding of urban sprawl. This is the precondition for the development of successful regulation systems enabling a more dense urban development which lessens the presently alarming trends of land consumption.

In the next section we shortly review established approaches to model urban dynamics that motivate the introduction of qualitative attractiveness models. We then introduce the basic concepts underlying our approach and the mathematical theory in the third and forth, the methodological sections. The fifth section presents an example of Leipzig to illustrate the steps necessary to define the model, including the empirical base. The application demonstrates the deductive abilities (and limitations) of the new approach, which are again discussed in the final section.

2 Comparison of current methods and rationale for QuAM-models

There exist a variety of formal dynamic modelling approaches to urban development, each of them emphasizing different facets of the complex phenomenology and variety of interacting mechanisms which generate urban dynamics. Although not explicitly dealing with urban expansion a methodically paradigmatic branch started with the checkerboard model of segregation by Schelling [52]. The basic idea is that the decision to stay or to move is made in dependence on the (e.g., racial) composition of an actor's neighbourhood. In case of moving, the composition of both, the old and the new neighbourhood is changed, thereby directly influencing the appropriateness of these for other actors and possibly initializing new moves. This generates different developments depending on the initial distribution in space, the size of the neighbourhood and the rule describing an acceptable neighbourhood composition. Eventually these development paths lead to either large scale spatial segregation or other patterns. Recent applications are shown in, e.g., Zhang [60] and Fossett and Waren [20]. Characteristic for this approach is the emphasis on the immediate feedback of location decisions of moving actors on the decisions of others, a property which is due to our research on urban sprawl a decisive element in understanding the observed dynamics [42].

These segregation models set the stage for the introduction of *cellular automata* in describing land use dynamics in general [55] and modelling of urban development in particular [10]. The checkerboard model can already be understood as a cellular automaton, but in the latter the number of considered actors or land use types was increased. More complex rules for the appropriateness of a neighbourhood were the result; more complex neighbourhood structures and stochastic elements were introduced [58]. Such models are widely used for urban growth simulations, albeit there is a large variation in the importance of the endogenous (rule-based) dynamics compared to exogenous settings. The latter comprise, amongst others, pre-given aggregated growth rates for each land use type to make the results compatible to the observed spatial-temporal development by constraining the endogenous rule-based development. The uncertainty arising from mapping originally qualitative (e.g. ordinal scale) relations on - to some extent arbitrarily chosen - quantitative representations is one important reason for the necessity to introduce strong exogenous constraints for the endogenous dynamics into the models. The modelling approach suggested in this paper addresses this problem, at least for up to intermediate spatial differentiations.

Another actor oriented view including behavioural aspects of migration was introduced by Wolpert [59]. The very rough assumptions on the "appropriateness" of a neighbourhood as applied in the cellular automata are investigated in detail. Examples are the studies on the relation of stated preferences for city sizes and locations (as inferred from surveys) and trends in population distribution in the USA by Fuguitt and Zuiches [21] and

Brown et al. [6]. Although these approaches deal mainly with the reasons for migration (i.e. push- and pull factors), some of the studies also indicate how migration feeds back on the properties of locations. One example is Weichhart [57] who shows that the natural environment of a location is an important determinant of residential preferences - a spatial property which is certainly strongly influenced by in-migration. Others, e.g. Filion et al. [18] study location preferences in a dispersed Canadian agglomeration. They found a high harmonisation of the residents' preferences with the attributes of dispersion and inferred the future "entrenchment" of the present urban structure. These findings support the chosen model structure which emphasizes the interaction between different actor groups.

Geographical economics mainly consider land prices and transportation costs to explain location decisions of economic actors in an equilibrium setting [56, 2]. In these theories the spatial concentration of economic activities was postulated but only partly explained. By introducing economies of scale and monopolistic competition, Krugman [32, 33] and Fujita and Mori [22] solved this theoretical problem in a non-trivial way. This approach extends the elaborated apparatus of economic theory to spatial dynamics under the standard premise of invariant actor preferences. By its very nature, this approach focuses on the economic dimension of spatial structure without necessarily looking at feedback loops of transport costs and development.

Loops of cause-effect relations are the core hypothesis of systems dynamics models. They allow for flexible inclusion of non-economic relations between actors by quantifying these with plausible mathematical functions, and by computing transient dynamics far from equilibrium [19, 1]. These models were the first that mathematically investigated the influence of complex and differentiated relations between actors and places on the qualitative spatial dynamics of an urban region. Systems dynamics models include relations that have to be quantified with plausible, albeit not always further justified mathematical functions. To give an example, knowing that an urban region becomes less attractive for retailers with a decreasing fraction of residents needs to be described by an explicit function (linear or exponential etc.) in systems dynamics models although this is somehow arbitrary if only the direction of influence is known. This exemplifies the problems of measurement, of quantifying qualitative characteristics and of uncertainty in determining model parameters of socio-economic systems, which goes along with all quantitative modelling approaches.

Serious concerns have been expressed about the use of computer simulations of urban dynamics in general, partly due to various epistemological and methodological objections. Concerns are related to the use of large-scale quantitative models that are often claimed to be too general in purpose [9], and to the application of models to examine (only) land-use changes [13]. Large models tend to become a black box, making them an unsuitable tool for learning. Not all of the approaches outlined above are explicitly dynamic in time. Some of them integrate social with economic processes. But, the complexity and contingency of social processes makes deterministic predictions impossible. Further problems of modelling coupled socio-economic and bio-physical systems relate to heterogeneous knowledge from different scientific disciplines and to uncertainties that cannot be expressed by probabilities [15]. However, quantitative models are also known for their power in making assumptions and definitions explicit and for systematically exploring their consequence by deductive reasoning [53]. When this potential is to be used to understand urban development, the above objections need to be considered carefully.

