DRAFT OF CHAPTER 7 FROM "URBAN SPRAWL IN EUROPE"

Chapter 7. Modelling urban sprawl: actors and Mathematics

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In this chapter we discuss urban sprawl as a process that results from the decisions of multiple actors. Amongst the many possibilities for decisions taken by these actors we concentrate on locational decisions (see, e.g., Colombino and Locatelli 2001) which - as an aggregated effect - change the conditions of the location for subsequent actors' locational decisions: actors who move - according to their preferences - to low density zones, contribute to densification and change thereby the conditions for further "low density seekers". This is only one simple illustration of a multitude of such feedback mechanisms which occur in economic, social and environmental dimensions. In explaining cases where a complicated net of such feedbacks leads to urban sprawl, a system dynamics approach seems appropriate I (Meen and Meen 2003; Deal and Schunk 2004). This opens the door to the application of formal methods of deduction (formal logics, mathematics) widening the scope for establishing hypotheses with a larger number of explicit relations than can be evaluated by "unsupported" reasoning alone. However, it should be stressed that the deductive step which can be improved by the application of these formal methods is only one in the complex process of scientific understanding while the inductive or dialectic process of hypothesis formulation from empirical material (Shank, 2001) is largely untouched.

In the next sections of this chapter we will discuss the step from many individual actors to 'actor classes'; the relations between structural variables; and an actor based understanding of the sprawl process. These ideas are then applied to a number of case study areas. There is then a section devoted to the mathematical formalisation of these relationships: known as Qualitative Dynamic Modelling. The next section shows some simulation results and discusses how they can be used for validation of the hypotheses on actor-class preferences and feedbacks. Finally there is a discussion about the ways in which qualitative dynamic modelling can be used in the policy making process.

7.1. Actors, actor classes and sprawl

The archetypes of sprawl explained in the preceding chapters address the spatial scale of the whole agglomeration or - at least - the whole sprawling area, thereby following rather a macro-perspective (in contrast to the micro-perspective of single individuals). These macro-processes can be understood as the aggregation of the consequences of a multitude of single decisions, made by different individuals (see, e.g., Filion, Bunting et al. 1999). In the context of sprawl, two types of actors have to be distinguished: actors which take decisions related to their *moves in space* (locational decisions of residents, retailers, industry) and non-moving actors (political authorities, developers etc.) who influence sprawl by directly setting conditions for the decisions of the moving actors.

For various reasons a system analytical treatment seems to be more promising for the moving than for the non-moving actors. Firstly, the space-function feedback is much more direct for the moving actors and their decisions directly affect the physical phenomenon of sprawl. Secondly, a system analytical approach demands a clear setting of the systems boundary. To endogenise, e.g., mechanisms which generate specific spatial policy decisions (i.e. decisions of a non-moving actor) would interfere strongly with our aims, namely to assess or develop promising policy options to regulate sprawl. This touches on the reflexivity problem of social sciences, which cannot be solved in general but where at least a clear statement can be made about the actual hypothesis - who is the observer and what is observed. So we follow a system characterisation that allows us reasonably to ask questions such as: what is the influence of the establishment of a Green Belt on further settlement development, i.e. decisions of non-moving actors are treated as boundary conditions for the systems dynamics and have to be set as scenarios.

The next question is about the right level of aggregation of the moving actors. Is it adequate to speak about "young families with middle income" in an aggregated manner or is it necessary to address each single household as one actor in its relation to all others? The latter is realised in "multi agent-based modelling" (Epstein 1999; Hare and Deadman 2004) which is mainly aimed at explaining emerging macro properties from micro-interactions. The former finds its application in mainstream economic theory, which is based on one representative household.

In the case of the urban sprawl analysis the question of the appropriate aggregation can be investigated empirically. An aggregation of households into an actor class is appropriate when they are homogenous with respect to the properties relevant for the relations in the sprawl context, in particular their preference structure and their specific influences on the regions they move to (White 1981; Thill 1993).

For the case study area of Wirral/Liverpool a sample of the population were surveyed by a postal questionnaire. Responses were fed into a cluster algorithm to test if homogenous actor classes could be formed (Couch & Karecha, 2006). The survey sought the preferences for specific residential locations. 14 characteristics of locations were pre-given and the respondents ranked the importance of each in influencing choice of location. The ranking ranged from irrelevant – slight important – fairly important – very important - to crucial. Furthermore 24 potential characteristics of the respondents were also sought, including family status, profession, age of the heads of households, their commuting time and the number of cars available in the household. From this empirical material three very persistent clusters of high preference homogeneity emerged (independent from the applied clustering algorithm):

- Retired people and those over 60 years old. They were mostly adult couples (60%) and elderly persons living alone (26%) with one car (64%). They prefered being in a low-crime and quiet neighbourhood near the countryside or coast, with good road connections, good bus and railway links, and in proximity to food shopping.
- Professional and managerial households with child/children which mostly comprised adult couples with child or children (88%) in professional or managerial positions (78%). The head of household was mostly of middle age (91% between 35-59 years old) and in possession of 2 or more cars (100%). Most were looking for a low-crime and quiet neighbourhood with good schools. The proximity of countryside and coast was also of interest for the actor class.
- Professional and managerial households without child/children represents adult couples (93%) in professional or managerial positions (100%). These were mostly young people (64% younger than 34 years of age) or of middle age (29% between 35-59 years old). This actor class sought, as did all other actor classes, low-crime and quiet neighbourhoods; but with this group the availability of affordable housing was an additional preference.

Furthermore but with less strength, the algorithm also revealed:

- Lower-middle class households with and without children, mainly between 35 and 59 years old (61%) but also of some younger age (24%) and distributed among many occupations. This group sought a low-crime and quiet neighbourhood with affordable housing near to friends and family.

- <u>'Other' households(single adult and adult couples)</u> are mainly unemployed persons, with 95% under 60 years. They consist of single adults living alone in most of the cases (70%) and some adult couple households (15%). Also here living in a low-crime and quiet neighbourhood ranks highest importance, but the provision with good bus and railway links, the proximity of friends and family and affordable housing were all of significance.

Table 7.1. Actor classes as defined independently by the different case study groups

Case Study	Actor I	Actor II	Actor III	Actor IV	Actor V	Actor VI
Leipzig	Middle Income Households	High Income Households	Industry/ Businesses	Large Retail/ Leisure Centres		
Värmdö (Stockholm)	Upper Class Older Couples Without Children	Upper Class Families not feeling connected to Värmdö	Family Enterprises feeling connected to Värmdö	Old Residents	Summerhouse Converter (for permanent living)	Summerhouse Owner (use it temporarily)
Vienna	Young DINKs	Young Families	Single Parents	Middle-Aged DINKs*	Retired People	
Nadarzyn (Warsaw)	Middle Income Green-seeker	High Income Green-seeker	Nadarzyn-Fans	Dwelling-Standard-Fans		
Wirral (Liverpool)	Retired People	Professional and managerial households with children	Other households	Professional and managerial households without children without Children	Lower-Middle Class households	

* DINKs – Double income no kids.

