PUMA: MULTI-AGENT MODELLING OF URBAN SYSTEMS

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Abstract: It is increasingly recognised that land use change processes are the outcome of decisions made by individual actors, such as land owners, authorities, firms and households. In order to improve the theoretical basis of land use modelling and to represent land use chnages in a behaviourally more realistic way, we are developing PUMA (Predicting Urbanisation with Multi-Agents), a full fledged multi-agent system of urban processes. PUMA consists of various modules, representing the behaviours of specific actors. The land conversion module describes farmers', authorities', investors' and developers' decisions to sell or buy land and develop it into other uses. The households module describes households' housing and work careers in relation to life cycle events (marriage, child birth, aging, job change etc.) and also their daily activity patterns. The firms module includes firms' demography and their related demand for production facilities leading to (re)location processes.

The paper describes the model specification and calibration of the households module. The households module was implemented and tested for the Northwing of the Dutch Randstad, including about 1.5 million households and 1.6 million dwellings. The paper describes the implementation and the first model results.

Keywords: multi-agent models, integrated land use transportation models

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1 Introduction

For more than four decades, social scientists have developed simulation models of land use conversion processes to assess social and environmental effects of land use changes as well as the sustainability of land use policies or to examine the interaction between transportation and land use development (Lowry, 1963; Wegener et al., 1991; Waddell et al., 2003).

Traditionally, land use changes and urban development have been modelled using aggregate models, based on zonal information (see Timmermans (2003) for a review). Notwithstanding their usefulness in many applications, a drawback of these models is their weak theoretical basis. In particular, they describe land use patterns as the outcome of an allocation process at the zonal level, which is hardly linked to the behaviours of relevant stakeholders. Even if behavioural models, such as discrete choice models, are used, they are commonly applied at an aggregate level. Moreover, these models are focused on the existence of equilibrium, whereas in reality land use is an ongoing process rather than an end state. This is especially problematic since spatial policies usually have a long temporal stretch, affecting citizens throughout the process (Batty, 2005). Finally, the theoretical basis of these aggregates models becomes increasingly less appropriate due to the dominance of the service sector and information technologies, and the shift from regulatory planning to developmental planning. As a consequence, the models should not treat zones, tracts and grid cells as the decision makers shaping a particular city, but actors such as households, firms, institutions and developers. Also, policy makers have become increasingly interested in such issues as regeneration, segregation, polarisation, economic development and environmental issues (Batty, 2005), which require analyses on the individual level.

This paper is based on the contention that agent-based models with their focus on individual actors deserve exploration as they potentially do not share the theoretical weaknesses of conventional models and offer considerable flexibility in modelling behavioural processes by applying validated theories and calibrated models. The use of agents offers the opportunity to apply advanced behavioural models to represent agents' behaviour in a more realistic way. In addition, it is possible to model agents as more advanced cognitive units, which are able to display pro-active behaviour, engage in long term planning and learn about their environment. Another advantage of the use of agents is that interactions and feedback effects at various levels can be modelled (see section 2).

Having noted the potential advantages of agent-based modelling of urban systems, it should be noted that operational agent-based models of larger (metropolitan) urban systems are still scarce, or limited in scale and scope (e.g. Benenson et al., 2002; Mathevet et al., 2003) especially since the increased level of detail required for agent based modelling implies many new challenges in terms of computational algorithms, data organisation and model architecture. This paper describes ongoing work on the development of an agent-based model PUMA (Predicting Urbanisation with Multi Agents), aiming at the operationalisation and application of an agent-based model of urban systems at the metropolitan scale (the Northern Dutch Randstad). The paper describes the conceptual model, the first phase of operationalisation and first application of the model.

2 Conceptual model

2.1 Objectives and scope of the PUMA model system

We start from the principle that changes in land use take place in response to individual and/or societal needs, such as the need for housing, commercial buildings, recreational facilities, infrastructure etc. In turn, these needs arise from activities that individuals, households, firms and institutions want or need to realise, implying that a model of urban development should in some way represent changes in the populations of these agents, changes in their intended activities and changes in their need for physical facilities. The objective in developing PUMA is to represent these changes in a theoretically and behaviourally sound way, using state-of-the-art models of individual and institutional choice behaviour.

In particular, the PUMA system includes various processes that in one way or another influence the urban system (see Miller et al., 2004):

1. The evolution of the population through demographic development (birth, death, marriage, divorce etc.), but also though both internal and external migration. Population development is considered a basic driver for land use development, since it determines the demand for dwellings of various kinds. Also, the spatial

distribution of population may determine the location of commercial activities that need the proximity of market of labour force.

2. The evolution of firms (and organisations in general) in terms of their ' birth' , location decisions and development of number of jobs. Not only are firms, through their demand of facilities, a driver of land use change. Through the supply of jobs, they also influence the spatial distribution of population.

3. The evolution of the land use system. That is to say, the conversion of land (farm land, nature) into other uses (residential, commercial), which is the outcome of decisions made by owners (farmers, real estate owners, authorities) and buyers (developers, investors, authorities). We hypothesize that the decisions of these actors are at least to some extent based on the demand for dwellings and commercial buildings, stemming from processes 1. and 2.

