Spatial urban dynamics[*]
A vision on the future of urban dynamics:
Forrester revisited

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Abstract

The development of a dynamic spatial model of an urban area is described in this work. The system dynamics method is used to create a model that copes with the criticism on the original *Urban Dynamics* model (Forrester 1969) by disaggregating the urban area into 16 zones. It was found that the trajectory of the behavior (growth, overshoot and stagnation) in the Forrester model is observed in each zone, but the overall behavior of the city shows a relatively small overshoot. The zonal division creates opportunities to explain and understand the dynamic behavior within the city in a more satisfactory manner. Finally, it is concluded that the system dynamics method remains very useful for creating insight in urban management for urban planners and students, despite the fact system dynamics has never become an established method in the field of urban planning (Alfeld 1995).

1 Introduction

1.1 Urban development

Urban development is the growth process of urban areas. An urban area is traditionally defined as a system of interacting industries (figure 1), housing and people (Forrester 1969). Under favorable conditions the interplay between the parts of a new area cause it to develop. As the area develops and its land area fills, the processes of aging cause stagnation. As the urban area moves from the growth phase to the equilibrium phase, the population mix and the economic activity change. Unless there is continuing renewal, the filling of the land converts the area from one marked by innovation and growth to one characterized by aging housing and declining industry.

In this research, an urban area is defined as a system of interacting business structures, housing and people with an explicit formulation for the spatial component.

In figure 1, the system observed in this study is displayed. The behavior of the system is endogenously driven. The conditions within the system control the dynamics of the system and these conditions are part of various feedback structures. The urban system incorporates two markets:
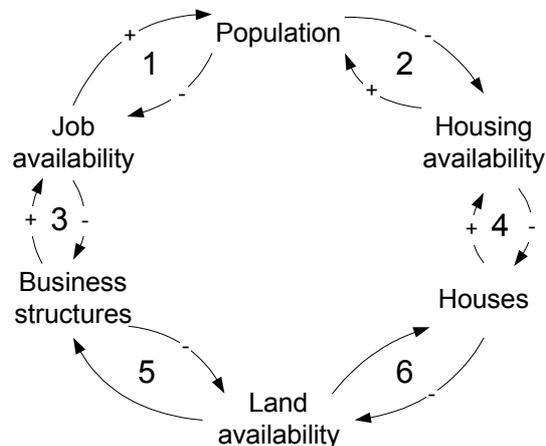1. Labor market
2. Housing market

Figure 1: Urban system area is a system of interacting sectors (Alfeld and Graham 1976)

Figure 1 shows that an expanding population can strain the area's resources. As the population increases the job availability (loop 1) and housing availability (loop 2) will decrease. The lower job and housing availability correspond with a lower attractiveness of the urban area due to perception of high rents, severe crowding, unemployment and low pay. The diminished attractiveness leads to less immigration and more out migration.

A high housing availability (4) leads to lower rents and therefore suppresses new construction of housing. Similarly in loop 3, a shortage of jobs implies an excess of potential employees, who are probably available on short notice and for low wages. This stimulates the construction of new business structures and expanding of existing structures.

The land availability modulates the construction of both housing and industry in a non-linear way (loop 5,6). When almost no land is occupied, an increase in housing and business structures stimulates further development because an area becomes more attractive, due better transportation facilities and more attractive potential for market growth. In the period that the area starts to approach full land occupancy, the construction of housing and business structures decline. The parcels that are developed last are probably fragmented and situated at the least desirable locations.

1.2   The problem of urban management

The problems in urban areas identified by Forrester (Forrester 1969) are still present. The municipality of Rotterdam (second largest city in the Netherlands) published a report (Rotterdam 2003), which identifies problems as urban decay, filtering down of housing and a large fraction of underemployed population in the city. In the report, a systematic approach is advocated.

The phenomenon that Forrester calls "counterintuitive behavior of social systems" (Forrester 1969, Forrester 1971) is as insightful as three decades ago. Counterintuitive

behavior or policy resistance (Sterman 2000) means that actions taken to alter the state of the system feed back (unanticipated effects) into the system. Unanticipated effects often arise in complex systems, like urban centers, because cause and effect are distant in time and space.

As explained in figure 1, a city is a complex system consisting of an interlocking structure of feedback loops. The system dynamics literature contains a large body of evidence stating that people are incapable of assessing the effects of their actions in a complex system (Paich and Sterman 1993). Urban planners encounter the same problem in their work. This leads to the conclusion that a simulation model can assist them in building understanding in the behavior of an urban system.

An example of policy resistance in urban management in the Netherlands is the policy whereby the underemployed population was subsidized so they could live in worker housing (in a neighborhood in Den Haag). The worker housing filtered down very fast because labor population left this neighborhood and the abandoned worker housing (economic obsolete) could only be filled with underemployed population. The urban planners underestimated or neglected the effect of social mixture on the migration. The result of good intentions to relieve the city of the pressure on underemployed housing market is a neighborhood with a poor image and prospects. The current mixture of the population and the characteristics of the neighborhood create the challenge of reviving this neighborhood.

The objective in this research is to build understanding in how urban areas develop as a result of the interactions between people, housing and business structures. This is vital in order to develop a good policy to alter the behavior of a system.

2 From urban dynamics to spatial urban dynamics

2.1 Traditional urban dynamics

Jay W. Forrester's well-known publication *Urban Dynamics* in 1969 introduced a new perspective on analyzing urban problems, forming a bridge between engineering and the social sciences. Today, this perspective is known as *System Dynamics*. The use of the system dynamics methodology to analyze socio-economic processes in order to simulate urban development is called *urban dynamics*.

The traditional urban dynamics models define an urban area as a system of interacting industries, housing and people. The area:

> *Could be the political boundary of a city but usually will differ. The area treated here (in urban dynamics) would be only a part of our larger cities. The appropriate area is small enough so that cultural, economic and educational interchange is possible between its component populations. It could be a suburban area or the core area of a city but probably not an area containing both (Forrester 1969).*

Figure 2 illustrates this definition. A suburban area would be considered part of the environment or an endogenously driven system of its own.
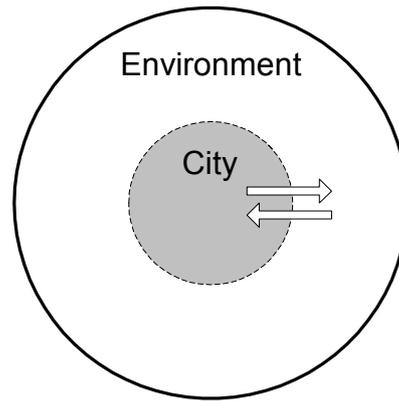
Figure 2: The urban area in its limitless environment

The urban area is represented as a social system set in an environment with which it communicates. People can move in and out of the area. The flow to and from the city depends on the relative attractiveness compared to its surrounding environment. Conditions in the surrounding environment are taken as a reference (which can change) the attractiveness rises or falls with respect to that moving reference. The attractiveness of the area, compared to its environment, depends on the conditions and the activities within it. The environment is taken as a limitless source. It can absorb or supply people as long as the area is more attractive respectively less attractive. These three concepts:
1. specific area;
2. relative attractiveness;
3. limitless environment;
are important in understanding the model of urban processes.

The boundary of the urban system
The boundary is chosen so that it includes the concepts that interact to produce the behavior of interest. In the classical urban dynamics model, this behavior is the growth, overshoot and stagnation of an urban area. Urban growth, overshoot and stagnation do not appear to require changes in the world environment as a cause. The behavior of a city is much more directly dependent on its own economic merit and its changing internal mix of industry, housing and population. It is assumed that an urban area in the urban dynamics models is small enough in the world setting not to affect the outside environment. The urban area is therefore taken as a living system that communicates with an environment it does not influence.

Relative attractiveness
Using the environment as a reference point means that conditions within the urban model are generated relative to the environment. The model shows how the area becomes more or less attractive than the surrounding country and other cities and thereby causes the movement of industry and population to and from the area. Only differences between the area and environment are significant. The model does not deal with changing technology and rising national standard of living as it assumes these developments to be equal for the urban area and its environment.

2.2 Reviewing urban dynamics

The publication of *Urban Dynamics* in 1969 documents one of the most insightful applications of the system dynamics (SD) methodology. However, the book generated

intense controversy (Alfeld 1995). The fundamental criticism on the methodology of urban dynamics breaks down in three parts:
1. the boundary problem;
2. the problem of the limitless environment;
3. the use of data

The boundary problem
The problem of choosing the system boundary in a way that its environment does not substantially influence the system and vice versa is called the boundary problem. The main criticism deals with the perceived exclusion of interactions between the city and its suburbs (Graham 1974; Gray, Pessel, and Varaiya 1972; Rochberg 1972).
In the eyes of critics there are a number of observations that invalid the assumption that its environment does not substantially influence the urban area (Garn and Wilson 1972). First, the urban dynamics model does not include commuting across the boundary; people who work in this city reside there. Second, the model rules out the possible effects of actions taken to improve the situation in the city on the larger society, by the choice of the closed boundary.
In other words, critics challenge the principle that the system does not influence its environment in significant way. They question the assumption that the dynamics of cities are endogenously driven.

The problem of the limitless environment
The unlimited environment means that people are available from the outside for migration into the area whenever the area appears more attractive than the point from which people may come from (and vice versa). In this formulation, the limitless environment is actually the rest of the universe.
Babcock (Babcock 1972) and Gray (Gray, Pessel, and Varaiya 1972) observe that the majority of people in the US live in cities. Thus, the environment should be viewed as a collection of cities. This naturally leads to the criticism that Forrester's model encourages local (citywide) optimization rather than global (national) optimization.
The concept of the limitless environment omits the spatial dimension. The development of the city Amsterdam in the Netherlands will be hardly influenced by its relative attractiveness compared to a town in China. However it will be influenced by the attractiveness of the satellite city of Almere.

The use of data
The urban dynamics model was formulated without recording empirical data. Therefore the model specifies a hypothetical city. Garn and Wilson explain this point as followed (Garn and Wilson 1972):
> *It is one thing to make the methodological point that the latter functions (parameters and multiplier functions) should be nonlinear. It is quite another to know what the critical functions are, as well as their range and shape. Again, there is little empirical support provided for the assumptions.*

This point of criticism is well known for SD applications in general. The standard response of SD practitioners is that it is better to include an estimation of a variable than omitting this variable, in other words denying its influence (Forrester 1969; Forrester 1980). The value of the mental database is emphasized in the urban dynamics model (Forrester 1969).
The use of the data invalids the results of the Forrester model (Gray, Pessel, and Varaiya 1972). Forrester draws general conclusions from his specific model.