Figure 7.1. Position of the residential actor classes in an economic status / age scheme

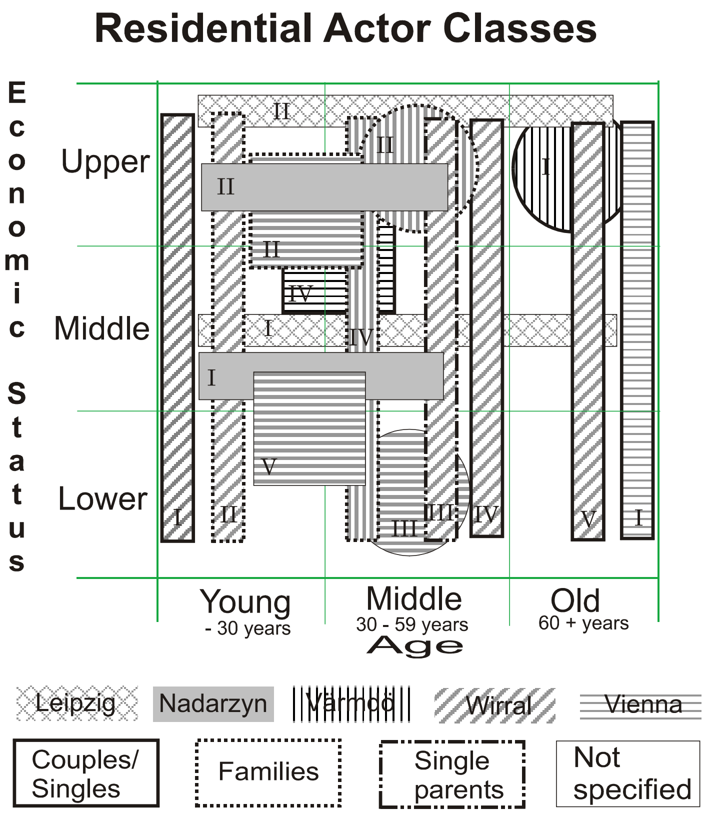

Figure 7.1: Position of the residential actor classes in an economic status / age scheme. The case study is symbolized by colour and the family status by the line style of the borders. The number of the actor class is depicted by Latin numbers. Unspecific with respect to these criteria are the Värmdö residential actors II, V and VI as well as the Nadarzyn actors III and IV. Therefore these are not included here.

This case shows on an empirical basis that the aggregation of households into sufficiently homogenous actor classes is possible. In Table 7.1 we summarize the relevant moving actors as identified in our research for the respective case study areas. In the different regions different characterisations of the actor classes were necessary. In Figure 7.1 we show the position of the residential actor classes in a scheme of economic status, age and family status which clearly shows the heterogeneity of the actor class sets of the different cases. For example, the Vienna actor classes are age oriented while the Leipzig and Nadarzyn (Warsaw) classes are separated by economic status. This may reflect the differences between countries in transition and Austria as a saturated capitalistic system where places are already more class-homogenous. Wirral and Värmdö each show a different and complex mixed structure reflecting specific relevant mechanisms of sprawl.

7.2. The actor versus the structural perspective on sprawl

The question now arises how the more structural properties of the urban system relate to the actor perspective. To do this, a moving-actor class oriented process model has to be defined in some more detail.

Classes of actors (different kinds of residents, retailers, etc) are characterised by homogeneous ways in assessing the attractivity of different urban zones with respect to their decision to move there. The attractivity of an urban zone will be used here in an extended sense, closer to the migration decision: it comprises the usual locational properties and the affordability to move for the actor class being considered. In this notation a zone which, for example, does not offer affordable housing is not attractive for a specific actor class, regardless of other advantages. The attractivity assessment for an actor class depends on three aspects:

a) the fixed characteristics of the respective zone.
b) the presence of other actor classes (competition, synergies, homogeneity, customers, etc.) and
c) externally influenced properties (incentives, taxes, infrastructure ...).

Actor classes migrate along attractivity gradients (move from a zone of lower to a zone of higher attractivity). Thereby they reduce their population in the zone they leave (zone of origin) and increase their number in the zone they move to. This migration may change the attractivities of both zones for all actor classes with respect to mechanism (b) and cause further changes in migration fluxes. This means that the mechanisms cited in (b) can be endogenised into the formal model while (a) and (c) will be considered exogenous.

The Qualitative attractivity migration model: QUAM

The following section discusses some important macro variables as commonly used in structural explanations of sprawl (as, for example, applied in other chapters within this book) and shows how they are related to the actor class oriented structure (called QUALITATIVE ATTRACTIVITY MIGRATION MODEL: QUAM). It is clear that the macro variables (indicated by italics in the following paragraph) may either be exogenous to the QUAM-model and cause

1. a **C**hange in **A**ttractivity of a zone for a specific actor class (type CA)
2. a **C**hange of the **N**umber of actors in a specific class (type CN)

or address aspects which are endogenous to the model, i.e.

3. the **D**ynamics of the spatial **D**istribution of actor classes (type DD):

The macro variables concern:

The topic d*emographic and household change* is mostly interpreted in terms of increasing 1-person households, changes in the population pyramid or changing family status, which can be mapped on a change in total size of actor classes like "young single", "old single" or "young family" (type CN).

The Migration, segregation and filtering aspects are much more diversely interpreted, but aspects like immigration (either foreign or rural) and emigration can also be mapped on to the change of the total size of respective actor classes (type CN) while aspects like social homogeneity, east-west divide, gentrification of inner city areas, concentration of foreigners in old densely built up outer areas, migration from inner city areas to rural areas and filtering processes are represented by the dynamics of the spatial distribution of actor classes (type DD).

With respect to the *sectoral composition and transformation of the economy* the processes of industrialisation/de-industrialisation and tertiarisation are of importance. From the residents point of view this modifies the attractivity of different zones for specific employees depending on commuting distance, and may influence the attractivity of expensive housing zones for different actor classes, depending on income (type CA). The trend to smaller firms with more flexible location decisions has to be mapped on the change of the respective actor class (type CN). Labour market structure changes do not add new paths of mapping, the same is true for foreign investments and shifts of location of economic activity: they change the attractivity of a zone for residential actor classes (type CA).

The lack of space in inner city maps on increasing or decreasing supply with adequate dwellings which can be represented as increasing or decreasing attractivity for residential actor classes in the model (type CA).

Changes in income, the distribution of incomes and spending patterns in the sense of income growth, polarisation of income distribution, household expenditure etc. can be mapped on to changes in the size of actor classes of different income levels (types CN, DD) or a change in the attractivity of, e.g., a housing area for a fixed actor class with changing income (type CA).

Changes in land prices and/or housing costs due to supply changes can be reproduced by a shift of the attractivity functions of the different actor classes (type CA).

Infrastructure investments - transportational and other increases the attractivity of remote places for most of the actor classes (type CA). Transport itself depends on the spatial distribution of specific actor classes (residents, industry).