4. Daily activity and travel patterns of individuals and (workers in) firms and institutions. These activity patterns are important for various reasons. First, they have to be carried out within the current spatial system, and in that sense generate demand for facilities (stores, work places, recreation, schools) and transportation infrastructure. If one of these is insufficient (or if the demand of an individual/household/firm changes) this may lead to adaptations such relocation or suppression of activities. In the latter case, a demand exists for facilities or infrastructure, which may trigger changes in the physical spatial system (e.g. additional development of residential area). Second, it is through the generation and execution of daily activity patterns that mismatches between demand and supply become evident, changing the perceived quality of the urban system and possibly leading to adaptations. For instance, if demand for road space is too high, congestion will occur, leading to deterioration of accessibility and possibly causing households or firms to relocate.

The description of these fundamental processes illustrates that the mutual interaction between these processes (Figure 1) occurs through interactions between individual agents or between agents and higher-level components of the system. These interactions are discussed in more detail in 2.4.

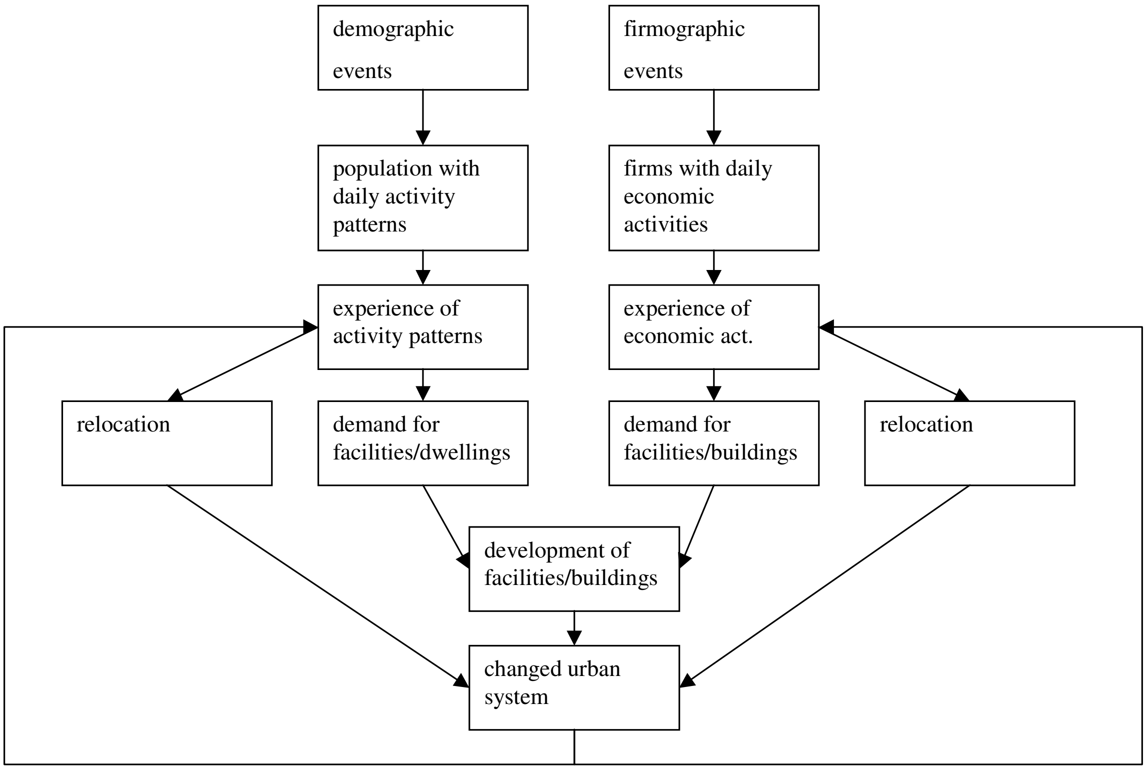

Figure 1: interaction between system components

2.2 Components

The PUMA system consists of various components. First, the spatial land use system is represented as a grid-based system, which serves as the spatial reference point of agents. Each grid cell is defined by the coordinates of its centre point. In addition, the grid cell contains spatial characteristics, such as the number of inhabitants, dwellings, firms, jobs etc. and the accessibility level of the cell to jobs or population. The grid cell may also inherit properties of larger spatial units (such as TAZ zones) in which the grid cell falls.

In PUMA the grid cells serve as containers of smaller, spatially fixed, units, such as dwellings, commercial buildings, social and recreational facilities and jobs. Each dwelling, commercial building and job is defined as an individual agent, which carries attributes such as dwelling type, market value, size (in case of dwellings), size, market value and functionality (in case of commercial buildings) and sector, required education level and salary (in case of jobs).

To simulate daily activity and travel patterns, a transportation system is required that connects the potential activity locations, and defines the travel times between locations, accounting for the effect of traffic intensity on travel speed. For this purpose, transportation networks for car traffic, public transport and slow modes are used in a very similar fashion as in numerous transportation studies. The connection between the spatial system and the road network takes place on the grid cell level.

The drivers of the urban system are active, spatially non-fixed agents such as individuals (organised in households), firms (or non-commercial employers) authorities, land owners (e.g. farmers) and developers, who either use of the urban system through their activity patterns and (re)location behaviour or directly change the spatial or functional characteristics of it (see 2.3). The agents are connected to a number of base locations, such as dwellings or work places.