To overcome some of the above-mentioned shortcomings we introduce a new model class, the Qualitative Attractiveness Migration models (QuAM-models). They follow the systems dynamics heritage and combine them with a number of characteristics of the other approaches. Qualitative attractiveness models mathematically treat the influence of actors on each other as relations, but in contrast to simulation models not as mathematical functions. Only qualitative relations, increasing or decreasing influences between the systems variables, are considered instead. Such a modelling approach allows a projection of the variables' development into the future. The mathematical concept of qualitative differential equations (QDEs), which was first introduced by Kuipers [34], allows realizing this program by representing qualitative relations without choosing one quantitative function arbitrarily. An interesting consequence of this "honest" representation of knowledge in the model is that the resulting dynamics (that can be deduced in a mathematically sound way) differ from usual outcomes of quantitative dynamic models: different possible developments may occur and they are rather described in terms of trends and trend changes than in terms of explicit numbers. This is to some extent unusual for the description of a driver for environmental damages but - according to our view - robust statements like "given policy intervention X the present expansion trend will monotonically decrease and eventually reverse" are sometimes preferable over exact quantitative projections which are based on a - sometimes intransparent - multitude of assumptions.

3 Methodological Approach

We suggest an actors approach assuming that households are the central elements in the suburban migration process. But also business entities, retail units etc. are actors that condition the location characteristics of a place. If the location preferences of these actors are known, they can be modelled. This approach is related to action space research (Aktionsraumforschung), in which the city is a production of the cumulative actions of individuals [23]. Individuals do not only shape the city around them, they are also influenced by their own cumulative developments and do not act independently [23]. In response to the postulated insufficient consideration of the individual actors' roles in shaping the environment and sprawl development [47] this approach supposes a strong individual motivation.

In action space research, groups of individuals are of particular importance since only an agglomeration of actions will change the structure and therefore the production of the city. For that reason we look at migrating household classes and businesses within the suburban area, groups of actors with similar location preferences and attributes. Homogeneity in preferences and attributes is assumed to lead to recursive dynamics via two mechanisms: (1) Groups of similar location preferences might result in a similar imprint on the city's development, because they are looking for similar residential areas; (2) Similar social strati and living conditions of households as well as economic attributes of business actors are assumed to leave a similar feedback on the location characteristics. The combination of (1) and (2) can change the migration patterns and results in a dynamic process.

The boundaries of the suburban area that is to be modeled are not necessarily administrative. We are following a functional definition of space [31]. All neighborhoods with a remarkable number of new migrants and a recent influx of defined homogenous groups of inhabitants are covered.

The underlying assumption that the presence of certain actor classes is changing the attractiveness of the region generates dynamics. The influences of actor classes on the different location preferences (dimensions of attractiveness) have to be specified. Attractiveness of a suburban region is used in an extended sense, closer to the migration decision: it comprises the usual location properties *and* the affordability to move for the considered actor class. In this notation a region which, e.g., does not offer affordable housing is not attractive for a specific actor class, independent from other advantages. The attractiveness of a region for an actor class depends on three aspects:

a. The fixed characteristics of the respective region, e.g. orography,
b. The presence of other actor classes, and
c. Policy influences.

Actor classes migrate along attractiveness gradients (move from a region of lower to a region of higher attractiveness). Thereby, actors reduce their population in the region they leave and increase it in the region they move. This migration may change the attractiveness of both regions for all actor classes with respect to mechanism (b) and cause further changes in migration fluxes. Aspect (a) can be and (b) is endogenous to the formal model (both can be altered by the actor class populations); (a) can also be and (c) is exogenous. The model considers net migration of actor classes, i.e. some actors of the class may well move in the other direction; the model describes the aggregated net fluxes under mean preference assumptions. The main ideas are similar to established attractiveness models in urban dynamics (see, e.g. [1]) but QuAM-models differ in modelling qualitative relationships between variables.

4 Qualitative Differential Equations (QDEs)

We formalize the relations sketched above with the mathematical theory of QDEs [34] which is based on dynamical systems theory, i.e. the state of a system is related to its rate of change. In the realm of usual quantitative modelling this is represented by differential or difference equations where explicit numerical relations between the variables and their rates of change are needed. In contrast, QDEs deduce the time development of the variables from a much weaker, namely a "qualitative" understanding of the interactions of the system elements. This qualitative understanding can be characterized by the following:

1. Which elements are directly related? (e.g., A and B may be directly related)
2. What is the direction of the influences? (e.g., B may influence A)
3. Is it a strengthening or alleviating influence? (e.g., B may alleviate A)
4. Is it an influence on the variable or its rate of change? (e.g., B alleviates the change of A)

Levels 3 and 4 imply that it is possible to describe the elements A and B of the system by ordinal scale, i.e. a "greater/less than" relation can be defined. At level 4 of the determination QDEs can be applied and generate the time course of the variables by their trends and trend changes. As QDEs are a generalized system analytic method, the boundaries of the system, its elements, their qualitative relations and exogenous drivers have to be identified. In all cases where this can be done at least in parts the method is applicable. It was originally developed and applied by Kuipers and his group in physics and human physiology [34]. Further applications emerged, e.g. in finance [3], epidemiology [29], chemistry [30] and the automotive industry [51]. It is increasingly used in ecology [28, 4, 61]. In sustainability science it was applied on smallholder agriculture in developing countries [43], fisheries management [16] and urban dynamics [47, 35]. Here, it was the aim to calculate possible future developments from the qualitative systems understanding, to choose desirable outcomes from the developed set of possible futures, and to identify critical branching points that allow assessing policy options with a positive influence on the development.