With regard to *public regulation, taxes and subsidies* the competition between municipalities and spatially specific as well as demand side taxes/subsidies are of importance. These can be mapped on changes of attractivities with respect to a region and/or an actor class (type CA).

Public regulation, land use planning, housing policy includes aspects such as tenant-protection,, housing privatisation and problems of restitution (type CA).

The aspects subsumable under the *quality of the inner city* are of type DD: reputation, supply with adequate housing, infrastructure (cultural, schools, traffic, water supply etc.).

This list shows that almost all structural and macro properties usually used in sprawl explanations can be represented by an actor class oriented approach.

7.3. Identifying the feedbacks

The example of the Leipzig periphery is used to illustrate the second step in defining an actor based process model: the identification of actor specific preferences and feedback from the actor class population on the characteristics of the location (see also Lüdeke et al., 2004). This is a crucial element in sprawl related dynamics.

For the urban fringe of Leipzig four relevant actor classes have been identified (see Table 7.1). For them seven potentially relevant dimensions of attractivity to the choice of location have been identified. According to empirical studies and literature review (Lüdeke et al., 2004) the 7 dimensions concern:

- dwelling standards (heating, bathroom, windows etc.),
- dwelling prices (rents or purchase prices),
- the physical environment (density of settlement, proximity to natural landscape etc.),
- infrastructure (roads, train and bus lines),
- the neighbourhood (social environment and image),
- the accessibility of major centres (e.g. a shopping mall) and
- the catchment area (number of customers able to visit a shopping mall)

The last dimension is only relevant for actor class 4 (large retail/leisure centres) while the standard of flats only applies for actor class 1 – the middle income households (according to empirical studies). Prices, physical environment, neighbourhood and infrastructure are relevant for both residential actor classes 1 and 2 – middle and high income households. Infrastructure also matters for the economic actor classes 3 and 4 (industries/ businesses and large retail/leisure centres), as the accessibility to large areas does. These issues are summarized in Table 7.2.

Table 7.2. Dimensions of attractivity of the Leipzig periphery identified to be relevant for the actor classes

Attractivity-relevant aspects	for actor
standard of flats (heating, bathroom etc.)	P_1
prices (rents, prices of houses)	$P_{1,2}$
physical environment (density of settlement, proximity to natural landscape)	$P_{1,2}$
infrastructure (roads, train lines)	$P_{1,2,3,4}$
neighbourhood (social environment)	$P_{1,2}$
accessibility of large areas (for, e.g., a shopping mall)	$P_{3,4}$
catchment area (number of customers able to visit a shopping mall)	P_4

“Middle income households”(P_1), “High income households”(P_2), “Industry/business”(P_3), and “Large retail/ leisure centres”(P_4).

Starting with actor class 1, the middle income households, the assessment of the Leipzig case study group revealed that the attractivity dimension dwelling standardsstandard of flats is not significantly influenced by further in-movement of any actor class. The supply of high quality dwellingsflats is and probably will also for the nearer future be sufficient due to attractive depreciation possibilities for investors throughout the 1990s. The second important dimension is price. Here experts do not expect an increase from scarcity of building land but an increase of prices due to an improvement in the image of the zone when the population of the high income households grows. Therefore increasing high income households has a negative influence on this attractivity dimension for the middle income households.

The attractivity due to the physical environment is not influenced by in-movement because of the still low settlement density and the generally low aesthetic quality of the Leipzig periphery compared with the inner city. Traffic infrastructure is abundant and congestion is not yet a serious problem. In a wider sense of *infrastructure*, the development of shopping malls in the periphery is welcomed by the middle income households. With respect to the *social environment*, a slightly positive influence of in-movement of high income households on the attractivity can be observed. So an increase in high income households has two competing effects on the attractivity of a region for the middle income households (increased prices due to an improved image and better social environment). The net effect will be negative, as for the middle income households the *price* effect is more important than the *image* effect.

Regarding the attractivity of the zone for the high income households we find a somewhat reversed situation: here the *social environment/image* plays a much more important role than the price. Therefore the positive effect of increasing high-income households yielding more social homogeneity more than compensates for the negative impact on prices. In the case of *infrastructure* and *physical environment,* these aspects will be left unchanged under population change for the same reasons as mentioned above. The difference is that the development of new retail/leisure centres will not increase the attractivity of the zone for high-income households because these centres are much less attractive to them as compared with middle-income households.

The attractivity of a peripheral region for industry/business appears to be determined by *accessibility* and *infrastructure*. Due to the strong competition between communes for jobs and profitable businesses, the first dimension is not a limiting factor as land is likely to be made available in response to the wishes of potential investors. With respect to *infrastructure* there is a synergistic effect between the different industries/businesses resulting in a positive influence of industries/businesses on their specific attractivity.

Table 7.3. Attractivity dimensions and their influences

a)

A_1:	P_1	P_2	P_3	P_4	Remarks:
standard of flats	o	o	o	o	oversupply
Price	o	-	o	o	oversupply, image
phys. environ.	o	o	o	o	still low density
infrastructure	o	o	o	+	oversupply
neighbourhood	o	+	o	o	image
AGGR.EFFECT	**o**	**-**	**o**	**+**	
A_2:	P_1	P_2	P_3	P_4	
neighbourhood	o	+	o	o	image
phys. environ.	o	o	o	o	still low density
Infrastructure	o	o	o	o	oversupply
Price	o	-	o	o	competition
AGGR.EFFECT	**o**	**+**	**o**	**o**	
A_3:	P_1	P_2	P_3	P_4	
accessibility of large areas	o	o	o	o	competition of communes
Infrastructure	o	o	+	o	Synergies
AGGR.EFFECT	**o**	**o**	**+**	**o**	
A_4:	P_1	P_2	P_3	P_4	
catchment area	o	o	o	o	not sprawl-relevant
accessibility of large areas	o	o	o	o	competition of communes
Infrastructure	o	o	+	o	benefits from P_3
AGGR.EFFECT	**o**	**o**	**+**	**o**	

b) $sign\left(\partial A_j / \partial P_i\right)$

Population→ ↓Attractivity	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

a) Attractivity dimensions of the Leipzig periphery for the four actor classes (ordered according to importance for each actor) and how they are influenced by actor population changes. For details see text.
b) Resulting aggregated attractiveness matrix

Columns: influence of increasing P_i on the attractivity A of this region for each actor class j.
"o" means no relevant influence,
"+" a positive and
"-" a negative influence.

P_1 - Middle income households,
P_2 - High income households,
P_3 - Industry/business and
P_4 - Large retail/ leisure centres.

Reading example (row 1): for actor class 1 an increase of the population P_2 would decrease the attractivity while an increase in P_4 would increase the attractivity of the region. Changes in the population of P_1 or P_3 would not affect the attractivity of the region to P_1.

For large retail/leisure centres the *catchment population* is a crucial aspect – but closer inspection shows that in the era of high car ownership this is the total population in the whole agglomeration and thereby does not contribute to the retail/leisure centres' decision to move to the periphery or not. Instead *accessibility of larger centres* is important. This dimension of attractivity is not significantly influenced by an hypothesised increasing demand as communes will offer adequate spaces to attract investors. But it appears that the provision of *infrastructure* is influenced positively by the presence of industry parks, synergetic effects appear.