2.3 Agents' behaviours

2.3.1 Households/individuals

As noted before, households are one of the main drivers of urban development. Through their emergence and evolution they create a demand for dwellings and facilities like schools, jobs, stores, recreational facilities etc. which triggers the development of such facilities in reality, either through developing undeveloped areas or through redevelopment of existing urbanised areas. Also, by residing or working in certain areas, the households determine the characteristics of neighbourhoods and the attractiveness of such areas for other households. As a consequence, the relevant behaviours of households include demographic events, residential choice and work location choice. In addition, households' daily activity patterns are of importance, as these determine, on an aggregate level, patronage levels of infrastructure and facilities, leading to negative externalities such as congestion and pollution. Also, these externalities are experienced in the daily activity pattern, for instance in the form of congestion.

(Re)location decisions

Demographic events like getting married or cohabitate, having children and leaving the parental house will be determined by factors such as age, gender, education level, work status and cohort (e.g. attitudes towards marriage, career and parenthood may change considerably within a generation). These demographic processes are modelled using empirical data of life trajectories.

Regarding the (re)location behaviour of households, an elaborate discussion of the approach is given in Devisch et al. (2005). In this paper, we will only discuss some key aspects. We assume that agents will try to optimise their lifetime utility. For instance, if we term the utility experienced in dwelling *d* in year *y* as U_{dy}, households will try to maximise:

$$U_d = \sum_{y=1..n} U_{dy} \rho_y \quad (1)$$

where *n* is the length of a households planning horizon and ρ_y is a discount factor to represent that short term utility may be more important than longer term utility. The utility given household and dwelling characteristics, U_{dy} can be defined as:

$$U_{dy} = U_{by} + U_{ly} \quad (2)$$

where U_{by} is the utility derived from the remaining monetary budget after housing expenditures. This reflects that households make tradeoffs between the budget to spend on housing and the budget to spend on consumption of goods. The utility U_{ly} reflects the direct utility of living in a particular dwelling, depending on characteristics of the dwelling and the surroundings.

Obviously, when a household first chooses a residential location (dwelling) it will choose the dwelling *d* yielding the highest utility U_d. However, if a household already lives in a dwelling, it may occur that an alternative dwelling *e* is available, with a higher utility U_e. The decision to move will then depend on the gain in utility traded off against the transaction costs of relocation.

As noted by various authors, housing relocation is a process consisting of various stages. The first stage, called awakening, implies that a household becomes aware of the fact that it can improve its utility by moving to another dwelling. This awareness can be caused by various factors. An important classification of triggers is into push and pull factors. The push factors are related to changes in the household or in the living conditions, such as a change in household composition or finding a new job elsewhere. Pull factors are related to the opportunity to find a better dwelling elsewhere. Note that the attractiveness of alternative dwellings may increase over time as a result of for instance growing income or changed household circumstances.

The process of relocating to another dwelling is now conceptualised as follows. First, as defined earlier, a household derives a lifetime utility U_d from the current dwelling. In addition, a household will have a perception of the housing market. In particular, it will have some idea of the utility to be derived from the most attractive dwelling available in the market. If we term this utility abstract utility (denoted U_a), a household will decide to start searching for another dwelling if $U_a > U_d + \tau$, where τ represents tranaction costs. An important implication is that the decision to start searching for another dwelling may be due to a decrease in the current utility U_d, but also to an increase in the perceived abstract utility U_e.

It is noted that the availability of an alternative dwelling and its utility depends on the household's perception of the market. Building up this perception may take place in a gradual indirect way, such as by coming across advertisements and newspaper articles, but also in a direct way by receiving a direct offer (e.g. a family member or friend selling his/her house). Once a household perceives that the utility of alternative dwellings is higher than the current utility, it will actively explore its options and possibly move to another dwelling.

Work participation and location choice

An agent's work situation determines his income and through that where he can afford to live. In addition, work location choice is relevant since the spatial distribution of jobs affects the spatial distribution of residents. In our modelling approach we have treated work status by developing a model that describes the probability that an agent works as a function of gender, education level, age and life cycle.

Work location choice resembles residential choice in that workers will choose one out of a set of available jobs, based on considerations such as salary, job type, distance to the dwelling, and personal preferences regarding type of organisation etc. In the current era where dual income families are the norm, distance between the current dwelling and the job, possibly implying the need to relocate the household, is increasingly important. However, multiple candidates usually apply for one job. This implies that the labour market can be depicted as a real market, with a demand for workers by firms and institutions, and a supply of labour by individual workers. With respect to changing jobs, we hypothesize that workers will trade-off the utility from their current job against the potential utility (in terms of salary or other factors) of another job. Again, this perception is based on job advertisements, job changes by friends and relatives etc.

Daily activity patterns

Daily activity patterns are of importance, as they constitute the confrontation between the physical urban system and individuals' behaviour. On the one hand, the aggregated individual behaviours lead to system user levels and externalities such as congestion and pollution. On the other hand, it is through their daily trips and activities that individuals/households experience the externalities and respond to them, for instance by relocating their residence or job. Since the objective of the PUMA system is to represent changes in the urban system as the outcome of agents' behaviours and to represent these behaviours in a realistic way, we argue that the daily activity and travel patterns should be modelled using activity based models.

2.3.2 Firms/institutions

Firms (and non-commercial employers) are of importance as they influence the urban system by locating on a particular place, affecting the spatial distribution of jobs and the use of the transportation system. The main challenge in agent-based modelling is to represent firms' behaviour in a behaviourally sound way. That is to say, firms are represented as individual agents that can be started, develop (in terms of number of employees), search appropriate locations in various stages of development and hire employees. Thus, firms are related to fixed agents such as business estates and spatially non-fixed agents such as individuals who work for them. De Bok and Sanders (2005) give an example of modelling firms' location behaviour, which depends on accessibility levels, distance to the old location, agglomeration considerations and land uses in the surroundings. An example of modelling the demography of firms can be found in Van Wissen (2000). Inclusion of firms' spatial behaviour in PUMA is planned for the coming months and will not be discussed in further detail in this paper.