Tailored to attractiveness migration models, the formal base of QDEs is as follows. We divide the area under consideration into a set of m regions, indexed by $r=1, ..., m$. It is assumed that there are n distinct actor classes (different kinds of residents, retailers, etc), indexed by $i=1,..., n$, and that members of each actor class assess the attractiveness of urban regions with homogeneous preferences. The population of actors of class i in region r (at a given point in time) is expressed by the variable P_{ri}. The attractiveness of an actor of class i assigned to the region r (at a given point in time) is denoted by A_{ri}. This implicitly assumes that the attractiveness can be expressed as a one-dimensional, aggregate quantity. We will see, however, that the method does not require a measure of aggregate attractiveness on a rational scale. For the exposition it is yet clearer to take all variables as measurable with rational scale. The attractiveness $A_{ri}(P_{r1}, ..., P_{rn}, E_{ri})$ depends on the presence of other actor classes in the region r, and possibly on further influences E_{ri}. As for attractiveness, E_{ri} is implicitly a variable that needs to be measured quantitatively. E_{ri} may represent the influences from actors in other regions, other urban areas, policy measures. Crucial is here, that E_{ri} is exogenously set, while the dynamics of the other variables evolve by endogenous rules. Population changes in time t assign to that region according to $dP_{ri}/dt = f_{ri} (A_{1i}, \ldots, A_{ri}, \ldots, A_{mi})$, where f_{ri} is an increasing function in A_{ri} and a decreasing function in all other arguments determining the population change of class i in region r depending on the attractiveness of this region in comparison to the other regions.

If all these variables, dependencies and functions were known quantitatively, this formulation would set up a dynamic system that can straightforward be simulated with readily available software. However, as discussed above, this is generally not the case for urban and socio-economic systems. Measuring attractiveness is prone to diverse subtleties. We therefore restrict ourselves to characterise the effect of a changing number of the population of actor class i in region r (P_{ri}) on the attractiveness of, e.g., actor j in the same region (A_{rj}) only by the direction of influence (e.g.: "the attractiveness of an urban region for retailers decreases with a decreasing number of residents"). Mathematically, this amounts to taking only the signs of the partial derivatives $s_{rij}=\partial A_{ri}/\partial P_{rj}$, $e_{ri}=\partial A_{ri}/\partial E_{ri}$ as given. These signs can be, for example, expressed as a causal loop diagram (see Figure 1) or as a matrix (see Table 1). To obtain the signs techniques of quantitative as well as of qualitative data collection (interviews, oral history, focus groups, Delphi groups) and data analysis (hermeneutics, discourse analysis, grounded theory) can be applied (for the potential role of these techniques in the different stages of model development and interpretation of model results see [37]). We will show an example in section 5. QDEs will determine all possible population paths in time that are compatible with the qualitative statements made in the form of the causal loop diagram or matrix. As a consequence of the limited information used, the resulting dynamics cannot be characterised by quantitative rates of change (e.g., "500 middle income families with children will move to the periphery during the next year") but only by trend combinations and their change (e.g., "while the population of retired residents will continuously increase, the number of families with children in a particular region will first increase and then decrease").

Figure 1 Causal loop diagram for a two actor classes/ two regions case: residents (*i=1*) are attracted by their own actor class, retailers (*i=2*) are attracted by potential local customers. The spatial distinction is between core (*r=1*) and periphery (*r=2*) of an urban area.

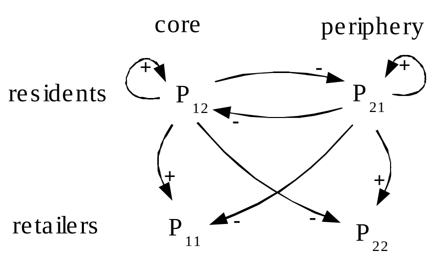


Table 1 Matrix of signs in the causal loop diagram in Figure 1

Population P_{ri}: / **f_{ri}, change in P_{ri}:**	P_{11}	P_{12}	P_{21}	P_{22}
F_{11}	+	0	-	0
F_{12}	+	0	-	0
F_{21}	-	0	+	0
F_{22}	-	0	+	0

Now, how can trends be projected based on qualitative statements of that kind? We illustrate this with a simple example with just one region (*m=1*) and two actor classes (*n=2*). We therefore skip the index *r* and consider that the signs of the partial derivatives of f_i and A_i become equal. Let us assume that the population P_1 likes its own kind, but is neutral to P_2 and to exogenous influences, such that $s_{11}>0$, $s_{12}=e_1=0$. In contrast, actors in P_2 try to distinguish themselves from their own kind, and are neutral towards P_1 as well, i.e. $s_{22}<0$, $s_{21}=0$. We also assume that the spatial attractiveness for P_2 positively depends on some policy ($e_2>0$) that is increasingly exercised ($dE/dt>0$). We summarize these relations in Table 2.