Alternative data should be presented to valid the policy recommendations (Jaeckel 1972).

System dynamics practitioners reacted on the criticism in *Readings in Urban Dynamics volume I* (Mass 1974) *and II* (Schroeder, Sweeney, and Alfeld 1975).

2.3 Building on the insights of urban dynamics and its critics

2.3.1 The reaction on the criticism

The most fundamental criticism concerns the boundary choice of the urban dynamics model. In a reaction to this criticism Walter Schroeder (Schroeder 1975) formulates an alteration of the Forrester model to include the relationships between the city and its suburbs, similar extensions are made by Kadanoff (Kadanoff and Weinblatt 1972), Laudet and Fournier (Laudet and Fournier 1979; Fournier 1986).
The research suggested by Kadanoff is comprehensive, however the formulation for the interaction between the different sub sectors is primitive. Burdekin (Burdekin 1979) divides the city in 16 zones for which the construction rates of different housing types and business structures depend on a combination of citywide and zonal characteristics. The development of the population is not disaggregated but specified like in the Forrester model.

Figure 3 illustrates the development of urban dynamics research described in the section above.
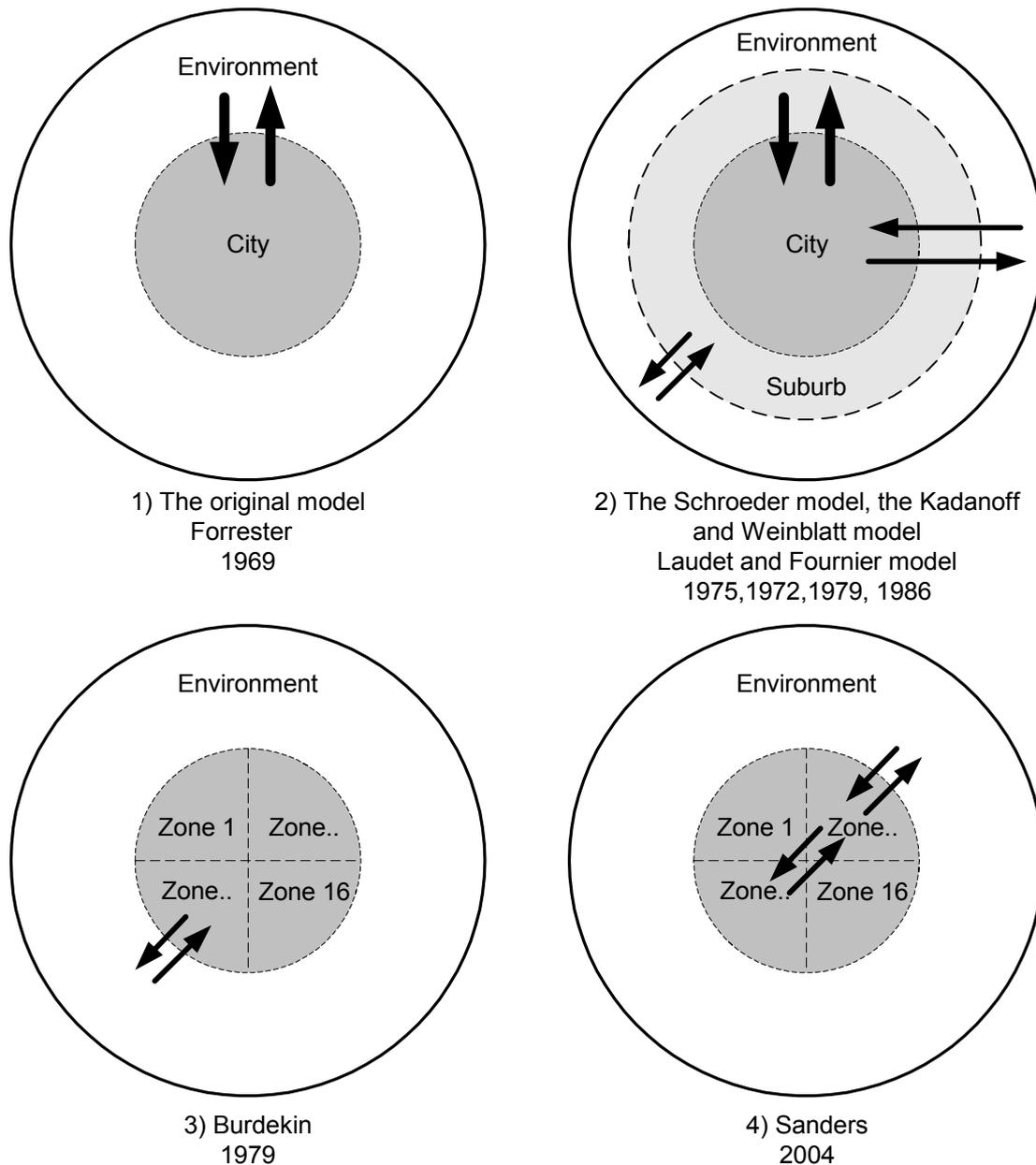
Environment

City

1) The original model
Forrester
1969

Environment

City

Suburb

2) The Schroeder model, the Kadanoff
and Weinblatt model
Laudet and Fournier model
1975,1972,1979, 1986

Environment

| Zone 1 | Zone.. |
| Zone.. | Zone 16 |

3) Burdekin
1979

Environment

| Zone 1 | Zone.. |
| Zone.. | Zone 16 |

4) Sanders
2004

Figure 3: The development of the spatial dimension in Urban Dynamics

All the research mentioned in figure 3 utilizes the attractiveness principle to regulate the migration flows (between the city, the environment and zones). Therefore it is important to understand how this principle works. The basic assumption is that there is a normal fraction of residents that migrate into the city (zone) or out of the city (zone). These normal fraction rates are modulated by the attractiveness of the city compared to its environment (which has attractiveness '1') or other zones. Alternatives for this formulation are logit models or gravity models (Wilson 1974) where the available residents will be allocated again and again every time step.

Schroeder 1974 and Burdekin 1979
The model of Schroeder will be discussed briefly in this section. In figure 4, the simple feedback relation model is formulated.
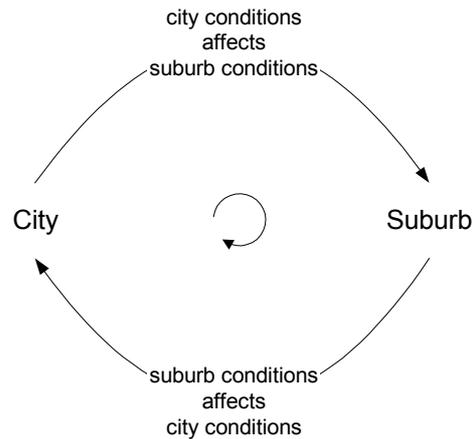
Figure 4: A city-suburb feedback relationship

Schroeder wants to answer two questions. First, if any feedback relationship between the city and the suburb explain the urban life cycle of growth, maturation and decline? Second, if the feedback between the city and suburb changes the policy recommendations of the Forrester model.

The approach adopted by Schroeder is to develop two (Forrester) urban dynamics models, which are identical. One model is representing the city and the second model represents the suburb. The total migration into the city is determined by the total attractiveness of the city (central city plus the suburbs) relative to its environment. The total migration into the city is distributed over the central city and suburb based on their relative attractiveness. The migration between the central city and suburb depends on the residential conditions. In short, people work and live in one area or they work in one area and live in the other area. However it is assumed when people arrive in one area they work there too. To illustrate this point, if people arrive in the central city they work there too and the only possibility is that they start living in the suburb.

Schroeder's model is a simple extension of the Forrester model to tackle the model boundary problem (figure 3). This extension is subject to the same criticism as the Forrester model. The major assumption is that the behavior of the two areas is endogenously driven and that the influence of the environment does not significantly contribute to the behavior of the city and the suburbs.

The division of the metropolitan area in a city and suburbs introduces the spatial dimension. However, this is done in a correct but unclear way. The visual complexity of the model is increased tremendously by the introduction of suburbs in Schroeder's model.

Burdekin (Burdekin 1979) splits the urban area in 16 zones, in order to model the mixture of different housing types in zones of a city. It is assumed that the residents in the urban area are distributed over the zones proportional to the housing types in the various zones. The migration into and out of the city is based on the citywide conditions but the population is not disaggregated over the different zones (figure 3).

Sanders 2004

The concept adopted in this research is to divide the urban area into 16 zones. This represents the reality in a more accurate way, because it includes the zones in a city as individual endogenously driven systems that all communicate with their environment (figure 3).

This is an improvement to the previous versions of urban dynamics models, in which the suburbs are aggregated (into a suburb ring). This aggregation does not justify the settlement patterns observed in the reality and the aggregation omits the possibility that the zones in a city have different characteristics (mixture of population, housing and business) and therefore different functions in a city. For this reason it is better to formulate different zones in a city.

A second reason to disaggregate city in different zones is the possibility to introduce competition between the zones. Furthermore, the disaggregation allows a better representation of the behavior of individuals in an urban system, because individuals relocate over relatively short distances (within the city). The relocations of people within the city are very important in the development of neighborhoods in the city. The social environment of a person allows him to observe opportunities within the city (zones) sooner than in the surrounding environment. In other words, if an area has high-perceived attractiveness, this will observed sooner by individuals that live closer to this area.

The statement above is supported by the evidence presented in Blijie, de Bok and Sanders (Blijie, de Bok, and Sanders 2003). The majority of the relocations of households are over a very short distance. 90 % of all relocations in the Netherlands are within a distance band of 40.5 km (with an average of only 13.5 km). Depending on the reason for the relocation the distance varies. If the reason to move is job related the distance is on average longer (50.8 km).

The inter-zonal migration can influence the total migration to and out of the city. A difference between the attractiveness of two zones will be balanced by the internal migration and consequently make the total attractiveness of the city relative to its environment different from what it otherwise would have been. The latter leads to different migration to and out of the city.

The difference between the Burdekin model and spatial urban dynamics model is that the population is disaggregated based on the zones in the city. This allows the model to include zonal factors as social mix, housing availability and job accessibility, which are important determinants in movement behavior of individuals.