2.3.3 Land use conversions

Changes in the spatial distribution of population and economy can also occur through the conversion of land to other uses. For instance, changes in agriculture may lead to transitions of agricultural land into residential, commercial or recreational use. With respect to the conceptualisation of land use conversion processes, we posit that the owner of the land has the strongest influence on what will happen to the land and in fact takes the decision about the land use. We assume that associated to each grid cell is a landowner, who is characterized by attributes such as:

1. type of owner (farmer, developer, private person, authority etc);
2. spending power (which investments can be made);
3. technological and managerial knowledge.

At each point in time, a landowner can decide to (see Hunt et al., 2003):

1. leave his land as it is:
2. develop his land by changing the land use and exploit it;
3. develop his land by changing the land use and sell it;
4. sell his land to another owner.

However, for some owners the options are more limited. For instance, a farmer cannot develop his property into residential area, as he lacks the necessary investment power and skills. Also, not all actions may be allowed given planning regulations. To start, we distinguish between three types of owners with specific options: farmers (options: exploit, sell or buy), authority (options: keep, sell to farmer, sell to developer or develop and keep), and developer (options: develop and sell, (re)develop and exploit, sell).

Ultimately, the decision which action to take depends on the expected utility of each alternative to the owner. In case of *commercial owners* utility will coincide with profitability: the action that delivers the highest profit will be taken. In case of authorities, also social benefits will play an important role, whereas for farmers personal and emotional reasons may affect their decision.

An important factor in deciding whether or not to sell the land (with or without developing it) is the market price. According to the agent-based perspective chosen in his study, the market price depends on the willingness-to-pay (WTP) of other agents. Also in this case, the profit that can be made with the land will be an important factor for the WTP. However, also non-commercial values, such as the natural quality of land, can play an important role. The factors that we assume to influence a) owners decisions to sell, exploit or develop b) their WTP are the profitability of land in its current and new use, conversion costs of the land, the land price, the demand for dwellings and real estate, the price level of dwellings and real estate, land uses in environment, environmental and liveability concerns and characteristics of the firm or organisation.

The fact that owners' decision to take particular actions also depends on other agents' WTP, suggests that in fact a market for land transactions exists, where sellers (e.g. a farmer) and buyers (e.g. a developer) negotiate about the price of a transaction. In this respect, both parties will base their negotiations on their perception of other transactions in the market, and buyers will also base their decision on their perception of the WTP of potential buyers after development.

2.4 Interactions and timescales

PUMA will encompass behaviours by various agents on varying time scales. Most of the behaviours (residential and job location choices by households, location decisions and growth processes of firms and land use development decisions) take place on a longer-term time scale and can be updated annually. Obviously, daily activity and travel patterns take place (and should be simulated) on a daily basis. When simulating urban systems over various decades, the simulation of daily activity and travel patterns will take place only for a subset of all days, but sufficiently frequent to represent non-daily activities such as social visits.

Interactions can, in PUMA, occur between system components on various scales (Figure 2). We distinguish between individual agents, the aggregate urban system containing every micro-level agent or component and markets, on which supply and demand of land, buildings and facilities takes place.