Table 2 Matrix of signs for the one region example described in the text, including an exogenous policy influence E

Population P_i: ***f_i - change in P_i:***	P_1	P_2	E
f_1	+	0	0
f_2	0	-	+

Now suppose that the region is currently in a situation with a trend combination where both populations increase at the same time (dP_1/dt, $dP_2/dt > 0$). Is it possible that P_1 or P_2 will begin to decrease later? We first consider a trend reversal for P_1. Since the first derivative with respect to time is $dP_1/dt > 0$, this is only possible if the second derivate is d^2P_1/dt^2 *is* negative. By the rules of calculus, differentiating yields

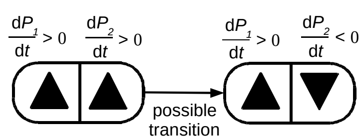
$$d^2P_1/dt^2 = \partial f_1/\partial A_1 \, (s_{11}\, dP_1/dt + s_{12}\, dP_2/dt + e_1\, dE/dt) = \partial f_1/\partial A_1 \, s_{11}\, dP_1/dt.$$

Since all terms on the right hand side are positive, it is impossible that P_1 becomes negative. This situation is different for P_2, where

$$d^2P_2/dt^2 = \partial f_2/\partial A_2 \, (s_{21}\, dP_1/dt + s_{22}\, dP_2/dt + e_2\, dE/dt)$$
$$= \partial f_2/\partial A_2 \, (s_{22}\, dP_2/dt + e_2\, dE/dt).$$

Since the summands in the brackets have opposite signs, the overall sign of d^2P_1/dt^2 is indeterminate, i.e. depends on the absolute value of the coefficients. Since they are not explicitly known in the model, it must be concluded that it is possible that P_1 begins to decrease. This means that the system may change from a qualitative state characterized by increasing P_1 and P_2 values into a state of increasing P_1 and decreasing P_2. This is the only transition which is in accordance with the model assumptions. Figure 2 depicts this part of a qualitative trajectory in symbols that are easy to grasp.

Figure 2 Qualitative trajectory as described in the text showing the only possible transition from the positive trend combination



As mentioned before there is a further important feature of the method: Due to the qualitative assumptions made in the model, it may happen that multiple different trend combinations follow in time. Mapping all possible sequences of trend combinations can therefore result in “scenario trees”.

Making computations as above for a more complex model is cumbersome and bears the risk of errors. There are cases where the calculus is not as simple. For that purpose, different software tools were developed that take the list of variables, the signs of the partial derivatives and further qualitative constraints as input (e.g. [34, 4]) and determine all possible trend combinations and sequences of trends automatically. For the purpose of this paper, these program packages appeared to be unnecessarily comprehensive and a specific and fast version with a simplified constraint satisfaction algorithm could be implemented based on the techniques developed in [14, 36, 15].

In summary, setting up a qualitative attractiveness model involves the following steps:

1. Determine actor classes with homogeneous preferences and attributes.
2. Determine which actor classes contribute to or diminish the attractiveness for other actor classes or the same class, and express this as a matrix of signs.
3. Compute all possible trend combinations and their sequence.

In the following, we present a real-world example and show what implications follow for urban policy and plan making with respect to urban sprawl in Leipzig.

5 Application to urban sprawl in Leipzig

The analysis of sprawl in Leipzig is taken from an EU-project called URBS PANDENS [42]. The identification of prominent actor classes, location preferences and attributes as well as feedbacks of the actor class population on the properties of the location was achieved through expert interviews (urban researchers and local experts). Other case studies that used qualitative attractiveness models based this information on household surveys [47]. For the urban fringe of Leipzig four sprawl relevant actor classes (P_1 - P_4) have been identified in the post-reunification period (approximately 1990 to 2005) on a level of aggregation which allows representing the most important feedbacks:

1. Middle income households (P_1)
2. High income households (P_2)
3. Industries/businesses (P_3)
4. Large retail/leisure centres (P_4)

For all P_1 - P_4 seven potentially relevant dimensions of locational attractiveness have been identified (not all dimensions apply to all actor classes):

- *Standard of flats* (heating, bathroom, double-glazing windows etc.),
- *Price of accommodation* (rents, prices of houses and premises),
- *Physical environment* (density of settlement, proximity to natural landscape etc.),
- *Transport infrastructure* (roads, train and bus lines),
- *Social aspects* (social environment and image of the area),
- *Accessibility of large areas* (e.g. for a shopping mall) and
- *Catchment area* (number of customers able to visit a shopping mall and contributing to its profitability).

Attractiveness dimensions represent the preference for certain location characteristics. After their actor class specific determination they are ordered (see Table 3, first column). In a following step, the influence of the actor class populations on each dimension of attractiveness has to be discussed and determined (shown in Table 3, columns 2 - 5). Again, expert knowledge of the project participants and local researchers was used as basis, which is documented in [42, 40, 12, 35]. Empirical investigations would be favoured and can be taken up at a later stage to back up these postulated relations (cf. [47] for an extensive example based on a household survey).

Table 3 Attractiveness dimensions of the Leipzig suburbs for the four actor classes (P_1 to P_4) ordered according to importance for each actor) and how they are influenced by actor population changes (- : negative; o: neutral; +: positive influence).