2.4 Spatial Dynamics

2.4.1 Spatial dynamics in biological systems

The spatial dimension has not received a great deal of attention in system dynamics modeling. An intensive literature review showed that there are only a number of articles dealing with this subject. A summary of the relevant literature is given in *Modeling dynamic biological systems* (Hannon and Ruth 1997) and in *Modeling the environment: An introduction to system dynamics modeling of environmental systems* (Ford 1999).

Hannon and Ruth (1997) recognize the importance of the spatial dimension in the modeling of biological systems. A *mobility framework* is specified in which migration from one state to another depends only on the current status of the donor state. They use this formulation to introduce a spatial dimension to the classical predator-prey model, making it possible for the prey to migrate to another region. The migration of the prey is referred to as mobility. The spatial aspect is modeled by defining four subdivisions of the landscape as laid out in figure 5.
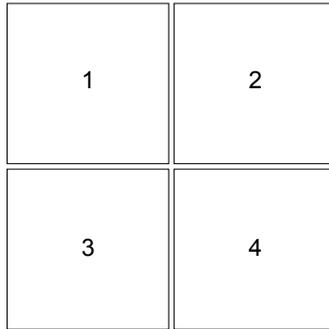
Figure 5: The spatial aspect in the classical predator prey model.

The specification in this model only allows the predators to migrate to an adjacent cell. This means that only migration from cell 1 to cell 2 or 3 is possible. The prey migrates routinely regardless of their population in the starting or the receiving cells, and predators migrate to a new cell when they begin to starve in their current cell.

The examples described in the book are very simple models. Despite the simplicity of the model the specification already leads to a great deal of visual complexity. A second observation is that the interaction between cells is only with adjacent cells. For many biological problems, like the migration of toxic fluids across a landscape, this is fine. However if one looks at the migration of people this implicit assumption is incorrect.

It can be concluded that there is analogy between the biological examples and the application of urban dynamics. However, a different formulation for the spatial dimension is necessary.

The obvious way to link urban dynamics with the insights in this section is to define an endogenously driven system for each cell. This endogenously driven system determines the internal conditions for the total area. These internal conditions (for example job opportunities, housing availability or availability of accommodation for business structures) represent the relative attractiveness of each area. Based on this relative attractiveness, people and firms will relocate (change between different areas).

The major difference with the spatial dynamics described in biological systems is that migration is possible between areas that are not flanking (figure 6). The reader should keep in mind that time scale of the dynamics of interest is different for biological systems and urban systems. During the migration of people in an urban area they have to travel through adjacent cells, however this short-term dynamic behavior is not necessary to capture in the long run dynamics.
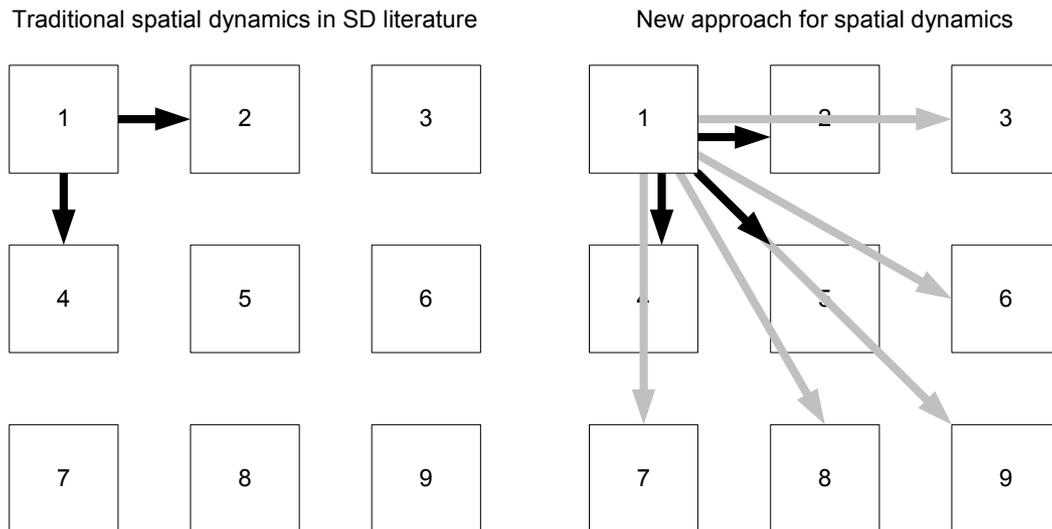
Traditional spatial dynamics in SD literature   New approach for spatial dynamics

Figure 6: The difference between the traditional and new approach for spatial dynamics

In the traditional approach the migration out of area 1 must be to an adjacent area 2 or area 4. The total number of possible flows is 18 divided by 2, because the relative attractiveness of two areas leads to one flow. If area 1 is more attractive than area 2 only a flow between area 2 and area 1 is specified and no flow between area 1 and area 2.

The new approach for spatial dynamics makes it possible to specify the migration flows between all 9 areas. A migration flow is the total number of people who leave zone 1 to settle in for example zone 5. The total number of possible flows is 72 (=9*8) divided by 2. The challenge is how to define the flows between the regions. A good suggestion is to use matrix based calculations, which are possible through the array functions in the SD software packages.

2.4.2 The formulation of an alternative hypothesis

The alternative hypothesis proposed in this paper challenges two elements in traditional urban dynamics research. First, the poor representation of the spatial dimension in the mentioned urban dynamics models is challenged. The author feels that the influence of the spatial dimension is underestimated in these models. For example the distance between a persons job and home is very important in the decision to commute or to migrate.

Second, to view urban areas as endogenously driven systems is a good assumption. The urban area is divided into 16 zones. This alteration makes it possible to judge the influence of the different zones on each other and on the total behavior of the system. This introduces competition between the different zones in a city.

Furthermore this will create different attractiveness levels for the different zones. These attractiveness levels control the migration flows within the city (between the zones) and from and to the city. The behavior is not necessarily different from the behavior observed in the Forrester model. However, the introduction of a more sophisticated spatial representation will lead to better understanding of the urban system and can present evidence on the value of the traditional criticism. The users will perceive the model as a more accurate representation of the reality, because it matches their firsthand knowledge about the system (the state of different neighborhoods in a city). This hints at a possible failure of the Forrester model. The

level of aggregation may be to high, because users of the model do not recognize the problems experienced by them in various zones in the city in the overall behavior.

The level of aggregation should be zonal. Evidence for this statement is given in the next table that includes the migration for the city of Rotterdam (the second largest city in the Netherlands). The migration consists of two types, inter-zonal and migration to and out of Rotterdam in the year 2002.

Table 1: The migration for Rotterdam in the year 2002 (COS 2004)

The 15 zones	# of migrants from other zones	# of migrants to other zones	# migrants to the Rotterdam	# migrants out of the Rotterdam
Stadscentrum	2103	2547	2527	2100
Delfshaven	6538	8144	5467	4886
Overschie	908	893	470	682
Noord	3954	4768	3448	3123
Hillegersberg-Schiebroek	3176	1919	1626	1635
Kralingen-Crooswijk	3939	4325	2962	2850
Prins Alexander	4244	3266	2889	3319
Feijenoord	5758	6245	3803	3117
IJsselmonde	4439	2908	2544	2788
Charlois	6019	6439	4861	4455
Pernis	76	85	63	115
Hoogvliet	1881	1518	1510	1602
Hoek van Holland	116	86	312	276
Habor	11	19	24	21
Total	43162	43162	32506	30969

The information in the table illustrates that the inter-zonal migration is considerable in relation to the cross-city boundary migration.

The main purpose of modeling is problem solving. In light of double-loop learning models, Argyris and Schön (Argryris and Schön 1978), problem solving can take different forms. At one level, the main challenge is to convince urban planners and politicians that a problem exists and that improvement are possible.

The model should include behavior that the users observe in reality. As the users of the model gain trust in the insights, one could use aggregated models to explain the urban system to third parties. As the problem is acknowledged, the problem is often dealt with at another level where more detailed and advanced policy analysis may be appropriate.

The model described in this paper belongs to the first category, because it focuses on building of understanding and facilitating learning of the urban system in general. An application of this model to a specific city would belong to the second category.

The complexity of the urban system makes simulation absolutely necessary in the development of effective policies.

The developments in the SD modeling software make it possible to reduce the visual complexity of the model compared to previous research (through arrays, figure 3) and therefore test the alterations in the model structure and the model boundary.

The hypothesis:

The behavior of the original Urban Dynamics (growth, overshoot and stagnation) will change when one includes the spatial dimension in an explicit way and additionally will result in better understanding for policymakers.

3 The spatial urban dynamics model

The dynamic hypothesis in this research builds on the model of Forrester. Therefore it is important to show the relationship with the Forrester model. The core of the model is quite similar to Forrester. The added structures are:

1. Explicit spatial dimension (figure 7)

The city area is divided in 16 equal squares of side 3.125 miles. The 16 squares add up to the 100,000 acres in the spatial urban dynamics model like in the Burdekin model (Burdekin 1979).

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Figure 7: The zones of the city

2. Disaggregation

The different types of housing, industry levels (including an additional group of industry, service industry) and people are identified within each zone. Each zone has its own stock of housing, industry and residents.

3.1 The spatial urban dynamics model

In figure 1 (section 1) the interactions between the important stocks within the urban system can be observed. The figure shows that people need a house and a job and the housing and industry sector compete for the available land. In this section the interactions between the three major sectors are explained, beginning with the housing sectors. The industry sector and the migration of individuals are described thereafter.