In Table 7.3 all attractivity dimensions and their dependence on changes in the actor populations are summarized. A_1 represent the attractivity of the region for P_1 – the middle-income class; A_2 stands for the attractivity for P_2 – the high-income class, A_3 indicates the attractivity for P_3 – industry/businesses, and A_4 shows the attractivity of the region for P_4 – the retail/leisure centres.

As shown in section 7.2, attractivity is influenced by:

a) the fixed characteristics of the respective region
b) the presence of other actor classes (competition, synergies, homogeneity, customers, etc.) and
c) externally influenced properties (incentives, taxes, infrastructure ...).

So far we have discussed mechanism (b) (Brainard, Jones et al., 2002) in this section. But if we want to describe the Leipzig case after reunification external influences (c) have to be taken into account which is in the case of Leipzig the continuous increase (from 1990 to 2000) in the supply of attractive dwellings in the inner city mainly due to clarification of ownership relations and the shift in subsidies from support for new dwellings to the restoration of old buildings. These external influences tend to reduce the difference in attractivity between inner city and periphery for the residential actor classes and thereby the net-attractivity of suburbia. This reflects back onto the attractivity matrix. The modified matrix is displayed in Table 7.4: in addition to the 4 columns P_1 - P_4 which characterize the influence of population changes on the attractivity for the different actor classes, a fifth column is added to describe the external influence. Additionally to the population effects the factor t influences the attractivity of the periphery for the residential actor classes P_1 and P_2 negatively over time. This factor competes with the population related influences and might be or not be overcompensated by other matrix elements in Table 7.4.

Table 7.4. Attractivity matrix for Leipzig

$$sign\left(\partial A_j \big/ \partial P_i\right)$$

Pop.;Time→ ↓Attractivity	P_1	P_2	P_3	P_4	t
A_1	o	-	o	+	-
A_2	o	+	o	o	-
A_3	o	o	+	o	o
A_4	o	o	+	o	o

Attractivity matrix for Leipzig including the additional external effect on the attractivity for the residential actor classes, represented by the "t-column".
As time t - in contrast to the P_i - increases always, the fifth column acts as a continuously negative influence on A_1 and A_2.

P_1 - Middle income households,
P_2 - High income households,
P_3 - Industry/business and
P_4 - Large retail/ leisure centres.

We illustrated the system analytic characterisation of a sprawl region using the Leipzig case. As mentioned in the introduction of this chapter, this allows for the application of formal, mathematical methods to perform further deductive steps, including model validation and policy analysis. In both cases the aim is to deduce the dynamic behaviour (i.e. the time course) of the actor populations - in system analytic terms the "trajectories" of the system - from the stated interrelations as summarised in Table 7.4. This mathematical method is relatively new and has some interesting properties bridging the gap between quantitative and qualitative methods.

7.4. Operationalising the qualitative attractivity migration model

The mathematical theory which allows us to evaluate system descriptions as in Table 7.4 is called "Qualitative Differential Equations" or QDEs (Kuipers, 1994). The method is based on system theoretical process thinking, i.e. the state of a system is related to its rate of change. In the realm of usual quantitative modelling this is formalized by differential (since Leibnitz and Newton) or difference equations where explicit numerical relations between the variables and their rates of change are needed. In contrast, QDEs try to deduce the time development of the variables from a much weaker, namely a "qualitative" understanding of the interactions of the system elements. This has some advantages. In particular, it is very appropriate for the evaluation of social systems' behaviour where indicators are difficult to specify and especially to quantify.

This qualitative understanding can be characterized by the following hierarchy of determination:

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

Levels 3 and 4 imply that it is possible to describe the elements of the system by ordinal scale variables, i.e. a "greater/less than" relation can be defined. At level 4 of 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. To apply QDEs the construction of an influence diagram is necessary in order to depict the system's elements and their qualitative relations. To obtain this, techniques 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 Luna-Reyes and Anderson (2003).

The method was originally applied by Kuipers and his group to qualitative physics and human physiology. In the realm of sustainability science it was applied to smallholder agriculture in developing countries (Petschel-Held and Lüdeke, 2001, Sietz et al., 2006), fisheries management (Eisenack et al., 2005) and industrial agriculture (Lüdeke and Reusswig, 1999). Here the aim was to calculate possible future developments from qualitative systems understanding, to choose from these sets of possible futures the desirable ones, to identify critical branching points and to assess policy options to influence the development positively.

The scale of application is characterized by an intermediate functional resolution, resulting in a number of interacting elements not larger than about 40. This means, for example, that the algorithm in its present form is not applicable to typical multi-agent based modelling (MAB) which deals with hundreds of agents.

The outputs of the method are time developments in terms of trend combinations of the variables and possible future changes of these combinations. Depending on the input, branching and/or cyclic time developments may result, i.e. different possible futures. The strength of QDEs is that powerful mathematical system theoretical methods become available even if only qualitative knowledge of the interactions of the system's elements is available, e.g. in the form of an influence diagram. One disadvantage is that in some cases the result, i.e. the qualitative trajectories, may be very ambiguous in the sense that very many branching points occur. The extreme case would be that the filtering ability of the qualitative model is so weak that almost every future development is possible. But this simply means that the input - our knowledge of the system - is insufficient to make any forecasts. This method can be directly used to evaluate models like the one shown in Table 7.4. For a more mathematical formulation see Appendix 1.

7.5. Validation and future scenarios

To illustrate the validation process of a QUAM model we return to the Leipzig example. Here it was possible to obtain a qualitative description of the suburbanisation development since 1989 with respect to the population trends (a so called "qualitative trajectory") in the periphery of the city for the 4 identified actor classes.

The graphical representation of the results (as in Figure 7.2) is as follows: a rectangle depicts a dynamic state of the zone. This state is characterised by the actual trend of the population of each actor class, depicted by an upward- or downward arrow. A rhombus symbolises an undefined trend. The rectangle is partitioned by columns, depicting the actor classes from the left to the right (P_1, P_2, ... P_i). The dynamic state of a zone is changing, if at least one defined trend of one P_i changes its sign. Then a new ellipse is drawn as the successor to the former development stage. Possible successors of a dynamic state are indicated by long arrows between the qualitative states. A typical property of QDE-solutions is that there may be more than one successor for a given dynamic state.

The observation reveals an increase in all actor class populations during the 1990s while at present the trend of the residential actor classes P_1 and P_2 becomes negative (see Figure 7.2a). The exact sequence of the trend reversals of P_1 and P_2 is not known but two different qualitative trajectories are in accordance with the observations (see Figure 7.2b)

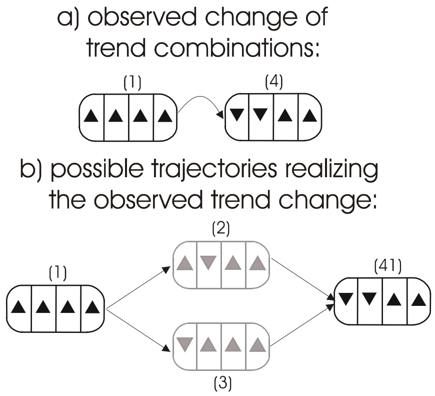

Figure 7.2: a) Trend combinations for the Leipzig periphery as observed during the 90s (left hand side state) and now (right hand side state). b) As it is improbable that the trends of P_1 and P_2 changed their sign exactly at the same time two different qualitative trajectories reproduce the observation.