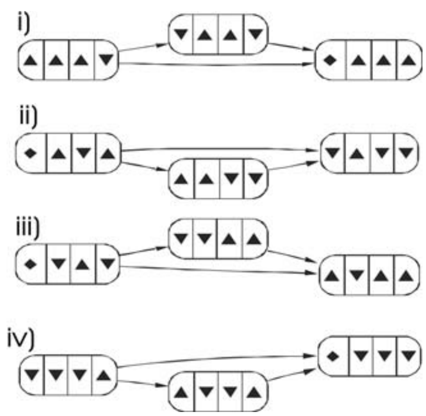
***A*₁** for Middle income households (*P₁*)	*P₁*	*P₂*	*P₃*	*P₄*	Remarks:
Standard of flats	o	o	o	o	Oversupply of new flats due to depreciation possibilities for investors.
Price	o	-	o	o	In general oversupply, but image gain drives prices upwards.
Phys. environment	o	o	o	o	Still low density, relatively low aesthetical value of Leipzig's periphery.
Infrastructure	o	o	o	+	Oversupply of traffic infrastructure due to meanwhile debated "Ostförderung". Shopping malls are welcomed.
Neighbourhood	o	+	o	o	Image gain of the region by increasing high income household.
AGGR.EFFEKT	**o**	**-**	**o**	+	
***A*₂** for High income households (*P₂*)	P₁	P₂	P₃	P₄	
Neighbourhood	o	+	o	o	Image gain of the region by increasing high income household.
Phys. environment	o	o	o	o	Still low density, relatively low aesthetical value of Leipzig's periphery.
Infrastructure	o	o	o	o	Oversupply of traffic infrastructure due to meanwhile debated "Ostförderung". Shopping malls are not welcomed.
Price	o	-	o	o	In general oversupply, but image gain drives prices upwards.
AGGR.EFFECT	**o**	+	**o**	**o**	
***A*₃** for Industries/ businesses (*P₃*)	*P₁*	*P₂*	*P₃*	*P₄*	
Accessibility of Large areas	o	o	o	o	Competition of communes makes land being available.
Infrastructure	o	o	+	o	Synergies of transport and other infrastructure.
AGGR.EFFECT	**o**	**o**	+	**o**	
A**₄** for Large retail/ leisure centres (*P₄*)	*P₁*	*P₂*	*P₃*	*P₄*	
Catchment area	o	o	o	o	Often include the whole agglomeration, not sprawl-relevant.
Accessibility of Large areas	o	o	o	o	Competition of communes makes land being available.
Infrastructure	o	o	+	o	They benefit from P_3 with respect to, e.g., transport infrastructure.
AGGR.EFFECT	**o**	**o**	+	**o**	

Table 4 Resulting aggregated attractiveness matrix. Columns represent the influence of increasing P_i on the attractiveness A of this region for each actor class j. Reading example, row 2: For actor class 1, an increase of the population P_2 would decrease the attractiveness while an increase in P_4 would increase the attractiveness. Changes in the population of P_1 or P_3 would not affect the attractiveness of the region to P_1.

Population→ ↓Attractiveness	P_1	P_2	P_3	P_4
A_1	**o**	**-**	**o**	+
A_2	**o**	+	**o**	**o**
A_3	**o**	**o**	+	**o**
A_4	**o**	**o**	+	**o**

Already in the case of four actor classes a relatively complex net of relations is established, as Table 3 shows. It will be difficult to answer questions about the dynamics of actor classes by a short sequence of computations on the paper. At this point qualitative dynamic modelling develops its strength. It enables the mathematical deduction of time developments from a qualitative system's analysis like the above. In Table 4, all attractiveness dimensions and their dependence on changes in the actor populations are summarised. This matrix is the main input into the qualitative dynamic modelling algorithm with respect to the endogenous interactions and produces the following result (Figure 3).

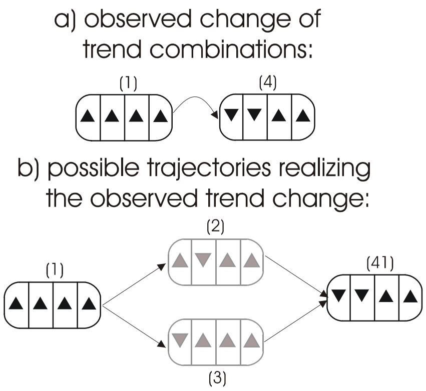
Figure 3 Trend combinations in a qualitative trajectory according to the dynamics as specified in Table 4. Reading the graphs: Ellipses denote qualitative states partitioned by the qualitative states of single actor classes. Partitions in the ellipses stand for actor classes from P_1 – left to P_4 – right hand side of each ellipse. An upward arrow stands for an increasing population trend, a downward arrow for decreasing populations, and a rhombus for the possibility of either direction. Slim arrows show possible transitions from one qualitative state to the next showing a development in time from left to right. The dynamic state of a region is changing, if at least one defined trend of $P_{1\text{-}4}$ is changing its sign.



The ellipses in Figure 3 show the computed scenarios for the temporal development of the Leipzig suburbs by a sequence of qualitative states (the ellipses). These are very simple examples but they already show the scenario character. Where two arrows start from the same node and end in another one, both paths are possible. In Figure 3i) one can see that, if all actor classes but the retail parks persistently increase, either the middle income households will decrease afterwards or the retails park become more numerous. With more actor classes and stronger interactions between them a lot more complex trend combinations will appear.