3.1.1 The housing sector

In order to explain the spatial urban dynamics model it is crucial to show the relations between the important stocks (housing, industry and people). In the next three sections it is illustrated how the different stocks are connected with each other.
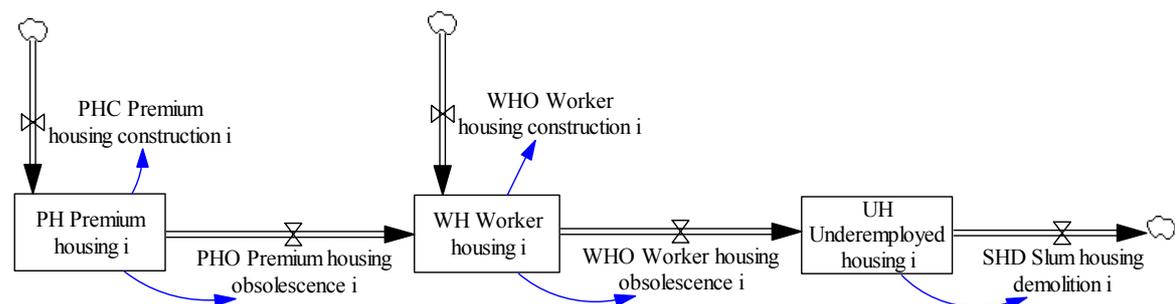

Figure 8: The housing sector

In figure 8, the process of housing filtering down is specified. Housing filter down denotes the process whereby aging and obsolescence of housing units invite occupancy by successively less affluent residents (Alfeld and Graham 1976). The physical deterioration (as repairs are never as good as the original) reduces the desirability and profitability of a housing unit. Another mechanism of importance is obsolescence. As the living standards rise and technological progress continues,

occupants start looking for new facilities in their housing units. As the process of aging and obsolescence continues the maintenance costs continue to rise. At some point in time, the housing unit is no longer viable as an economic entity. The premium-housing unit filters down to the worker-housing sector.

The reader may argue that the opposite process of aging and obsolescence can be observed in reality (retrofitting). In the current model this is possible when there is high demand for premium housing, a lack of space and there is a negative utility of living with lower economic groups. The obsolescence of premium housing can become very low in this case.

The next question is how the flows of housing construction and obsolescence are influenced by the state of the city. The construction rate and the rate of obsolescence are specified by the product of a set of multipliers, which consists of the various forces influencing the rates and the current level of housing units. This multiplier combines the influence of 8 forces:

- The demand for housing in the total city. As housing becomes scare, this provides incentives to increase the construction of housing.
- The social mixture of a particular zone. This accounts for the fact that the construction rate is dependent of the residential mixture in the zone.
- The blend of the housing types in a zone. As the fraction of premium housing increases the construction rate of premium-housing rate will increase relative to the construction of worker housing.
- The land availability in a zone. As the land in a zones fills the construction rate will increase because of the increased utility. The construction rate will diminish as the land becomes fully occupied.
- The tax level in the city. This factor illustrates the city's attractiveness compared to its surrounding based on the tax level. As the tax level in the city rises, the construction rate declines.
- The business confidence in the city. The establishment of new enterprises tends to encourage construction of new housing for the people associated with the industrial expansion.
- The momentum of recent construction (rate of change) in housing itself tends to carry forward and cause still more housing construction in a zone.
- The attractiveness of the zone based on the accessibility of the zone to jobs. As it becomes easier to reach jobs in or from a zone, the construction rate in this zone will grow.

This last factor reflects the zone's favorability for future households based on the access of the zone to jobs. If a zone has relative (to other zones) good access to employment the construction rate should be higher than it otherwise would have been. The zone's accessibility to jobs is measured as the number of jobs divided by the distance (to the power 2) to those jobs. The zone's job accessibility is compared to the average job accessibility of all zones to indicate its attractiveness for construction (equation 1). The numerator in equation (1) specifies how easy it is to reach the jobs in all zones from zone 1 (or any other zone).

The area's relative job accessibility:

$$\sum_{i=1}^{N} \left(\frac{MJ(k)}{TDFC(i,k)} \right) \Big/ \sum_{i,k=1}^{N} \left(\frac{MJ(k)}{TDFC(i,k)} \right) \tag{1}$$

N = The number of zones in the city

MJ = Manager jobs in zone k
TDFC = Trip distribution function construction i

The trip distribution function is the distance between zone i and zone k to the power 2, to include the deterrent effect of distance. The distance is taken as the length of the straight line between the midpoints of the zones. A more detailed description of the trip distribution function is given in Wilson (Wilson 1974).

The construction of housing in the zones is based on a combination of zonal factors and citywide factors. The term 'citywide' means that an influence is the same on all the zones in the city and consequently is not specified on a zonal level. The citywide factors are the impact of tax, the business confidence and the influence of the demand for housing. The five other mentioned forces are influences on a zonal level.
The construction rate for housing is constrained by the available labor for construction. The assumption hereby is that the construction rate is only constrained by citywide available labor, meaning that construction workers are able to travel throughout the complete city to do their work. This concept is also used in the industry sector and the worker-housing sector.

The factors controlling the construction of housing have the inverse effect on the filtration of housing. As the urgency of new housing construction increases, the obsolescence rates declines and the average life of housing unit's increase.

The worker housing and underemployed housing sector
The premium housing and the worker-housing sector are specified in the same way. However the premium-housing sector is influenced by managerial-professional sector and the factors related to this sector. For example, the pressure of the location attractiveness of a zone for premium housing construction is dependent of the accessibility to managerial jobs and the worker housing construction is controlled by the accessibility to labor jobs.
In the underemployed housing sector, the slum housing demolition multiplier controls the slum housing demolition. The latter is partly dependent of the accessibility of a zone to labor jobs. This means that the underemployed provide pressure to decrease the slum demolition rate in a zone if the accessibility to labor jobs is above average. It can be questioned if the underemployed can exercise this pressure.

3.1.2 The industry sector

In the model, two types of industry are defined: the basic industry and the service industry. The basic industry exists of new enterprises, mature business and declining business (figure 9).
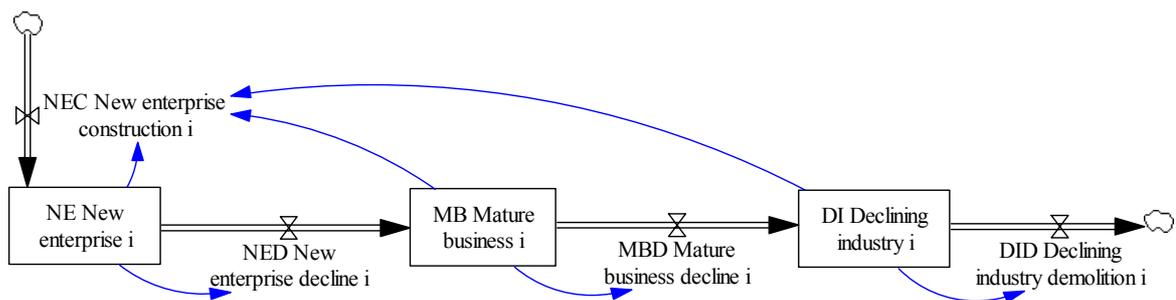
The basic industry sector

The basic industry sector is very similar to housing sector in figure 8. The construction of new enterprises changes through 6 forces:

- The fraction of managers in the city. As the fraction of managers grows in proportion to the managerial jobs the likelihood of establishing new enterprises increases, because the managerial population has more time and incentives to start new enterprises.
- The availability of land in the city. This concept is the same as discussed in the housing sector section, except that it deals with the citywide land availability.
- The availability of labor in the city. The construction of new enterprises is depressed if there is a shortage of labor in the city and encouraged if there is an excess of labor.
- The influence of the tax level on the new enterprise formation. As the tax level is high relative to the city's surrounding, the formation of new enterprises is discouraged.
- The influence of business confidence on the formation of enterprises. If the recent growth rate for new enterprises has been high, this will encourage further growth and vice versa.
- The mixture of the basic industry types. The new enterprise has weighting factor of one, meaning that a unit of new enterprises is most likely to form another new unit. The mature business has a weighting factor of 0.5 and the declining industry 0.3.

The creation rate of new enterprises is controlled by citywide conditions relative to the environment of the city like in the Forrester model. However the basic industry has a prior claim to certain zones (zone 1,5,6,9,10 and 13). This means that the growth of industry is only allowed in these zones. This concept implies that it is an external decision that determines in which zones basic industry is allowed. The designation of zones to industry could also be used as a policy variable.

The filtration of basic industry is influenced by the factors above in an inversed way, like housing demolition in the housing sector.

The service industry
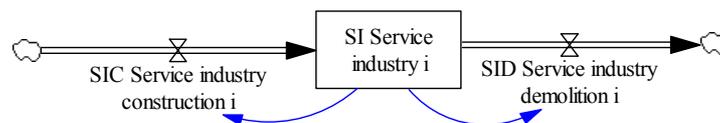Figure 10 displays the stock and flow diagram for the service industry.

Figure 10: The service industry

The service industry is second type of industry added to the model and consists of one stock for reasons of simplicity. The service industry is location sensitive. Location sensitive implies that construction of service units in a zone is dependent of the accessibility of that zone to housing units. In other words, the formation of service industry units will increase as the zone has more access to households (see equation 1). Besides this influence, these 7 pressures control the construction of service industry:

- The fraction of managers in the city. As the fraction of managers grows in proportion to the managerial jobs the likelihood of establishing new service units

increases, because the managerial population has more time and incentive to start new enterprises.

- The availability of labor in the city. The construction of new enterprises is depressed if there is a shortage of labor in the city and encouraged if there is an excess of labor.
- The influence of the tax level on the service industry formation. As the tax level is high relative to the city's surrounding tax, the formation of new enterprises is discouraged.
- The influence of recent developments on the formation of service industry. If the recent growth rate for service industry has been high, this will encourage further growth and vice versa.
- The availability of land in the zone. This concept is the same as discussed in the housing sector section.
- The influence of the density of housing units in a zone. The idea is that a normal service level should be maintained in a zone. The number of service units in proportion to the number of housing units should be around 1/150. If this ratio is smaller than 1/150 this provides extra incentives to construct service units.
- The influence of the citywide density of people. The normal service level in the city is one service unit for every 900 persons. If the current citywide service level is lower than the normal service level, this encourages the formation of service industry.

The construction and filtration of service industry is controlled by a blend of citywide and zonal pressures.