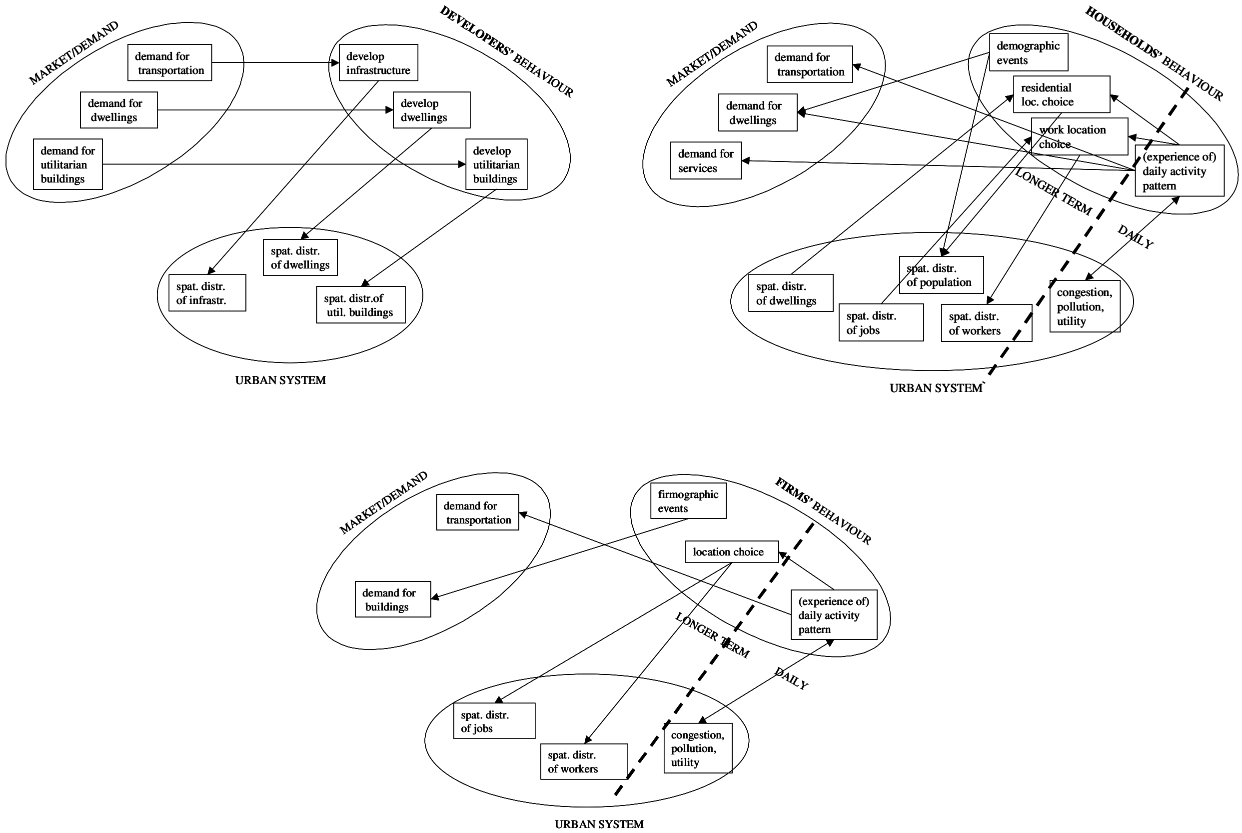

Figure 2: Interactions between agents and the urban system

Various interactions between system levels are hypothesized for households and individuals. Through residential and job location choice, households and individuals influence the physical spatial system in terms of the composition of neighbourhoods and concentration of workers. These can be considered aggregate system characteristics, which may in turn influence the behaviours of other households and firms. However, households display also short-term (or daily) behaviour in the form of daily activity and travel patterns. These may affect the physical system in a dynamic way, leading to temporary concentrations of congestion and pollution. Although temporary, these effects may affect other households' (re)location decisions. Another important aspect is that the experience of daily activity patterns may affect households' demands. For instance, the experience of limited options for recreation may lead to a relocation of a household and a demand for a dwelling in a particular area (or with particular characteristics). In a similar vain, demand for jobs may arise through daily experience. Finally, it is noted that also demographic events affect demands. For instance, the (anticipated) birth of a child may lead to a demand for a different dwelling, as may the desire from someone to leave the parental house.

Firms (or institutions) affect the physical system by their location choice. Through that, they affect the land use, the spatial distribution of jobs, but possibly also the spatial distribution of pollution and noise. Also, the flows of persons and goods to and from the firms/institutions results in the use of the spatial system with associated aspects such as congestion and pollution. Like households, if the utility of activity and travel patterns is insufficient (e.g. too much congestion or too few customers), the firm may decide to relocate to a more advantageous location, leading to a demand for commercial buildings and possibly an actual relocation.

To conclude, we note that an important form of interaction takes place on markets, where buyers and sellers (of land or buildings) or employers and employees negotiate the price and eventually try to make a deal. Modelling this process adequately is one of the main challenges in urban systems modelling. Important in this process are professional intermediates (brokers, recruitment agencies, real estate brokers etc.), which have access to databases of potential buyers and sellers and of transactions, and play a role in connecting buyers and sellers and setting the price. Therefore, we argue that higher-level agents such as brokers should be included in the model system.

3 Operational model

3.1 Scope of the operational model

This paper presents work in progress. To operationalize the PUMA system, we have decided first to develop a simple system, allowing for the possibility to exchange simple agents and agent behaviour with more advanced agents over time. In particular, the operational model focuses on households and individuals, as being the drivers of spatial development. Land use changes, brought about by developers, authorities and firms/institutions (and changes in the number of dwellings and jobs) are still exogenous to the model. Their daily activity patterns are also not simulated yet. Plans are to incorporate an updated version of Aurora (Joh, et al., 2003; Arentze and Timmermans, 2005).

3.2 Study area and input data

The study area consists of the northern part of the Dutch Randstad (see Figure 3). This area contains the major cities of Amsterdam and Utrecht as well as Schiphol airport. The area contains about 1.5 million households and 3.16 million inhabitants. The area is densely populated (950 inh/km2). In the next decades some 100.000 dwellings need to be constructed in the Randstad, a considerable part of which will be located in the study area. Due to the concentration of population and economic activity the area potentially suffers from negative feedback effects caused by congestion, noise and pollution.

Given the scale of the area and the potential effects, the area is an interesting test bed for the application of multi-agent models on metropolitan scale. The necessary data to run the model includes:

- Grid based spatial system, containing necessary spatial information: land uses/densities, facilities, accessibility levels, job availability;
- Transportation network, connecting zones/cells, and providing travel time matrix;
- Specification of individual dwellings: dwelling type, price and location (grid cell);
- Synthetic population of individuals organised in households, living in dwellings.

With respect to the spatial representation, the study area is divided into 500x500 meter grid cells. For each cell, data is available with respect to the available services, the percentage of public space and non-built area, the distance to arterials and highways, the number of jobs in various sectors and the accessibility to jobs and population. In addition, an OD matrix with travel times between each pair of cells was available.

For the base year 2000, a synthetic population was generated for the study area using Monte Carlo simulation as described in Veldhuisen et al. (2005). The synthetic dataset specifies households by the number of adults and children and the age of the household head. Using distributions, taken from CBS statistics, of age differences between spouses and between mothers and their children, an estimate was made of the ages of each household member. Based on the same statistics, the education level was drawn randomly.