Now a validation based on observations regarding qualitative states and existing trends can be performed. Empirically, all actor classes were increasing in suburban Leipzig at the beginning of the time period modelled. Such a qualitative state is only incorporated in the very right ellipse in Figure 3i) (a rhombus symbolises an upward or downward trend). This state is - except for P_1 - a stable one, i.e. no trend changes are expected for the future, which has not been proven true for Leipzig after 2000. The expert study team concluded that during the late 1990s' and early years of this century the formerly strong increase of middle and high income households, industry and retail parks in suburban Leipzig changed. A substantial number of residential households moved back to the inner city [40, 12] while the number of business actors kept increasing. This is shown in Figure 4. Passing from the beginning of the 1990s (state (1)) to the early 20th century (state (4)) is only possible by passing over state (2) or (3) in Figure 4b).

Figure 4 a) Trend combinations for the Leipzig periphery as observed during the 1990s (left hand side state) and the beginning of the year 2000 (right hand side state). b) As it is improbable that the trends of P_1 and P_2 changed their sign exactly at the same time two different qualitative trajectories reproduce the observation.

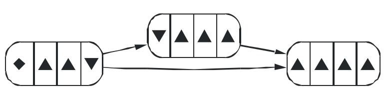


The divergence between observation and model output demonstrates that an important influence must have been forgotten in the model. There are two possible explanations: first, the aggregation of preferences (the steps from Table 3 to Table 4) should form another matrix, or second, external influences are remarkably important in directing household migration.

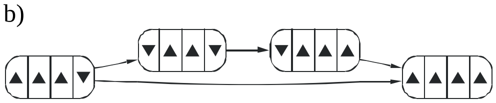
We investigated the first explanation by reconsidering the impacts of the high income households P_2 on the attractiveness for other residential households (column 3 in Table 3, effect of P_2 on A_1 and A_2: price vs neighborhood effect). When the influence signs of P_2 on A_1 and A_2 are changed (successively individually and combined), and new calculations are performed, results are as shown in Figure 5. It contains the observed state (1) still as stable state with no future changes in trends under all possible aggregations of P_2. All other relations are strongly assumed to be correct as they refer to commonly agreed economic synergy effects, infrastructure provision and fixed location characteristics.

Figure 5 Resulting trajectories after a) influence of P_2 on A_1 was changed to a positive sign and b) influence of P_2 on A_1 was changed to neutral.

a)



b)



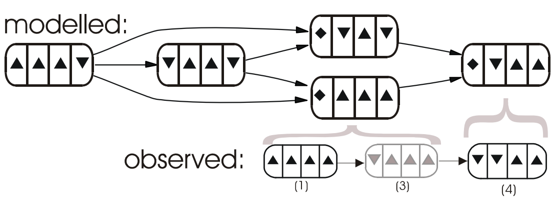
This clearly shows that a change of the aggregated attractiveness matrix does not generate new trajectories. The first alternative can thus not reproduce the observed development, such that we next consider the possibility of external influences. The continuous increase in the supply of attractive, renovated flats and houses in the inner city changed the demand for suburban premises; an increase that was only made possible due to the clarification of ownership relations and the displacement of fiscal stimulation from new buildings to the restoration of old buildings [40, 44]. These external influences tend to reduce the difference in attractiveness between inner city and periphery for the residential actor classes and thereby the net-attractiveness of suburbia; important influences which have to be incorporated into the model.

In Table 5 the modified attractiveness matrix is shown. Besides the 4 columns P_1 - P_4 as shown in Tables 3 and 4, a fifth column is added for the external influence *E*. It represents the increasing renovation of inner city accommodation after the solving of restitution claims in inner Leipzig [40] decreasing the attractiveness of the suburban areas.

Table 5 Attractiveness matrix for suburban Leipzig including the additional external effect on the attractiveness for the residential actor classes, represented by the "*E*-column". E is not dependent on P_i. It acts as a continuously negative influence on A_1 and A_2, reflecting the effect discussed in the text.

Pop.; Time→ ↓Attractiveness	P_1	P_2	P_3	P_4	E
A_1	**o**	**-**	**o**	+	**-**
A_2	**o**	+	**o**	**o**	**-**
A_3	**o**	**o**	+	**o**	**o**
A_4	**o**	**o**	+	**o**	**o**

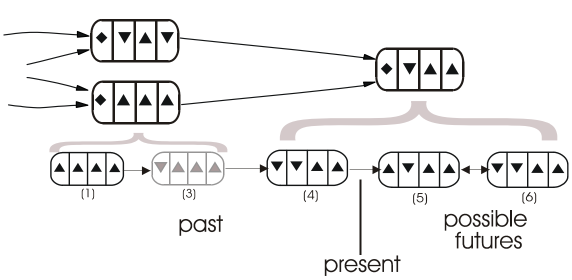
Figure 6 Graph resulting from the attractiveness matrix of Table 5 (upper part). Lower part: observed trend sequences



The respective output of the qualitative modelling algorithm is shown in Figure 6. The upper part gives all transitions of trend combinations according to the matrix in Table 5. It contains a branch which incorporates the observed state (1) (lower part of Figure 6) at the beginning of the 1990s and another (state (4)) at the beginning of 2000. This proves that the system analysis is in accordance with the observed trajectory. The now validated model can be used to discuss possible future developments.