3.1.3 Attractiveness principle and migration of people

The migration in Urban Dynamics is directed by the attractiveness principle. The moment the attractiveness within the area is higher than the surrounding environment the migration to this area increases and migration out of the area decreases. In figure 11, the three different groups of persons in the model are displayed and how they relate to each other.
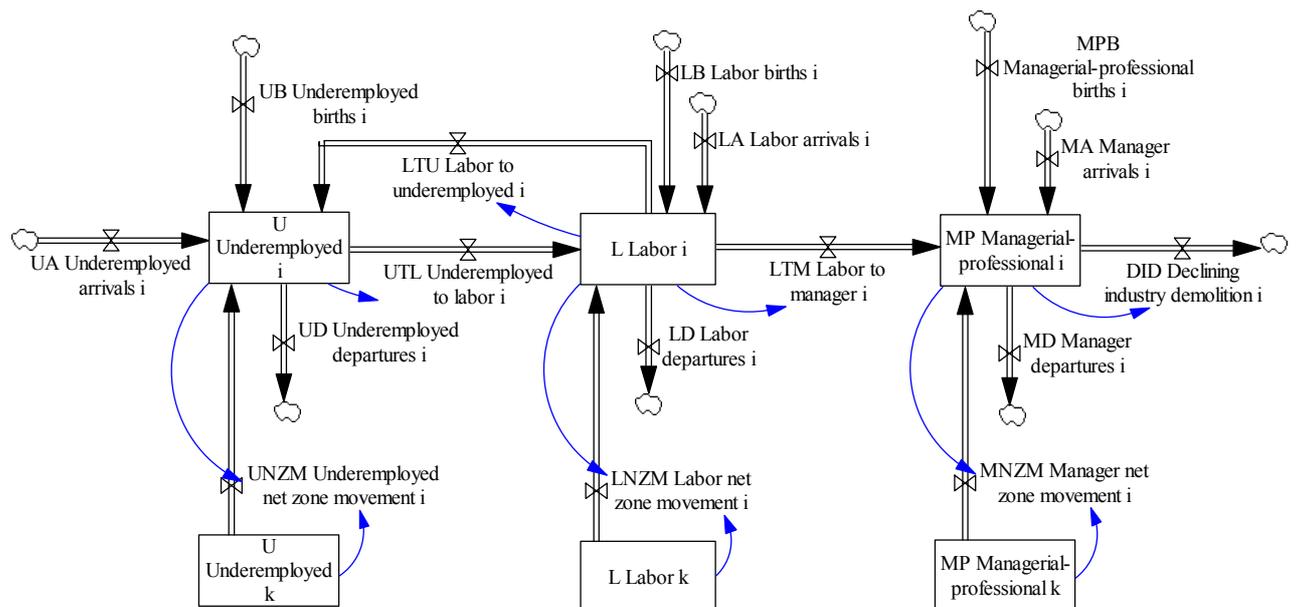

Figure 11: The migration of persons

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The first flows into the stocks of persons are the births of the three groups of persons. The flow is actually the net difference between the birth rate and the death rate in the city and is proportional with the distribution of the persons over the zones.

The arrivals and departures of residents into or out of the city are controlled by the attractiveness of the city relative to its environment. As the attractiveness of the city exceeds the attractiveness of the environment the arrivals will grow and the departures will reduce. The supposition is that persons will migrate to and out of the city based on the citywide attractiveness and consequently the flows are proportional with the distribution of the residents over the zones. The attractiveness is specified the same as in the original Forrester model (see appendix A or (Forrester 1969), p 137).

The flow of underemployed to labor represents the upward economic mobility. The upward economic mobility is influenced by the social and economic conditions in the city. As the scarcity of labor increases the upward mobility of underemployed will rise. The upward mobility is more difficult as the labor group decreases relative to the underemployed. It covers the influence of dominant blocks of underemployed in a particular zone where they do not intermingle with other economic groups. The effect of education in upgrading economic skills is made a function of the tax per capita. The flow of labor to managers is specified in a similar way. On the other hand, the flow of labor to underemployed grows as the proportion of labor to labor-jobs rises and is suppressed as this proportion falls.

The specification of the departure and arrival of the different groups of persons are controlled by the concept 'attractiveness'. The attractiveness is a product of different components of attractiveness: the upward mobility of underemployed, housing availability, economic opportunities and the public expenditure per capita.
The equations for the arrivals and departures from and to the environment can be combined to specify the migration flows between the zones within the urban area as suggested by Kadanoff and Weinblatt (Kadanoff and Weinblatt 1972). The underemployed arrivals are specified as:

$$UA \text{ Underemployed arrivals } i = (U+L)*UAN*AMMP \tag{2}$$

U = Underemployed i (person)
L = Labor i (person)
UAN = Underemployed arrival normal (fraction/year)
$AMMP$ = Arrival migration multiplier perceived (dimensionless)

And the equation for underemployed departures is:

$$UD \text{ Underemployed departures } i = U*UDN*UDM \tag{3}$$

U = Underemployed i (person)
UDN = Underemployed departures normal (fraction/year)
UDM = Underemployed departures multiplier (dimensionless)

This leads to the following equation for the migration (relocation of households) for underemployed population from zone 1 to zone 2:

$$\frac{(U_1/A_1) \times (U_2 \times AP_2)}{Total\_U} \tag{4}$$

Zone 1 includes underemployed population U_1 and A_1 is defined as the attractiveness of zone 1 for underemployed population U_1. Zone 2 has a perceived attractiveness AP_2 for the underemployed in zone 1 and represents a proportion of the total citywide underemployed group U, given by U_2 divided by the total underemployed group. It is

assumed that the migration is governed by the attractiveness in the same fashion as in equation (2) and (3). The probability that an underemployed person will migrate from zone 1 to zone 2 is proportional to the number of underemployed in that zone relative to the number of underemployed (citywide). The migration rate from 1 to 2 is a constant times the equation (4).

The next important question is how to formulate the attractiveness factor controlling the inter-zonal migration flows. Van Ommeren (Ommeren 2000) presents evidence suggesting that the two major forces in choosing a new residence location are: job opportunities and housing opportunities. In other words, a person that decides to move is basically tide to a job and to a housing elastic.

The accessibility of a zone to jobs is specified as in equation (1) and reflects the force of the job opportunities. The housing opportunities are included as a ratio of the number of houses and households of the corresponding level.

In the model, a third important force is included, namely the social mixture of a zone. The social mixture is important because managers and professional workers preferably do not choose a residence location (zone) in which a high fraction of underemployed persons is living.

The influence of tax level used in the Forrester model to partly determine the attractiveness for cross-city boundary migration has no influence in the inter-zonal migration because it is the same for all zones.

In summary, there are three migration flows. First, the migration flow to and out of the city is based on the citywide attractiveness but proportional with the density of the three economic groups in the zones. Second, there is the upward economic migration. This flow is controlled by a combination of zonal and citywide conditions. The last type of migration is the inter-zonal migration, which is naturally managed by the zonal attractiveness.

Implications of the new structure

The two markets mentioned in section 1 are disaggregated into zones in different ways. In the labor market, the zones in which the industry construction is allowed provide the demand for labor. The supply of labor is partly allocated by the access of people to jobs of their level of competence.

The housing market is now divided into zones. This means there is housing market in each zone. The market for service industry structures is basically the same as the housing market with no restriction on the location. The basic industry structure location on the other hand is pre-determined by external decision. Therefore no influence of the available labor on the location choice of basic industry is assumed.

4   The behavior of the model

The citywide initial conditions of the model are the same as in the Forrester model. The zonal initial conditions mainly distributed in zone 5 and 9:
- Premium housing: 2150 (zones 5 and 9), 50 in remaining zones
- Worker housing: 10150 (zones 5 and 9), 50 in remaining zones
- Underemployed housing: 480 (zones 5 and 9), 10 in remaining zones
- New enterprise: 100 (zones 5 and 9), 0.01 in remaining zones
- Mature business: 500 (zones 5 and 9), 0.001 in remaining zones
- Declining industry: 50 (zones 5 and 9), 0.001 in remaining zones

- Service industry: 85 (zones 5 and 9), 1 in remaining zones
- Managerial-Professional: 1676 (zones 5 and 9), 39 in remaining zones proportional with the premium housing density
- Labor: 6766 (zones 5 and 9), 33 in remaining zones proportional with the worker housing density
- Underemployed: 523 (zones 5 and 9), 11 in remaining zones proportional with the underemployed housing density

In order to present the results in a clear manner it should be noted that the results of zone 1-8 are symmetrical to the results of zone 9-16. The reason is the initial values for the stocks in the zones. The geographically location of zone 1-8 in relation to zone 9 is the similar to the geographically location of zone 9-16 in relation to zone 5 (see figure 8). The moment one changes the initial values of the stocks in the zones the symmetry of the zones would be lost and the results of all the 16 zones should be represented. In this paper, the output of zone 1-8 is presented in the graphs.

The equilibrium that is reached by the model is not sensitive to the initialization of the model. The equilibrium totals of the population, housing and industry units are constrained by the available land. However with a different initialization the distribution of the population, housing and industry units over the zones and the mixture in the zones will change.

4.1 The base behavior

The aggregate behavior
The equilibrium totals of the population and housing are equal and the total number of industry units is lower relative to the results of the Forrester model (figure 12). The latter is due to the mixture the industry sector. The service industry has the same characteristics (higher number of jobs per industry unit) as the new enterprises in the basic industry. This means in the current model a lower number of industry units offer the same amount of job opportunities in the city.
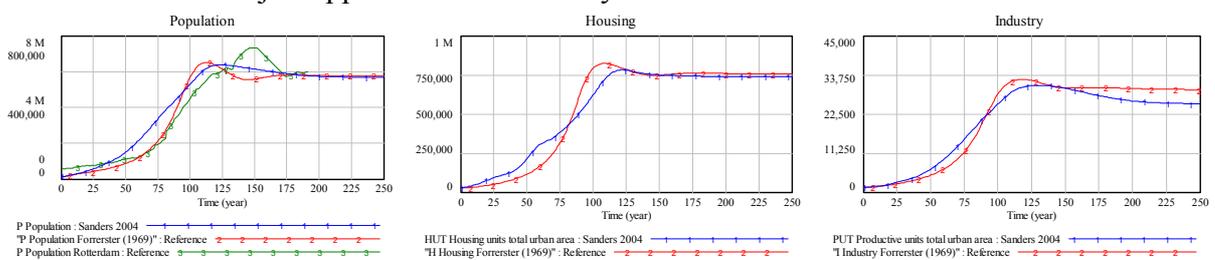

Figure 12: The base behavior in comparison with Forrester (1969)

The behavior type (growth, overshoot and stagnation) for population can be observed in the City of Rotterdam (line 3 in the first graph of figure 12). The overshoot of the spatial urban dynamics model is very small compared to the Forrester model and the city of Rotterdam (after WO II, there is second growth period because of new housing-types and new available land). However until WO II the growth pattern of the city of Rotterdam seems to be more consistent with spatial urban dynamics model than with original model. The match between real data and the model should not be emphasized and no conclusions should be drawn from this information; it is given as an illustration of the pattern of development of real city.