Figure 3: Study area

To initialise households' residential location and individuals' work location discrete choice and regression models were used that were calibrated on the Dutch residential preferences survey (WBO) (see Table 1). First, using a logistic regression model, the working status of each adult individual was determined. Next, the income was determined using a regression model. Finally, once these items are specified, the residential choice model (see 3.4) that is applied in subsequent stages is applied here to assign each household to a particular dwelling. Each dwelling is defined as an individual agent, with characteristics such as dwelling type, price and neighbourhood characteristics. The dwellings are taken from the ACN database, specifying each Dutch dwelling by type and exact coordinates. Therefore, each dwelling can be assigned to a particular grid cell and inherits the properties of the grid cell.

Once each individual is assigned to a dwelling, the working individuals are assigned to a working location using a discrete choice model (see 3.4). The assignment takes place of work location choice. In this stage of development, we do not work with a one to one relationship between jobs and workers, but simply describe the choice of workplace as the choice of a particular work zone.

Table 1: work status and work location choice models

	Logistic regression model of work status (1= working)		Multinomial Logit model of work location choice
Constant	0.867	Commute distance	-0.092
Age < 25	0.462	HighEduc*commute dist.	0.055
Age 40-54	-0.336	Kids*commute dist.	-0.029
Age 55-65	-1.980	Female*commute dist.	-0.050
Mother	-0.401	# jobs within 30 minutes by car	$0.425*10^{-5}$
Male	0.845	# inhabitants within 30 min. by car	$-0.156*10^{-5}$
Male*Age < 25	-0.785	HighEduc*% office jobs	1.539
HighEduc*Age < 25	0.443	HighEduc*# of jobs	$0.938*10^{-6}$
HighEduc*Age 25-39	1.128		
HighEduc*Age 40-54	1.081		
HighEduc*Age 55-65	0.786		

3.3 Simulating events

Given the behaviours included in the current version of the model, all households and individuals are updated in time steps of one year. In each period demographic events, residential relocations and job changes can occur. In PUMA all events are simulated for each agent/household subsequently, in order to ensure consistency within households and individuals. First, the demographic events are simulated, followed by residential location choice and job changes. However, within the category of demographic events, the sequence of events is randomised. The demographic events are aging, giving birth, leaving the parental home, getting married (used as a unifying term encompassing also a couple that decides to start living together) and divorce (also a couple living together splitting up). All events are regarded as binary probabilities. The probability of any event to happen is defined in probability tables as a function of age, gender and (in the case of giving birth) marital status. It is important to note that some events are conditional on household or personal characteristics, such as age, gender, marital status and position in the household (see Table 2).

Table 2: Necessary conditions for events

Event	Necessary condition of S_t
giving birth	female, age 18+
dying	no requirements
leaving parental home	living with parents, age 18+
marriage	single or living with parents, age 18+
divorce	being married
moving	no requirements

These conditions imply that earlier events may rule out potential later events. Table 3 summarises which events are ruled out by events that take place earlier in the year.

Table 3: Consistency between events

Event	Rules out (for the same year)
dying	giving birth, leaving home, marriage, divorce, moving
leaving home to live single	Marriage
leaving home to marry	Divorce
marriage	Divorce
divorce	Marriage

We argue that each event is equally likely to take place on any day of the year, implying that each sequence of events is equally likely to happen. This leads to the following approach: (i) determine relevant events based on state S_t; (ii) randomly determine the sequence in which to simulate the events; (iii) simulate emergence of events (yes/no), taking into account the fact that earlier events may rule out later events; and (iv) define the state of the next year S_{t+1}.

Some events may produce new households. For instance, someone leaving the parental home to marry or live alone creates a new household. Those leaving the home to marry but also singles deciding to get married are collected in two pools of male and female marriage partners. From these pools new couples are created, based on a distribution of age differences between spouses, based on national statistics. All new households (both couples and singles) select a dwelling from the list of vacant dwellings, according to the residential choice models described in section 3.4.

3.4 Behavioural models

3.4.1 Residential choice model

Households' (re)location behaviour consists of two phases. First, a household builds up a perception of available dwellings on the housing market and its opportunity to improve lifetime utility by moving to another dwelling. Next, a decision is made whether or not to start searching for another dwelling and eventually to move. Ideally, the representation of this process would require the modelling of individuals' learning about the housing market through their perception of transactions as well as their negotiation process to acquire a new dwelling. However, in lieu of such advanced models, we decided to model this process as a nested logit model, with three nests from higher to lower:

1. decision whether or not to search for another dwelling (dependent on the characteristics of the current dwelling, but also on the expected utility of moving to another dwelling);
2. decision whether or not to move (dependent on characteristics of the current dwelling and on the expected utility of moving to another dwelling);
3. residential choice of one out of a set of available dwellings.