Assuming that the exogenous influences persist, Figure 6 remains valid. It is again given in the upper part of Figure 7 and unfolds in the lower.

Figure 7 Possible futures of suburban Leipzig as calculated by QuAM on basis of Table 5 (upper part of the figure). The lower part: observed trends and future development.



Starting with the state of decreasing residents (P_1, P_2) and increasing commercial actors (P_3, P_4) (approximately the year 2000), the model predicts a possible trend reversal for the middle income households P_1. They may start to net-migrate to the suburbs again, even under increasing attractiveness of the inner city (state 5 in Figure 7). The present situation in Figure 7 represents the year 2005 (the time of the study). The qualitative states to its right, (5) and (6), draw possible developments after that time. The model projects a positive trend of business activities in the suburban area of Leipzig. High-income households are projected to constantly decrease in numbers while middle-income households may constantly oscillate between increase and decrease.

In case the external influence considered in the last model run ceases, as it has by now in the year 2010, a straight-forward analysis with the QDE algorithm reveals that the oscillation stops and the middle income families constantly contribute to sprawl. As shown in Figure 3iii), the QuAM-run without external influence clearly deduces that, next to the numbers of business actors and middle income households being continuously increasing, the number of high income households simultaneously decrease in the suburbs of Leipzig.

6 Implications for anti-sprawl policy in Leipzig

To use the output of QuAM-models for policy recommendations the sequence of trends has to be analysed. Our example demonstrates that the residential re-urbanisation in Leipzig starting in the late 1990's [47] can only be explained by the combination of mutual actor class interactions (i.e. the "free play of forces") and external, regulating influences on the attractiveness difference between inner city and suburbs. The observed development cannot be explained without an increasing supply of attractive flats and houses in the inner city (or elsewhere outside the modelled region) resulting from the clarification of ownership and the displacement of fiscal stimulation from new buildings to the restoration of old buildings. This is a strong hint that these political measures were necessary for and successful with respect to residential re-urbanisation in Leipzig.

The future situation as generated by the model shows that the population of the middle income households in the suburbs will increase again after the year 2005. This trend change - which is unfavourable with respect to a compact city paradigm and other sustainability criteria - can occur independently from the continuation of the above measures. It would generate middle class driven sprawl and a kind of gentrification of the inner city (the latter being one reason of the former). It follows that, e.g., strategies which ensure reasonable rents and land prices in the inner city are of great importance for a sustainable, anti-sprawl development of Leipzig. The price is an important attractiveness dimension for the middle income households, as it is the social environment (see Table 3). While it is assumed that this dimension is positively influenced by an increase of high income households, other measures addressing the social character of neighbourhoods should be initiated. Local policy and plan making would need to target their activities to the demand of the middle income households in order to keep them from moving to the suburbs.

With respect to business and industry the model predicts further sprawl. Here the co-operation between municipalities (including the city of Leipzig) becomes important in order to mitigate competition for investments (and inhabitants) and to reduce land consumption. If a halt of economic activity in suburban Leipzig would be favoured, a different matrix of signs needs to characterise the actors' interdependencies. At the point considered, it would need to be externally imposed.

7 Discussion

QuAM-models have proved to reproduce the qualitative suburban development in Leipzig, to be suitable for this kind of sprawl analysis, and to support the generation of advice for constraining sprawl and thereby extensive land consumption. The method has potentials and limitations, which we want to discuss in more detail hereafter.

The results of the Leipzig example show that the observed urban development can neither be reproduced by considering only endogenous, nor only exogenous influences. The link of natural, physical and social properties of space as well as actor preferences, actor interdependencies, and their externally imposed changes have to be considered jointly. These results may not hold for other examples, but the question is how they compare, in principle, with results obtainable with other approaches, e.g., geographical economics. The latter is strong in producing results of a general nature, but tailoring them to a particular case is empirically difficult and considering social dynamics is at least uncommon. A systems dynamics model would be an established option to jointly consider economic and social interactions. This has yet the difficulties to quantify those interactions and to empirically measure preferences. One work-around is extensive parameter and sensitivity studies. They would allow for outlining the mathematical functions and parameter sets that are consistent with the observed development path. However, finding (even only) one set of parameters bears the risk of mistake and granting this path as the only possible (see [27] for a discussion). Furthermore, producing a result as shown in Figure 7 would require even more computations: a broad variety of parameterisations with only endogenous influences need to be compared with a variety including exogenous influences. These problems also hold for cellular automata or agent based models, since these approaches allow for large degrees of freedom. However, a QuAM-model avoids these difficulties. It - formally – considers not only a single systems dynamics model, but jointly computes with *one* simulation run the set of *all* models that are consistent with the assumptions made by the signs in the aggregated attractiveness matrix.