The reason that the overshoot is smaller than in the Forrester model is that it takes place in every zone and on different points in time (see figure 17-19). For example, the land in zone 5 fills up and an overshoot can be observed in zone 5. This overshoot

is compensated by the growth that starts zone 6 and 1 (figure 17). Basically, the limited area in a zone does not impact the development of the total city very much because it is balanced by the growth in areas where land is still available.

The behavior of this complex model is not easy to analyze and explain. The reader must keep in mind that only the flows can change the stocks (housing, population and business structures). If growth takes place in for example the premium-housing sector this means that the construction rate is higher than the filtration rate. The causes for this situation can be found by examining the equations or by examining the behavior of the variables after simulation. This strengthens the author in his belief that an interactive learning environment (Davidsen 2000) would be an efficient tool in explaining the observed behavior in this model.

In an interactive learning environment (ILE), the user can be directed to the important structures to understand the behavior in an automated fashion. The attention of the users is led to the causes of the dynamic behavior. The interactive learning environment forms an environment in which the users of the ILE can execute policy testing and experiments in a controlled manner.

The zonal behavior

In zone 5 and 9 most of the early growth takes place because the construction of housing depends on zonal conditions that are higher in these zones than in the rest of the zones. The growth of the basic industry depends on the citywide conditions, causing the housing construction to spread outwards to other zones as zone 5 and 9 fail to provide the necessary labor and housing. The expansion and the growth of housing, due to the industry expansion, introduce delays in the total development process.
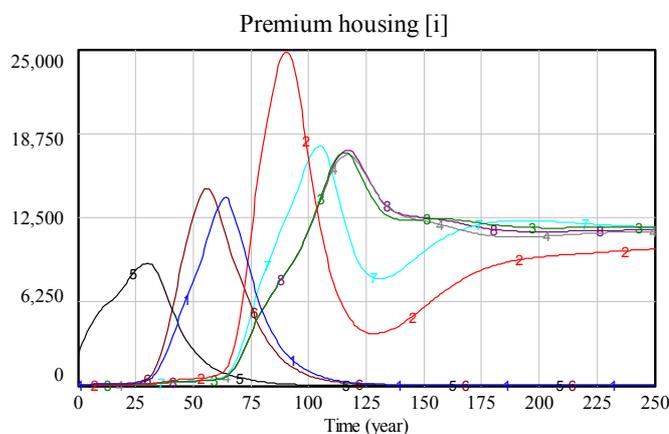

Figure 13: The base behavior for premium housing

The number of premium housing in zone 5 and 9 peak around year 30 (figure 13). After that the inner-city zones peak every 10-15 years, beginning with zone 6 and 10. In the zones where basic industry is present the premium housing almost disappears (except of zone 2 and 14). The assumption that the location attractiveness multiplier is less strong than for worker housing and underemployed housing, causes the premium housing to distribute mainly in outer zones (without basic industry). This assumption implies that people (managers) who live in premium housing are willing (and have means) to travel longer distances to their job than people in the other housing types.
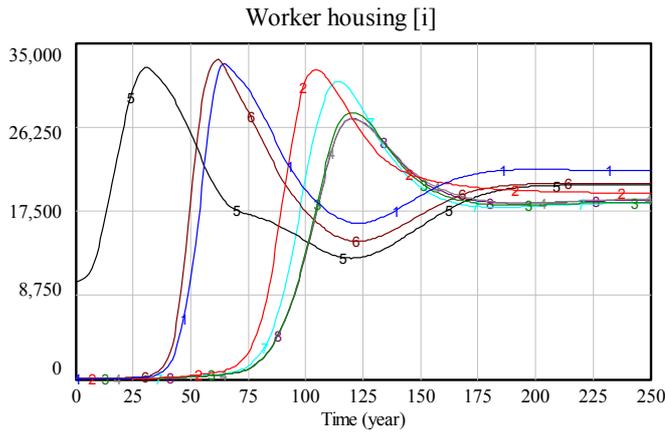
Figure 14: The base behavior for worker housing

Worker housing gets established in all zones because of the stronger location attractiveness multiplier and the filtration of premium housing.

The reader should note that the overshoot and stagnation behavior in the Urban Dynamics model can be observed in every zone (figure 13-15).

The development of the underemployed housing is more stable (figure 15). The volatile conduct as observed in the premium housing and worker-housing sector is more dampened. This is rooted in the filtration process, as the filtration from premium housing to worker housing is expressed as the number of premium housing multiplied with a fraction. The variation in the level of worker housing becomes less volatile because the flow of premium housing to worker housing dampens the variation effect (in this specification).
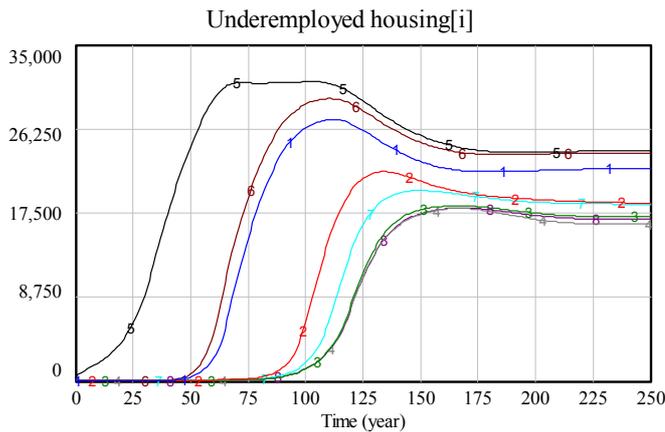
Figure 15: The base behavior for underemployed housing

The distribution of underemployed housing over the zones is originated in the competition for available land. In the non-industry zones, the service industry and the two other housing types (worker and premium housing) are established and sustained sooner.

The basic industry is not very interesting to discuss in detail. The growth is basically specified in the same way as in the Forrester model, because no location attractiveness multiplier is included and the growth is influenced by citywide factors.
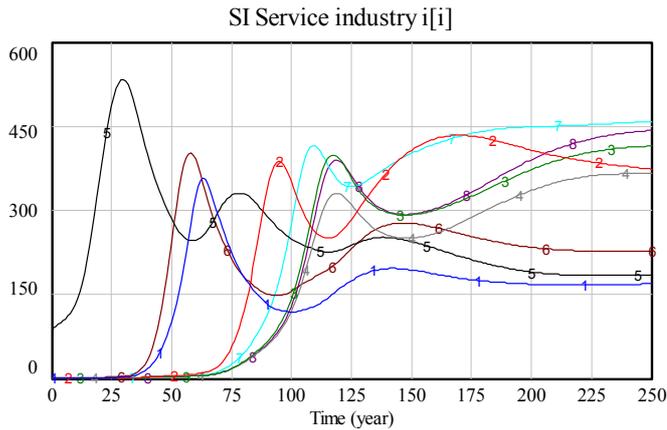
Figure 16: The base behavior of the service industry

The service industry on the other hand shows more interesting conduct (figure 16. In equilibrium condition the distribution of the service units over the zones is roughly proportional with the zones location attractiveness, as the total number of households is evenly distributed over the zones. The second mechanism that contributes to the development of the service industry is that zones 1,5 6, 9, 10 and 13 are already filled with other functions (basic industry and housing) and therefore no land is available in the zone.

The different classes of population are distributed over the different zones by the attractiveness principle. As one zone becomes more attractiveness more residents will migrate to this zone. The attractiveness of a zone is a combination of the housing availability, social mixture and the accessibility to jobs.

The dispersal of residents over the zones in the equilibrium state is proportional to the distribution of the matching housing sectors (premium housing for managers, etc), corrected for the zones accessibility to jobs and social mixture. The behavior has the same trajectory as the development of the housing types, because the jobs develop in a stable manner.

In figure 17-19, the reader can observe that the distribution of the persons is different from the distribution in the housing sector (figure 13-15) for the reason explained above.
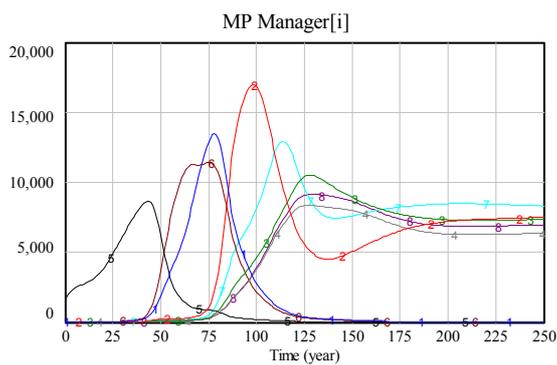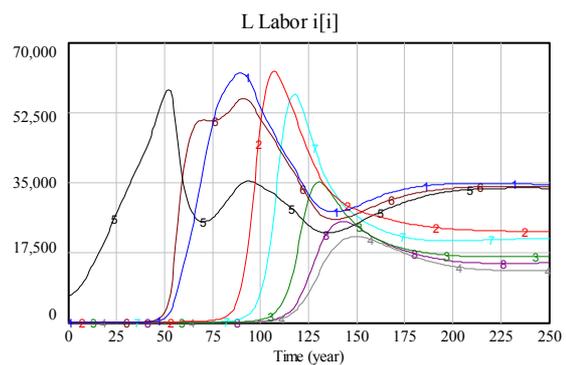

Figure 17: The base behavior of managers

Figure 18: The base behavior of labor
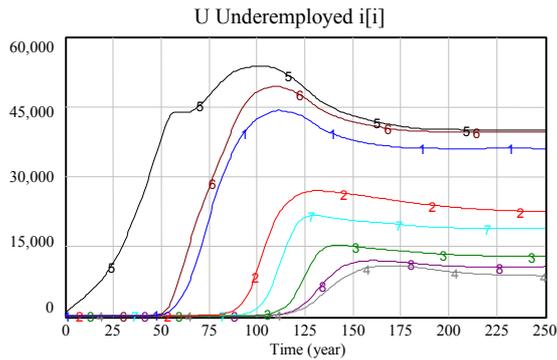
U Underemployed i[i]

Figure 19: The base behavior of underemployed

The reader can judge the effect of the job accessibility on the movement behavior, if he compares the order of the zones in figure 17-19 with the order of the zones in figure 13-15. For example in figure 17, the order of the zones is 7,2,3,8,4,2,1,6 and finally 5. In figure 13 the order is 7,8,3,4,2,1,6 and 5, meaning that zone 8 has the second highest number of premium houses. If the managers were distributed proportionally with the premium-housing zone 8 would have the second highest number of managers, which is not the case. Zone 8 has less access to manager jobs and is consequently less attractive for settlement.