In columns:
P_1 - Middle income households,
P_2 - High income households,
P_3 - Industry/business and
P_4 - Large retail/ leisure centres.

Figure 7.2. Trend combinations for Leipzig

The model is validated if the above observed trajectory can be reproduced. Evaluation of the model from Table 7.2 with the algorithm described in the preceding section yields the graph as shown in Figure 7.3. It includes a branch consistent with the observed state sequence (1)->(3)->(4). This proves that it is possible to reconstruct the observation.

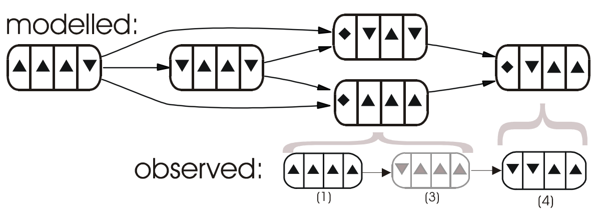

Figure 7.3. Modelled and observed trends in Leipzig

The verified model can now be used to discuss possible future developments (scenarios). Assuming that the exogenous influence which increases the attractivity of the inner city persists, the graph from Figure 7.3 stays valid. Starting with the present situation of an emerging decrease in residential populations (P_1, P_2) and a continued increase of the commercial actors (P_3, P_4), the model predicts the possibility of a future trend reversal for P_1: the middle income households may start again to generate net-migration into the periphery, even under increasing attractivity of the inner city. Looking further into the future a kind of "oscillation" between states with increasing and decreasing P_1 is possible (see Figure 7.4). If the external influence considered in the model were to stop, a strait-forward analysis with the QDE algorithm reveals that the oscillation would stop and the middle-income families would constantly contribute to sprawl.

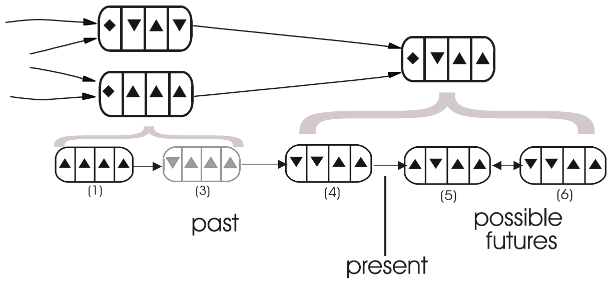

Figure 7.4. Possible futures for Leipzig

7.6. Using a QUAM model for policy analysis

There are two different ways illustrated here how the QUAM models can support policy advice:

1. moving from general targets to the identification of specific policy mechanisms which have to be influenced in order to control urban sprawl;
2. the evaluation of alternative suggested strategies and policy instruments to control urban sprawl

As an example of the first, we use the results of a stakeholder workshop held in Leipzig (Petschel-Held et al., 2004), where a consensus on a list of targets for the control of urban sprawl was achieved amongst the participating stakeholders and scientists. As an example of the second use we have employed the results of a questionnaire on strategies to combat urban sprawl and its consequences in the different case study areas.

7.7. From general targets to specific policy mechanisms: a model analysis

During the Leipzig workshop the project partners and stakeholders from seven European cities elaborated on general targets for urban development related to urban sprawl. Major goals for the political and planning system were formulated. These can be summarised as:

- An increase in the functional and social mix of urban areas
- Densification of the urban regions while avoiding over-densification
- A limit on urban sprawl

Each of the goals will now be discussed within the modelling framework for one or more of the project case studies.

Increasing the functional and social mix of urban areas, examined in case studies of Vienna and Nadarzyn/Warsaw

The goal is to enable or to increase the functional and social mix of urban areas. This is represented by a persistent trend combination where all actor classes show the same trend direction: either all actor populations increase or decrease. In contrast, mixed trend directions would yield (at least in the long run) a decrease in functional and/or social mix. Although the initial situation of the descriptive model runs performed so far was frequently characterised by an increase in all actor class populations (due to the choice of hotspots of sprawl), this combination was never persistent. In particular the final trend combinations where never homogenous.

Vienna (Peripheral zone A3a, south-western municipalities of Mistelbach district and adjacent municipalities of Gänserndorf-district). From a previous study about the 'dreams of habitation' in the Vienna agglomeration (Trappeiner et al., 2001) and further statistical material, 5 clusters were chosen to represent the actor classes involved in sprawl in Vienna:

P1 - Young DINKs: describes young couples in the age of 15-29 years, both persons are working, have no children and are financially well off.
P2 – Young families: with only one person working, the financial budget of the household is fully committed.
P3 - Single parents in the age of 30-45 years.
P4 - Middle aged DINKs: defines couples between 30-59 years of age, the financial background is robust.
P5 - Retired people, the budget of the household becomes smaller.

Starting from the existing model developed for Vienna the attractivity matrix for the 5 actor classes is shown in figure 7.5.

Population→ ↓Attractivity	P_1	P_2	P_3	P_4	P_5
A_1	o	o	o	-	o
A_2	o	o	o	-	o
A_3	o	o	-	-	o
A_4	o	o	o	o	o
A_5	o	o	o	o	o

Table 7.5. Attractivity matrix for Vienna's suburban zone A3a

P_1 - Young DINKs,
P_2 - Young families,
P_3 - Single parents,
P_4 - Middle aged DINKs,
P_5 - Retired people.

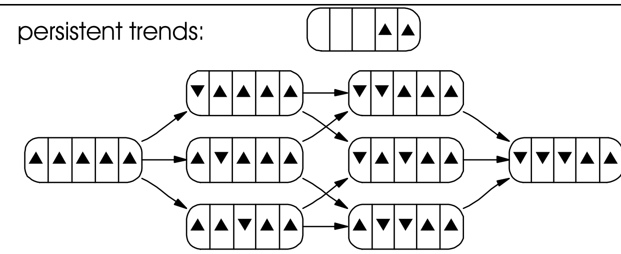

Figure 7.5. Sequence of trend combinations for the Vienna zone A3a

The projected final state of the zone is not very favourable from the viewpoint of social and functional mixture. The middle-aged DINKs and retired people are steadily increasing while the other actor classes constantly move out. Here the hypothesis is that the social mix would increase if all actor classes would move into or out of the zone (by that inducing either an increasing or decreasing total population). To ensure that one of these trend combinations is persistent one needs to go back to the attractivity matrix. Here we see that the attractivity for P1, P2 and P3 decreases when more people of P4 move in. This is due to the stimulation of rising dwelling prices by this actor class (middle aged DINKs). For a higher social mix in the region the negative influence of the middle aged DINKs on the attractivity of the young DINKs, the young families and the single parents needs to become negligible. The '-' have to change to '0'.