This feature of QuAM-models is not miraculous at all, since the solution algorithm uses very general deductive rules and only determines sequences of trends instead of quantitative time series. It can be shown mathematically that the algorithm determines the qualitative "abstraction" of all quantitative models subsumed by an aggregated attractiveness matrix simultaneously [34, 15]. However, the very generalizing power of the method comes at a price. Qualitative input can only produce qualitative output. Results are not unique time paths, but possible "branching" scenario trees that allow for alternative developments. Taking this view employs the QuAM-model yet with additional features that are interesting for certain applications. Since a QuAM-model formally subsumes a broad set of systems dynamics models, it generalizes from particular cases. Although the concrete actor classes, their detailed preference relations and their quantitative populations may be numerically different for other cities than Leipzig, they may in some cases be similar in the qualitative sense, i.e. they are expressed by the same aggregated attractiveness matrix. In this case (being, of course, an empirical matter), we would assume to observe similar patterns of urban development and similar ways to control urban sprawl with planning instruments. The method can be used to determine a typology of urban development on an intermediate level of generality (see [17], for a general discussion, and [42]).

Another feature, yet the other side of the same coin, is the robustness of the QuAM-model against uncertainties. Determining the actor classes does not require exactly homogeneous preferences. It is only necessary that all actors of one class are qualitatively homogeneous in the sense that they are attracted to or repelled from the same actor classes and exogenous influences. This is of great advantage for difficulties with respect to the parameterization of social cause-effect phenomena. In our example expert knowledge was used and proved to be sufficient to derive the necessary information for the qualitative model. In other cases actor classes and their preferences can be unearthed differently, e.g. by household surveys and clustering [47]. However, preferences do not need to be measured quantitatively, but only by signs. Population changes do not need to be determined by change rates, but only by trends. The strength of QuAM-models is that powerful systems dynamics methods are used even if only qualitative knowledge is available.

With respect to the application of QuAM-models to derive anti-sprawl policies and the above-mentioned disadvantages of other approaches, the QuAM-model is not a black box and therefore an adequate tool for learning in interdisciplinary research teams but also for decision makers which have to be confident in the model results [49]. The scenario-like outputs of QDEs seem furthermore, at least to our knowledge about the mechanisms driving urban developments, much more appropriate than the exact and unique quantitative outcomes generated by traditional modelling.

Although these features hold great advantages, an application of the QuAM-model might also need familiarization. The pace of sequences of qualitative states (time between ellipses) cannot be determined with the approach. Resource management policies on the contrary have to obey to relatively fixed and pre-given steps in time to deliver plans and assure its implementation. The application of QuAM-models for policy and plan making needs constant monitoring and thinking in non-traditional ways of time.

Discussing the explanatory power of QuAM-models refers to validation. In the setting of this paper, a qualitative model is refuted when it is not able to reproduce an observed (qualitative) time path of urban development. However, if a model is not falsified, nothing is said about its validity. The mode of inference used is thus one of abduction [41]: it derives one possible theory from a particular observation. Making a stronger statement would require testing several competing theories and their explanation of observations (see [27]). For QuAM-models this means to consider an even broader set of models (e.g. by variation in some signs), as outlined for the Leipzig case. A more profound critique is that even without variation in signs, the set of scenarios computed may be very general in the sense that very many branching points occur. In the extreme case the qualitative model is so general that almost every future development is possible, which would prohibit falsification. However, such a case would only show that the input - our knowledge of the system - is insufficient to make any forecasts or to discriminate between assumptions on the base of observational data. This contrasts precise quantitative simulations that derive logically stronger statements, being easier to falsify. In fact, usually every quantitative model is falsified in the strict sense, since computed numbers nearly always differ from measurements [8]. Yet, this does not necessary imply that the assumptions underlying the model are wrong. We conclude that QuAM-models allow for more robustness to uncertainties in urban development than conventional quantitative approaches. QuAM-models are logically weaker, but honest in the sense of a fair relation between the informational requirements to set up a model and the strength of its output. In comparison to other methods QuAM-models have complementary features.

8 Summary and Conclusion

In this paper we introduced and discussed the new QuAM modelling approach, which computes urban sprawl in a scenario-like, but deductive and fully transparent way. Unlike well-established quantitative approaches, QuAM-models allow for representing qualitative knowledge on relations between and within moving actor populations and properties of locations. The approach is strong in formalizing relations that are difficult to quantify, i.e. social processes such as migration and the relation between actors and their environment.

The dynamics resulting from qualitative relations can be computed using qualitative differential equations (QDEs). The strength of QDEs is that powerful mathematical system theoretical methods become available if only qualitative knowledge of the interactions of the system’s elements is available. It offers the possibility to represent qualitative relations, e.g. between actor classes and their location attractiveness, without choosing one quantitative function arbitrarily.

An interesting consequence of this "honest" representation of knowledge in the model is that the resulting dynamics (that can be deduced in a mathematically sound way) differs from usual outcomes of quantitative dynamic models: different possible developments may occur and they are rather described in terms of trends and trend changes than in terms of explicit numbers. This is of particular interest with respect to urban modelling predicting possible futures. The scenario-like outputs of QuAM-models seem very appropriate for the mechanisms that drive urban/suburban development.

We illustratively described the method by way of the suburban migration dynamics in Leipzig, Germany, after the unification. Our example showed that the suburban actors' development at that time was driven by both, the imprint of the actor classes on the environment's attractiveness and all other actors, and the depreciation and tax incentives as well as restitution claims that characterised the East-German legal passage to a market economy, respectively. We show that the interactions between social actors and their environment are strongly conditioning the suburban location attractiveness and therefore opt for its inclusion in urban simulation models. However, social interactions are not easy and "honestly" reproducible by quantitative modelling, which strongly speaks for the QuAM method. Moreover, with QuAM-models important policy implications can be derived concerning the abatement of sprawl around Leipzig in the future.

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