Notes on the overall behavior

The moment that the growth of basic industry is equal for all the zones where it is allowed (zone 1,5,6,9,10,13), the overall growth of basic industry is explained by the citywide conditions (like in the Forrester model). It should be noted that it takes time before zone 1,6,10 and 13 match the growth of 5 and 9, because of the higher initial values in zone 5 and 9.

The total behavior of the model is quite insensitive to changes in a single table function or parameter. The cause is the assumption of the fixed area that limits both the total numbers of industry and housing. However the industry and housing sector are tied together by the need of people to have both a house and a job. The fact that one zone can compensate for another zone causes the net cross boundary movement (citywide arrivals and departures) not to be very different from the original Forrester model.

Policy implications

The natural tendency of the city toward imbalance in which housing dominates industry might be corrected by urban policies that encourage industry and that discourage the construction of excess of worker housing. This policy is called 'Encouraging industry' in the *Urban Dynamics*. This policy is selected because it must be considered in the context the particular area to be revived (Forrester 1969). The insights of the explicit spatial dimension could be very useful as Forrester suggests using this policy on a local basis.

The policy consists of encouraging industry (increasing the new enterprise construction rate form 5 to 7% per year) and discouraging the construction of excess worker housing (slum-housing demolition 5 % per year) in all zones. The results of the Forrester model and the spatial urban dynamics are summarized in table 2. T = -5 year is the value of the model in equilibrium 5 years before the policy is applied (T = 0).
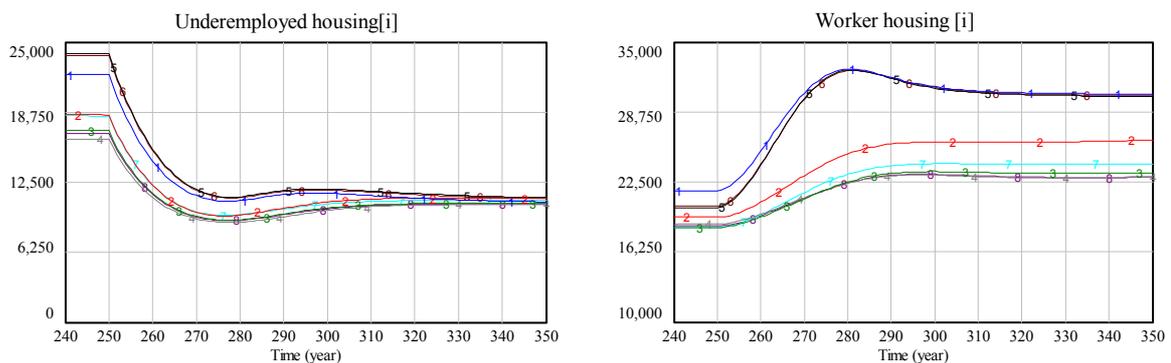
Table 2: The changes caused by the policy described above. (T = year)

Variable	Symbol	Urban dynamics			Spatial urban dynamics		
		T = -5	T = 50	Change(%)	T = -5	T = 50	Change(%)
New enterprise	NE	4900	8000	63%	3400	7200	111%
Mature business	MB	7800	12000	64%	5400	10500	94%
Declining industry	DI	16500	22200	35%	11400	15400	35%
Service industry	SI	----------	----------	-----------------	5300	5300	0%
Premium housing	PH	110900	152800	38%	113400	161000	42%
Worker housing	WH	335600	450600	34%	311600	425500	37%
Underemployed housing	UH	310100	175300	-43%	314100	173600	-45%
Managerial-professional	MP	71100	108700	53%	73000	109600	50%
Labor	L	392600	600000	53%	381000	587200	54%
Underemployed	U	377300	335900	-11%	378900	331400	-13%
Underemployed to labor net	UTLN	5500	9200	67%	5600	9700	73%

The table shows that the effect of the policy on overall behavior of the city does not change very much in comparison to the Forrester model. It should be noted that the model has not reached its equilibrium state yet (at T=50) after applying the policy. T = 50 is included in order to make comparison with the Forrester model possible.

The most significant change is the 111% change in new enterprises. In the spatial urban dynamics model there is a relatively small portion of new basic industry due to the addition of the service industry sector. In this policy, the land that becomes available due to the slum housing demolition is used to construct new basic industry (and not for service industry). The absolute growth of the total basic industry sector (new enterprises, mature business and declining industry) is not very different from the Forrester model (13.000 units versus 12.900 units in the spatial urban dynamics model). In conclusion, on an aggregate level the spatial urban dynamics model supports the policy recommendation of the Forrester model.

The benefit of the explicit spatial dimension lies in the fact that the reader can obtain qualitative insights. The model provides results for the various zones. In figure 20, the results of the policy for the housing sector in zone 1-8 are given. The policy is applied after year 250 because the spatial urban dynamics model is in equilibrium then. The graphs show how the policy changes the equilibrium state.
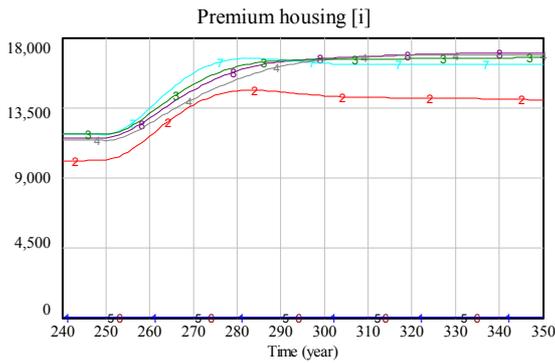
Premium housing [i]

Figure 20: The effects of policy 1 on the housing sector

The results tell the following story. First, the reader should remember that the basic industry is only allowed in zones (1,5,6,9,10 and 13). These zones are characterized by mixture of industry and housing biased towards underemployed housing. Naturally, the industry growth will occur in these zones. The unfavorable balance (old, low-income housing and basic industry) in the industry zones is corrected by this policy, creating a better balance between the housing types in the zones (figure 20). This improving balance is the opposite process of urban decay.

The policy at a zonal level
In the above description, the policy is applied to all the zones in the city. It is thinkable that in real life a policy is not applied to the whole city but only to the part with problematic behavior. The spatial urban dynamics model allows testing the implications of this fact. If the policy is only applied to zone 5 and 6, the fraction of underemployed relative to the total population in those zones decreases. The fraction of the underemployed in the other zones will increase (figure 21).
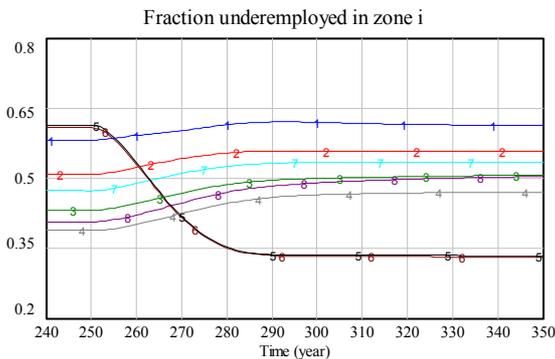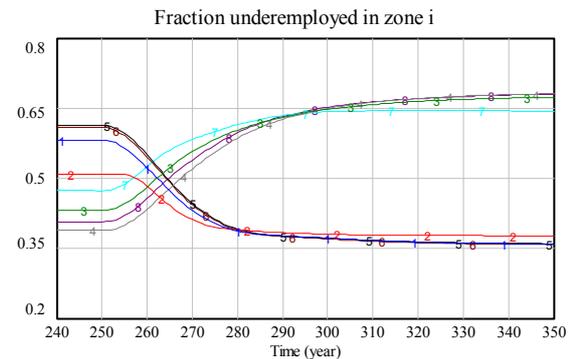

Fraction underemployed in zone i

Fraction underemployed in zone i

Figure 21: The fraction of underemployed in zone i

Figure 22: The fraction of underemployed in zone i

The total system is slightly better off as the decrease in zone 5 and 6 is not fully compensated by the increase in the other zones (the fraction of underemployed in the total city is 53.33% versus 52.40% after applying the policy).

If the policy is applied to the zones where basic industry is allowed (zone 1,5,6,9,10,13 and 2,14) interesting results can be observed (figure 22). The zones where the policy is not applied compensate (and become problematic) for the diminished fraction of underemployed in the zone where the policy is applied. In the total urban area the fraction of underemployed falls from 53.33% to 48.54% after the policy becomes operative.

The results described above illustrate the additional insights that the spatial urban dynamics model can provide relative to the Forrester model. Although the policy leads to a better situation for the total urban area, under particular circumstances the problematic behavior reoccurs in other zones within the city (figure 22). This may cause the following situation when the insights of the Forrester model are used on a zonal level. The policy is applied to a number of zones with success; the problematic

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behavior resurfaces in different zones in the city. The attention of the city shifts to these zones and the problematic behavior could reemerge in the original zones.

5 Discussion

In the previous section it is outlined that the citywide totals of population, housing and business structures in steady state are close to the original Forrester model (Forrester 1969). The trajectory of reaching this equilibrium condition is more stable. There is only a small overshoot in the citywide behavior, because of the division in 16 zones. The overshoot is visible in each zone on different points in time, but is compensated in the total growth of the city by the growth in other zones.

The division into the 16 zones allows for the reader to develop further insight and additional policies can be tested with this model. The internal dynamics of cities can be illustrated in a comprehensive manner without the model becoming too widely and losing its transparency. The current model shows the reader the different roles that the zones represent in the city. Zone 5 is a mixture of mainly basic industry and underemployed housing. This can be seen as the core of an old industrial town. The author feels that the division into zones has more appeal to the users of the model because it can illustrate why a policy is not effective on the citywide level when applied to one zone. Moreover, personal knowledge and interest is likely to be on a zonal level, so the model can facilitate effective learning.
The latter claim is strengthened by the possibility to show problematic behavior on a zonal level. Urban planners can learn how to manage the urban system by observing the interactions of people, housing, industry and the different zones. Policies trying to counter problems in one district in a town (as still can be observed in urban management) have little effect because of the interactions with other zones. A systematic approach of policies applied in a set of districts appears to be necessary.