If this change in the matrix can be induced the social mixture of the region will increase because all actor classes will persistently rise or fall in numbers once such a migration pattern has been activated.

This result from mathematics can be summarised as follows: eliminate the negative influence of rising P4 on the attractivity of the considered region for P1, P2 and P3. According to the model assumptions this influence is generated by market mechanisms.
The choice of policy instruments to achieve this outcome is for local planners to determine in relation to local circumstances. However, likely alternative policies include the direct provision of affordable housing, subsidies for non-profit housing, and rent controls.

Nadarzyn/Warsaw. Here a survey of inhabitants revealed the following actor classes involved in the urban sprawl process.:

P1 – Middle Income Greenseeker
P2 – High Income Greenseeker
P3 – Nadarzyn-Fans
P4 – People interested in dwelling standard

As in the former examples a good social mix is thought to be represented by a homogeneous trend combination for all actor classes. The output from the modelling of the dynamics in Nadarzyn is shown here:

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

Table 7.6. Attractivity matrix for the case study of Nadarzyn
P_1 - Middle Income Greenseeker,
P_2 - High Income Greenseeker,
P_3 - Nadarzyn-Fans,
P_4 - People interested in dwelling standard.

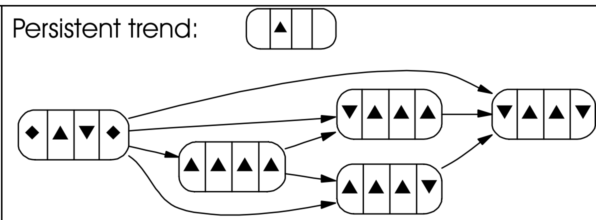

Figure 7.6. Trend combination sequence for the Nadarzyn zone

Figure 7.6 shows that the financially well-off actor groups are represented by P2 (High Income Greenseeker) and P3 (Nadarzyn-Fans) who move there because of the positive reputation of Nadarzyn. If they move to the zone they influence the housing market in that the prices for the available premises rise faster than they would have with the only influence of shrinking availability. In the matrix for Nadarzyn this is reflected by the negative influence of increasing P2 and P3 on the attractivity of the region for P1 and P4. By eliminating these negative influences, a persistent homogenous trend combination and thereby a development consistent with social mixing would be possible.

An instrument to avoid the impact of the higher income actor classes on prices in Nadarzyn can help to achieve/preserve social mixing. Which precise policy instruments would be successful, (e.g. rent limits, supply of affordable housing, subsidies for non-profit housing etc.) will depend on the specific situation and would have to be decided by local experts.

Densification of suburban areas, examined in the case study of Leipzig

Here we ask the question how to generate a more dense development in the Leipzig periphery. As at the moment "re-urbanisation" is the predominant trend, this question is aimed at establishing a future where the development of the inner city to a reasonable density (avoiding over-densification) will be completed and further growth in the periphery could occur as Leipzig tries to establish itself as a "growth pole" in Eastern Germany.

Under current conditions the following scenario for the further development of the Leipzig periphery was deduced:

Population→ ↓Attractivity	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

Table 7.7. Attractivity matrix for the case study of Leipzig

P_1 - Middle income households,
P_2 - High income households,
P_3 - Industry/business and
P_4 - Large retail/ leisure centres.

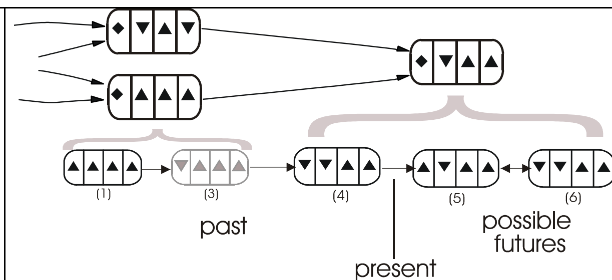

Figure 7.7. Trend combination for the Leipzig periphery

We anticipate a further increase of the population of actor classes P1 (middle income households), P3 (industry) and P4 (shopping malls/leisure parks). Inspection of the attractivity matrix, i.e. the underlying assumptions, suggests that spatial competition between the actors is very low - due to the large abundance of vacant land. One can expect that development under these conditions will be at relatively low densities because there are only weak restrictions on the availability of land. Aiming for a dense development in the periphery would mean that the supply of building land has to be limited. Such a limitation would change the conditions for the Leipzig periphery: now competition between the different actors will occur and generate new interactions. Consequently, the attractivity matrix is changed:

Table 7.8. Attractivity matrix for the case study of Leipzig under land restrictions

Population→ ↓Attractivity	P_1	P_2	P_3	P_4
A_1	-	-	o	+
A_2	-	-	-	-
A_3	O	o	-	-
A_4	O	o	-	-

P_1 - Middle income households,
P_2 - High income households,
P_3 - Industry/business and
P_4 - Large retail/ leisure centres.

If a simulation is performed on the basis of this modified matrix, we get a new dynamic end-state. It is now characterised by the situation that the populations of all actor classes except those for industry/businesses decrease, which means one gets *less development* instead of more and *denser development*. This is not what was intended. So the question arises: are there measures to enable further development under politically restricted land resources?

To get an idea how these measures have to modify the interrelations between the actor classes (i.e. the attractivity matrix) to be successful, all theoretically possible changes where analysed with respect to their impacts on the expected development. The most promising modification is depicted in Table 7.9, which assumes that the mutual negative interaction between the industry/businesses and the retail/leisure centres (P3 and P4) can be avoided. Simulation on the basis of this new matrix generates a dynamic end-state which consists of increasing populations including the high income households.

Table 7.9. Modified attractivity matrix for the case study of Leipzig under land restrictions

Population→ ↓Attractivity	P_1	P_2	P_3	P_4
A_1	-	-	o	+
A_2	-	-	-	-
A_3	O	o	+	o
A_4	O	o	+	o

P_1 - Middle income households,
P_2 - High income households,
P_3 - Industry/business and
P_4 - Large retail/ leisure centres.

It is now a question of choosing the right policy mechanisms to realise a situation where competition for land between residential and other uses exists but not between industry and large retail. In case that such a set of measures can be defined by local experts, a dense expansion of the city could be achieved.

"Limiting sprawl", examined at the case study of Värmdö

Accepting that sprawl is sometimes unavoidable but should be kept in reasonable limits, the aim here is to reduce net migration to the periphery, i.e. the aim is to stabilise the suburban population.

In the case of Värmdö we describe the mutual interactions between the 6 actor classes with the following matrix:

Table 7.10. Attractivity matrix for the case study of Värmdö

Population→ ↓Attractivity	P_1	P_2	P_3	P_4	P_5	P_6
A_1	o	o	o	o	o	o
A_2	o	o	o	o	o	o
A_3	+	+	-	+	+	+
A_4	-	-	o	o	-	-
A_5	o	o	o	o	o	o
A_6	o	o	o	o	o	o

P_1 - High income older couples,
P_2 - High income families,
P_3 - Family Enterprises,
P_4 - Old residents,
P_5 - Summerhouse converters,
P_6 - Summerhouse owners.