Table 4: Residential (re)location choice models

	Binary logit model: Search for new dwelling	Binary logit model: Move to a new dwelling	Mulitnomial logit model: choice of dwelling
Constant	-1.090		
Age < 35	0.242	0.262	
Age > 55	-0.446	-0.506	
Double income, no kids	-1.588	-2.736	
Price/Income	0.507	0.503	-0.00156
Income < 1000•/month	0.914	1.782	
Child < 12 years	0.941	0.929	
Lives in apartment	-0.601	-3.460	
Lives in app. With child	1.255		
Single	-0.683	-0.721	
Commute distance male			-0.117
Commute distance female			-0.109
Age > 55 * apartment			-1.195
Age > 55 * row			-1.144
Child * apartment			1.414
Child * semi detached			1.538
Child * detached			1.157
HighInc * row			1.470
HighInc * semi detached			1.288
HighInc * detached			2.357
3+HH * row			1.059
3+HH * detached			1.543
Adjusted ρ^2	0.33	0.32	0.34

Because this nested model did not converge, for now we used a set of separate MNL models, estimated using the Dutch WBO data set. The estimation results are displayed in Table 4. Important to note is the importance of the work location to residential location choice. Limiting the commute distance apparently is an important factor in residential choice behaviour.

New households, which emerge from demographic events such as home leaving and divorce, choose a dwelling based on the residential choice model in Table 4. For each existing households, we simulate subsequently whether the household searches for a new dwelling, (if so) whether the household will move and (if so) what new dwelling is selected. Households are simulated subsequently, each time followed by an update of the available housing stock.

3.4.2 Work location choice

Work status of individuals is also updated on an annual basis. In particular, based on the Dutch WBO, a logistic regression model was estimated, describing the probability of a person taking part in the work process (Table 1). According to the model, work force participation is a function of age, gender, having children and education level. Since the current model lacks history dependence, it is likely to overestimate the percentage of transitions, although the aggregate shares of workers and non-workers should be realistic.

If an individual switches from non-working to working he/she will choose a working location. Also, individuals not changing work status reconsider a change of work location each five years. In both cases, a work location is selected using a destination choice model that was calibrated on the Dutch WBO (see Table 1). Important to note is that distance from the dwelling is an important factor in explaining work location. This combined with the importance of commute distance in residential location choice suggests that changes in the spatial distribution of jobs and dwellings may both lead to changes in the spatial distribution of population and changes in commute patterns.

4 Application

4.1 Technical issues

The operational model is implemented in C^{++}, applying object oriented programming. Since for each simulated year, each household and each individual is updated, the simulation is quite time consuming. In particular, a total model run comprising of 30 years takes about 12 hours on a Pentium 4 PC. For each simulated year, data is stored on the individual level, allowing for the calculation of numerous statistics on various aggregation levels in post-processing procedures. An important tool in this respect is the visualisation of model outcomes per year in maps, based on grid statistics. These maps yield valuable insight in the spatial distribution of population segments in various policies.

4.2 Results and future applications

Figure 4 displays some demographic processes simulated by PUMA. The figure suggests that the total population remains rather stable for 40 years and then starts decreasing, especially due to aging of the population, leading to lower birth rates and higher mortality rates. The birth rate is rather high in the first 20 simulated years, due to the high proportion of population in the fertile cohorts (20-35 year). Given the low proportion of population in the cohort 0-20 year at the start of the simulation, birth rates drop gradually, with a temporary increase around 2035, when the first baby boom reaches the fertile age. Figure 4c also suggests that demographic events can be affected by urban system characteristics. Until 2030, the number of households that is created each year increases, especially, due to the number of people leaving the parental home. After 2030, the available housing stock can no longer accommodate the number of new households, leading to a drop in the number of newly created households. This is reflected in the drop in all demographic events leading to new households, such as leaving home, marriage and divorce. Overall, the demographic events appear to be logical given the input data, although we did not yet have the opportunity to check input data and outcomes against external data. Also, the results indicate the importance of interaction between demographic processes and spatial developments, such as regional housing stock development.