The author believes that the inter-zonal interactions are undervalued in comparison to cross-city boundary interactions in the original Forrester model. This claim is supported by evidence presented in section 1 (table 1) and by the policy insights presented in this work.

The model is a representation of a generic theory of urban development and consequently does not focus on numerical data. The conclusions of the model are generic too. In order to draw conclusions for a specific city, one must customize the model to this city.

6 Conclusions

The result for the citywide behavior (S-shaped growth and stagnation) in the model presented in section 3 is slightly different from the Forrester model. However, on a zonal level the conduct (growth, overshoot and stagnation) of the Forrester model is still present and the overshoot is even larger. The poor long-term equilibrium conditions of the Forrester model can also be observed in the spatial urban dynamics model.
The additional level of detail in the spatial component of the model facilitates the building of deeper understanding of the complexity of the interactions in a city, because the user can learn about the different effect of policies when applied on a

zonal level or on a citywide level (section 4). Regarding, the use of the policy of encouraging industry on a zonal level the following is concluded. The problematic situation one wants to alter in a particular zone *can* resurface in other zones within the city if the 'encouraging industry' policy is used.

In conclusion, the policies recommendations of Forrester are still valid in a disaggregated model when applied to the complete city. However when the policies are applied to only part of the city, poor conditions can develop in the other zones in the city. A zonal applied policy could be interpreted as successful if the side effects are not judged as structural consequences of this policy.

Possible further developments of this model can be divided in two groups. First, changes in the model that challenges the theory on which the model is built. A good suggestion is to make the fixed area constraint flexible. The industry growth could be made dependent of the demand for goods (in contrast to the current model in which the available land and labor are the constraints for the growth). The urban spread could be modeled in a more satisfactory manner. A generic approach is suggested by Despotakis (Despotakis and Giaoutzi 1996).

The second group of developments deals with the question how to explain the results to users. The author proposes the development of system dynamics based learning environment as advocated by Pål Davidsen (Davidsen 2000). This is very interesting for educational purposes emphasizing both the management of complex systems and the principles of urban planning (Erkut 1997). An example could be to visualize the growth of the city in a spatial dimension.

The model, like every model, has shortcomings. An explicit representation of the transportation sector would help to build confidence in the theory of this model. The current model is capable of representing a city with its surrounding suburbs. However, this feature is not used to its full potential.

As pointed out by Peter Allen (Allen 1997) it should be noted that this model is deterministic. Allen acknowledges the value of system dynamics models in urban planning. His models are also built form differential equations with a more prominent role for stochastic functions and variation.

A third remark is the absence of empirical data. This devaluates the results in the eyes of certain groups of users (with a strong appreciation for models that match numerical data). A solution is the application of the model to a real city.

The system dynamics methodology proves to be flexible and appropriate in analyzing urban systems, despite the fact system dynamics has never become an established method in the field of urban planning (Alfeld 1995). The flexibility is made clear in the development of the current model and the omissions of the Forrester model in the eyes of its critics have been included to a large extend.

Note
The reader can contact the author at peter.sanders@ifi.uib.no for the complete list of model equations or check the supplementary file in the proceedings of the 22nd International of the System dynamics society for the model in Vensim format.

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Appendix A

In this appendix, a detailed description of the stock and flow diagrams and equations is given. The section looks at the attractiveness principle and the migration of persons.

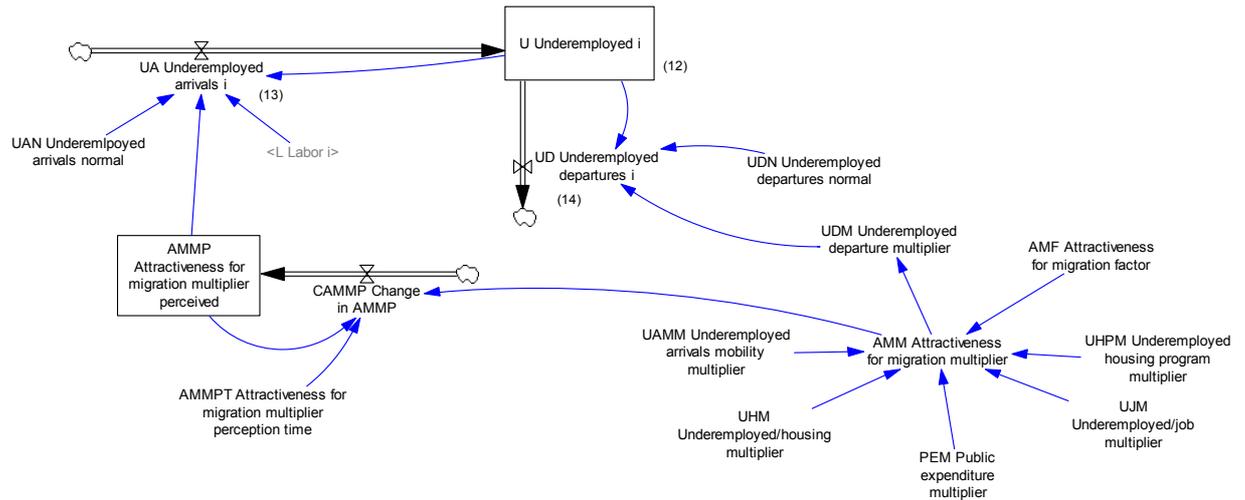**The attractiveness principle and migration of persons**

Figure 23: Migration out and to an area (selection of the underemployed view of the model)

The population is divided in three groups: unskilled workers (U), skilled workers (L) and management and professional workers (MP). The attractiveness principle works in the same way for the three groups. For the simplicity, the other flows influencing the U Underemployed namely UB Underemployed births, social migration to and from labor are omitted in figure 23 (the model includes these flows).

$\qquad$ U Underemployed i = INTEGRAL (UA-UD) $\hfill$ (12)
$\qquad$ UA $\quad$ = Underemployed arrivals i (person/year)
$\qquad$ UD $\quad$ = Underemployed departures i (person/year)

The UA underemployed arrivals are determined by a normal arrival rate multiplied with the underemployed and the attractiveness of the area as perceived by the environment.

$\qquad$ UA Underemployed arrivals i = (U+L)*UAN*AMMP $\hfill$ (13)
$\qquad$ U $\quad\quad$ = Underemployed (person)
$\qquad$ L $\quad\quad$ = Labor (person)
$\qquad$ UAN $\quad$ = Underemployed arrival normal (fraction/year)
$\qquad$ AMMP = Arrival migration multiplier perceived (dimensionless)

The UD underemployed departures are expressed by a normal departure rate multiplied with the underemployed and the attractiveness of the area compared to the environment as perceived by the persons in the city.

$\qquad$ UD Underemployed departures i = U*UDN*UDM $\hfill$ (14)
$\qquad$ U $\quad\quad$ = Underemployed i (person)
$\qquad$ UDN $\quad$ = Underemployed departures normal (fraction/year)
$\qquad$ UDM $\quad$ = Underemployed departures multiplier (dimensionless)

UDM underemployed departures multiplier in equation (14) is the inverse of the attractiveness multiplier that controls the UA underemployed arrivals.

The attractiveness factor for internal migration (AIMLM, (16) in figure 24) is the product of the housing availability (LAHM, (17)), the social mixture (LAUM, (18)) and the accessibility to jobs (LLAM, (19)). The latter denotes how easy it is to participate in the job market and therefore stands for the job opportunity force mentioned above. The formulation is based on equation (1) in section 3.
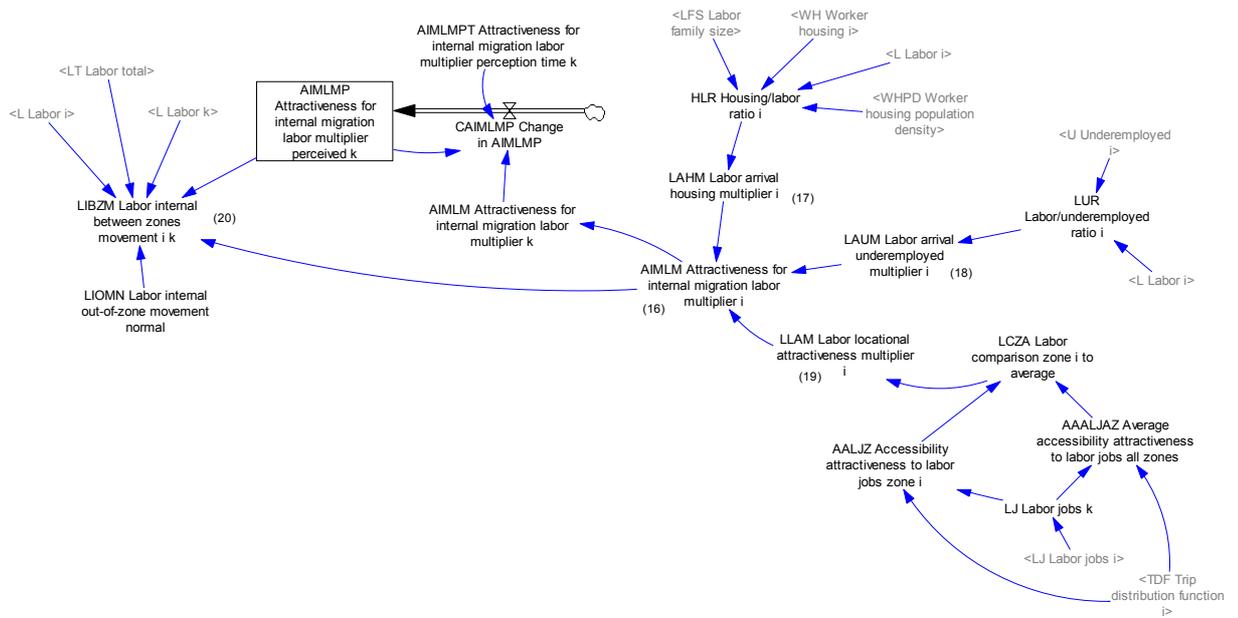

Figure 24: The attractiveness concept and the inter-zonal migration

LIBZM Labor internal between zones movement i k (20 in figure 24) is based on the formulation in equation (4) in section 3, in this equation the perceived attractiveness of k has a shorter time lag to represent the diffusion of information. This reflects the fact that it is quicker to access information about zones within the city than it is to access information about other cities.

The net zone movements are expressed as the net difference of the migration to a zone and the migration out of a zone. The migration between the different zones is formulated as suggested above in equation (4).