From this we calculate further in-migration of the high income older couples, the high income families, the summerhouse converters (converting from temporarily to permanent use of the summerhouse) and the summerhouse owners (temporarily use), an out-migration of the old residents and an undefined situation for the family enterprises in the future. Looking at the changes in in-migration trends, none of them is decreasing, i.e. we cannot expect a stabilisation of the population of Värmdö. How can the situation be modified to generate a stable trend combination with decreasing rates of migration?

A situation where the increasing populations of the high income older couples, the high income families, the summerhouse converters and the summerhouse owners (P1, P2, P5 and P6) will saturate the zone can be achieved by measures which add negative feedbacks of these actor classes on their respective attractivities (A1, A2, A5 and A6). This means that an increase of their own population decreases the attractivity of the zone for the respective actor class (see table 7.11). The effect is that the currently observed trend combination will not change their signs but net migration will become smaller and smaller, resulting in a stabilisation of the total population. Again, it is for local planners to determine the precise policy instruments to be used. One possibility might be to intensify market mechanisms by restricting the supply *specifically* for the respective actor classes (an unspecific restriction of building land would not work because this would add additional minuses to the matrix).

Table 7.11. Modified attractivity matrix for the case study of Värmdö

Population→ ↓Attractivity	P_1	P_2	P_3	P_4	P_5	P_6
A_1	-	o	o	o	o	o
A_2	o	-	o	o	o	o
A_3	+	+	-	+	+	+
A_4	-	-	o	o	-	-
A_5	o	o	o	o	-	o
A_6	o	o	o	o	o	-

P_1 - High income older couples,
P_2 - High income families,
P_3 - Family Enterprises,
P_4 - Old residents,
P_5 - Summerhouse converters,
P_6 - Summerhouse owners.

So far we have shown how certain general targets of urban development can be achieved. The results leave open questions of detail but they give hints as to which aspects of the urban system have to be modified.

In the following section we ask the other way around and test the consequences that might be expected from specific policy choices.

7.8. Discussion of case specific strategy-suggestions from a QUAM perspective

In the following section the model is used to test the impact of a range of policy instruments in selected cities. In this framework a strategy describes a recommendation that can be implemented through a combination of instruments, while an instrument will be understood as a tool or mechanism to achieve specific goals.

Leipzig

The Leipzig model showed that the present state of emerging residential re-urbanisation was not explained by mutual actor class interactions but by external influences on the relative attractivity of the inner city and periphery. These external influences are represented by the following suggested strategies (as proposed by the case study experts):

1. Improving the quality of inner city environment;
2. Increasing the proportion of owner-occupied dwellings;
3. Abolishing incentives for suburban development.

Strategies 1.and 3. are already in use and are - according to the model results - already successful with respect to residential re-urbanisation. With respect to the future situation the model shows that the population of the middle income households in the periphery will increase again. This unfavourable trend change 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. It therefore follows that a further strategy:

4. Ensuring reasonable rents and land prices in the inner city

is of great importance for the further development of Leipzig. Therefore instruments have to be developed to operationalise this strategy. With respect to business and industry the model predicts further sprawl. Here the suggested strategy:

5. Co-operation between municipalities (incl. city of Leipzig), in order to mitigate (land-consuming) competition (for investments and inhabitants)

This becomes important in order to minimise the land consumption of necessarily increasing economic activities in the periphery. The strategy:

6. Raising the awareness of politicians for the negative effects of sprawl

touches the preconditions of any measure against sprawl. Here the model does not make specific statements as it concentrates on the "moving actors", not on the actors which set the framework for urban development. But the model result underpins the importance of this strategy as an uncontrolled and moving actor driven sprawl would be disadvantageous.

7. Making urban development and land use change less attractive for municipalities

touches the question whether incentives or disinsentives should be used to influence the decision of a potential mover to the periphery. As a general conclusion from the QUAM model the incentive-strategy (making the inner city more attractive) is preferable, as disinsentives (making the periphery less attractive) could potentially lead to "evasive actions" of the movers, which can only be avoided if the disinsentives are equal across all areas - a condition difficult to realise. The strategy of:

8. Land use regulation

can be discussed from a similar point of view: only if the implemented regulations are ubiquitous, effects such as a tendency for development to leapfrog over the green belt, can be avoided. (Brown, Page et al. 2004).

Nadarzyn/Warsaw

The Nadarzyn model results show a future decline of middle income actors and a further increase of upper class residents, driven by the interactions between the actor classes. This will lead to a greater homogeneity among newcomers and impact on the social cohesion in the sprawl zone. To promote the integration of newcomers into the existing social structures of the old residents the strategy

1. Promoting social cohesion

should be taken serious and implemented by various means. On the other hand, it needs to be questioned whether such a homogenisation of the social structure is desirable. If not, specific strategies that support the retention of the less prosperous inhabitants and avoid gentrification have to be implemented before the out-migration of this actor class starts. The calculated scenario underpins the importance of:

2. Managing the direction of sprawl

as an increasing number of well-off people will build houses and probably try to get environmentally preferential locations, thereby generating a splinter development which damages the landscape and generates high infrastructure costs. These costs could in principle be borne by the future well-off inhabitants. Therefore the strategy of:

3. Ensuring the infrastructure by private investors

could be successful. But it should be kept in mind that such a policy would reinforce the tendency of social homogenisation towards the high income actor classes.

Wirral/Liverpool

Current strategies for the control of sprawl in Wirral include:

1. increasing employment opportunities in the inner city;
2. improving the environment of urban neighbourhoods;
3. restricting development on peripheral land.

The first two strategies particularly concern the improvement of the inner city of Birkenhead and Liverpool - the latter instrument affects the outer areas Both factors are related to the model as they change the attractivity for the different actor classes for the different zones. They will potentially alter the population dynamics in comparison to those calculated without these interventions.

The strategies concerning the outer areas aim to reduce the supply of peripheral land. In the model this is represented by an increasing price for available premises. Certain actor classes are sensitive to price changes and the attractivity of the zone for these actor classes decreases. The questionnaire survey revealed that professional and managerial households with children, lower-middle class households and 'other' households are especially price sensitive and would therefore tend to move out of the zone. The model shows that it is important whether lower-middle class households or 'other' households move out first. If the lower-middle class households increase first it is likely that Outer Wirral would develop into an attractive zone for other actor classes. But, if 'other' households migrate there first then the opposite trend is more likely. The zone would become less attractive to the retired, the professional households with children, the lower-middle middle class, which successively move to other zones.