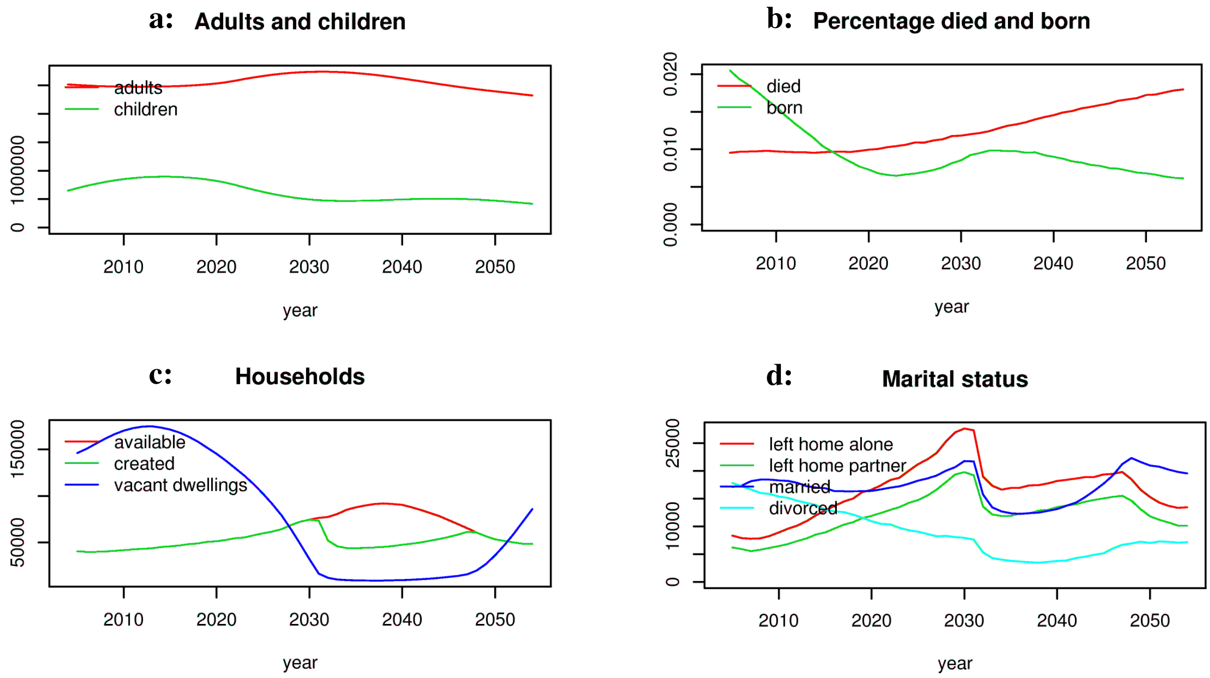

Figure 4: simulation of demographic developments

Figure 5 illustrates the development in spatial distribution of the population in relation to the urban system. In particular Figure 5a shows the number of vacant dwellings per grid cell, with high concentrations in the cities of Amsterdam, Utrecht and some smaller cities. Figure 5b shows that the concentrations of vacant dwellings have almost disappeared, due to the increase in the number of households that was also clear from Figure 4. In a similar vein, analyses can be made of the spatial distribution of for instance individuals in particular age cohorts, the proportion of working population or other socio-demographic segments.

The main conclusion from these first results, however, is that they support they feasibility of modelling urban processes on the ultimate disaggregate level of households/individuals on the metropolitan level. Although the system in its current form still lacks crucial processes such as firms'/institutions' behaviour, these processes will be computationally and memory wise far les burdensome, as the number of involved agents is far less. The feasibility of the approach in terms of computation time and data handling implies that a potentially very detailed and behaviourally sound model of urban dynamics can be developed, allowing for an the analysis of a variety of spatial effects at a much more detailed level than is possible in current aggregate models.

In the coming months the model will be tested more extensively. In particular, various scenarios, in which changes are made to the spatial distribution of housing stock or the distribution of jobs, will be evaluated to test whether PUMA produces plausible results.

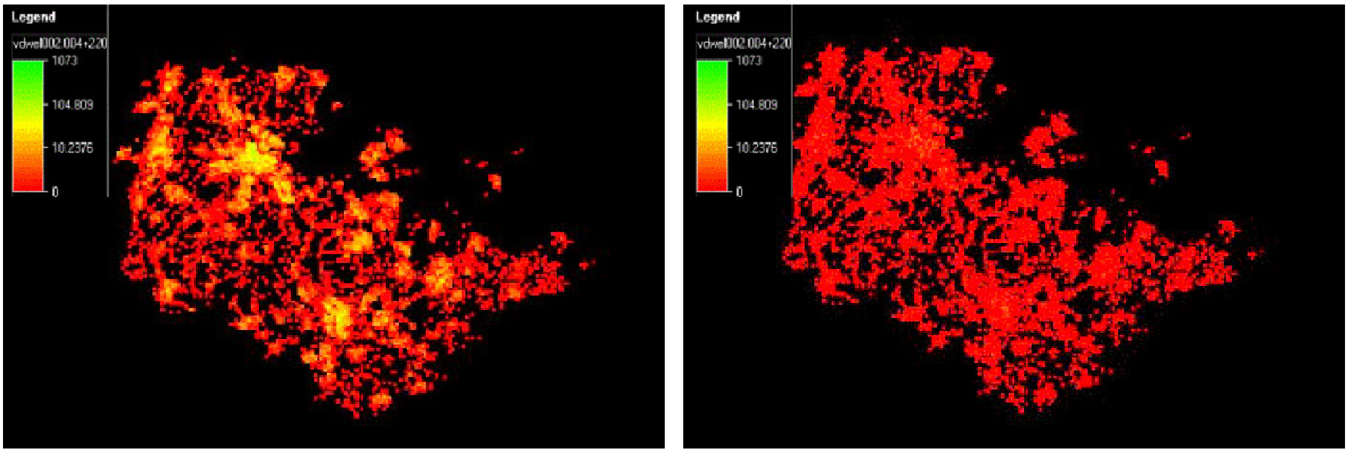

Figure 5: spatial distribution of vacant dwellings

5 Conclusions

In this paper, we have reported some results of the current implementation of the agent-based systems of land use dynamics, titled PUMA. Due to space limitations, we could only very briefly summarize the motivation underlying the system and the kind of models that are used. It is important to note, however, that the process of developing the system is to specify the scope and architecture, exploring the system first on the basis of easy to implement, well-know models and gradually replacing these with richer, new, behavioural models. Agents to be included in the future are for example cognitive agents capable of activity-scheduling and rescheduling behaviour, learning the environment and capable of adjusting their behaviour, agents for simulating housing search and choice, incorporating negotiation between developers and potential buyers in a dynamic context, and agents simulating life trajectories and their impact on transport decisions. These models have already been conceptualised and their implementation is now being tested.

Other agents, especially for firm demography and land use change need much more thinking though and development. This task is more difficult as firms and organisations are quite different and distinct. Moreover, data collection may be more difficult.

Despite the early stage of development, the simulation results reported in this paper, demonstrate the potential of an agent-based approach in terms of computation time and data handling. This implies that a potentially very detailed and behaviourally sound model of urban dynamics can be developed, allowing for an the analysis of a variety of spatial effects at a much more detailed level than is possible in current aggregate models

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