If this development can be pursued and in combination with the instruments that valorise the existing urban areas a re-urbanisation process seems possible and another strategy was to:

4. secure social mixing in residential neighbourhoods

The model shows that all actor classes move away from 'other' households since they decrease the perception of a low crime and quiet neighbourhood, as it was postulated (Witt, Clarke et al. 1998; Fagan and Freeman 1999; Carmichael and Ward 2000; Carmichael and Ward 2001; Raphael and Winter-Ebmer 2001; Lagrange 2003). It needs to be underlined that this does not correlate with actual crime rates (People not Profit

Newssheet, 2001[i]) but is the result of how people perceive the presence of others (Taylor and Jamieson 1998; Jefferies and Swanson 2004). Apart from that, all other actor groups show a quite similar development, in the way that they are willing to move to other areas successively, independently from the other actor groups except 'other' households. Therefore the issue of social mixing and integration seems a challenging but crucial task for the Wirral area.

Vienna

There are two levels of intervention proposed for the Vienna region. Many problems with Vienna's urban development, e.g. urban sprawl, seem to be associated with the fact that there are three different administrative units responsible for Vienna and its surrounding. Therefore strategies have been proposed that

1. Raise awareness, improve communication and set joint databases for the co-operation between different levels and divisions of government..

These strategies act on an organisational meta-level which is not explicitly incorporated in the model approach since here only moving actors (in contrast to administrative actors) have been taken into consideration. Nevertheless one can argue, if the results of the endogenous dynamics under current planning procedures do not lead to a favourable development, planning structures have to altered and adjusted.

The second level of planning recommendations concerns strategies which aim at specific aspects of urban development and are thereby related to the model assumptions and results.

Here it was suggested that there should be:

2. provision of flexible housing developments dependent on personal biographies, including alternatives to the single-family house;

Simultaneously the image of housing types other than single-family houses needed to be improved. A further strategy called for:

3. flexible, customer oriented planning of business locations.

Both strategies 2. and 3. concern the future share of actor classes. If one looks at the model results it is possible to predict what kind of housing and businesses might be needed in the future. For example in the outer city zone K3 (south-western municipalities of Gänserndorf-district) in the final state of the modelling for this zone all actor classes except of the middle-aged DINKs are increasing. Therefore all kinds of housing and shopping needs will be demanded, for couples, families and retired people: a broad range of housing forms and local business would be necessary.

In the peripheral zones A3a and A4a (eastern municipalities of Tulln-district) the model suggests that there will be a high demand for the requirements of seniors and middle-aged DINKs. Therefore, there will be a need for housing and shopping facilities for people from medium age (30 years) onwards. There will be less demand for family houses and the needs of younger DINKs. An additional specific strategy asks for:

4. ecological 'consequential charges' after spatial development activities.

Regarding this point we can assume that such a strategy will affect more intensively the socially middle or lower actor classes than it will touch upper class people. The most financially stressed actor classes are young families and single parents. Both actor classes have increasing populations in the final state for the projection of K3. This means that the implementation of such a strategy of charging the ecological consequences will perhaps hamper the development in region K3 but also result in a driving out middle class people, who at present contribute to the social mixture in this zone.

7.9. Conclusions

It is possible to demonstrate that an approach to urban sprawl which is based on classes of moving actors and the qualitative characterisation of their interactions is able to reproduce observed trajectories of urban development. This means that the actor-oriented approach can yield some important insights into the process of urban sprawl. Sprawl can be understood in part as a socially generated and reproduced process of actors' decisions. The characteristics of actors, their preferences towards a certain attractivity and their interactions on this attractivity represent important issues for sprawl. Projections generated with this approach have - due to their qualitative nature - more the character of scenarios (exploring possible futures) than of predictions resulting from quantitative modelling. This fits well with recent understanding of an adequate mapping of the future of human systems (Laumann et al., 2006) and respects the local situations.

We regard this feature of qualitative modelling as a strong advantage: local experts and planners are given decisive insights into the process whereas the decision about the implementation of specific appropriate instruments is left open to them. This can ensure a very interdisciplinary approach which could support the decision-making processes of politics and planning.

We defined clearly the borders of the system to be modelled by exogenising various macro-influences and considering them as well defined boundary conditions. This does not mean that these are of minor importance, it just means that we do not think that it is possible to explain them sufficiently with a formal mathematical model.

On the other hand this choice of model boundary reflects one of the main problems of steering urban development: how do endogenous mechanisms (of markets, social relations etc.) interact with exogenous attempts to intervene. The method of qualitative modelling is very appropriate here as it preserves the uncertainty of the outcome of opposed effects - so we frequently get less specific results than from quantitative modelling but the results are more reliable.

In the preceding section we showed the kind of policy assessment which is possible with a qualitative actor based system analytical approach to urban sprawl. One conclusion is that social mixing seems an important issue influencing urban sprawl in the European context (as, e.g., reported in Canada by Filion, Bunting et al. 1999). Frequently, the price driving impact on the property market by a well-off actor class is an obstacle to social mixing while other influences such as age structures, seem less important.

Another very important result is the recognition that the local situation is of high importance with regard to policy success. The implementation of a specific instrument in one case study area did not necessarily have the same impact on spatial development as in another. Frequently, to be successful, measures have to address different actor classes specifically, as shown in Leipzig concerning densification and in Värmdö concerning the limitation of sprawl. In contrast a uniform implementation of measures will often be not sufficient (see also Kasper 2003).

We have to assume that there is some persistence in the quality of actor classes (e.g. in their preferences) and the structure of their interactions. Under these conditions valid statements on consequences of external interventions are possible. One has to keep in mind that structural persistence is a much weaker assumption than trend persistence which is still assumed in many practical policy assessments.

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Appendix.

General Formulation

Attractivity *A* of a region *i* (*i = 1,...,n)* for an actorclass *k (k = 1,...,m)* depends on the populations P_{ik} of all actor classes in this region: $A_{ik} = A_{ik}\left(P_{i1},...,P_{im},\right)$.

Dynamic equations for the attractivity-migration approach for n regions and m actor classes:

$$\sum_i P_{ik} = P_k \qquad 0 \le P_{ik} \le P_k \qquad A_{ik} \ge 0$$

$$\frac{dP_{ik}}{dt} = \sum_{\substack{l=1 \\ l \ne i}}^{n} A_{lk}\left(P_{l1},...,P_{lm}\right) - (n-1) \cdot A_{ik}\left(P_{i1},...,P_{im}\right)$$

In its qualitative formulation the right hand sides of the above equations are only defined by the signs of their partial derivatives

$$s_{ikj} = sign\left(\frac{\partial A_{ik}}{\partial P_{ij}}\right)$$

which denote for each region *i* how its attractivity for actor class *k* is influenced by the population of actor class *j* in this region.

Reduced Formulation

If one exogenises the attractivity development for all actor classes *k (k = 1,...,m)* in all regions except the sprawl region the endogenous dynamics is described by the following m differential equations:

$$P_k \geq 0$$

$$\frac{dP_k}{dt} = A_k\left(P_1,...,P_m\right)$$

Again, in its qualitative formulation the right hand sides of the above equations are only defined by the signs of their partial derivatives

$$s_{kj} = sign\left(\frac{\partial A_k}{\partial P_j}\right)$$

which denote how the attractivity for actor class *k* is influenced by the population of actor class *j* in the sprawl region.